# PLANNING FIDER ODTIC NETWORKS

**Bob Chomycz** 

### Planning Fiber Optic Networks

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Bob Chomycz



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### Preface

The purpose of this book is to help the reader understand the details in planning and implementing fiber optic networks. Both short-reach and long-haul transmission links are discussed. All major fiber planning parameters are reviewed with appropriate background theory and practical design calculations. Guidelines are provided for planning both SONET/SDH and Ethernet networks. Practical examples are given to help the reader with theory application. The book is also easy to follow and concise. This helps the reader to quickly understand the technology without having to spend excessive time reading through copious text.

*Planning Fiber Optic Networks* can benefit the following professionals: engineers, network managers, planners, technicians, technologists students, and others interested in learning about this technology.

Suggestions and comments are always welcome. Please feel free to contact me at my email address shown below. I will do my best to try to respond to you in a timely fashion.

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# CHAPTER **1** Signal Propagation

#### 1.1 Introduction

It is important to understand the basics of optical fiber signal propagation to be able to better apply fiber design principles. This chapter introduces the theory behind signal propagation in a single-mode fiber. Multimode fiber is not discussed in this book.

#### 1.2 Carrier Wave Propagation

A single-mode fiber signal can be separated into two basic waveforms: the optical carrier and the information signal. The optical carrier is generated by a laser or LED in the transceiver and ideally has constant power (intensity), wavelength, and phase. The information signal is a waveform that contains serially encoded information that is transmitted in the fiber. Let's first consider the case of an optical carrier propagating in free space. It can be considered as a plane transverse electromagnetic (TEM) wave with the electric and magnetic field components represented by Eqs. (1.1) and  $(1.2)^{1}$ see Fig. 1.1. The electric field exists in the x-z plane and the magnetic field exists in the y-z plane both propagating along the fiber's z axis. Both electric and magnetic fields are perpendicular to the direction of propagation of the z axis and hence transverse. The components of these fields can be written as Eqs. (1.3), (1.4), and (1.5). Assume for now that the optical wave is monochromatic, consisting of just one wavelength. In reality this is not possible but is used here to help simplify the theory.

$$\vec{E} = \vec{e}_x E_x(t, z) \tag{1.1}$$

$$\vec{H} = \vec{e}_y H_y(t, z) \tag{1.2}$$

1

$$E_x = E_{x0}\cos k(vt + z) \tag{1.3}$$

$$H_{y} = H_{y0} \cos k(vt + z)$$
(1.4)

$$k = \frac{2\pi}{\lambda} \tag{1.5}$$

where  $\vec{E}$  = electric field vector polarized in x-z plane, V/m  $\vec{H}$  = magnetic field vector polarized in y-z plane, A/m  $E_x$  = electric field amplitude, V/m  $H_y$  = peak electric field amplitude, A/m  $H_y^0$  = peak magnetic field amplitude, A/m k = wave number, 1/m v = phase velocity of the propagating wave, m/s  $\lambda$  = wavelength, m t = time, s z = z axis, m

To determine how this carrier wave propagates in a dielectric waveguide such as a fiber, we must consult Maxwell's equations. In 1873, James Clerk Maxwell developed a theory that explained how electromagnetic waves behave in any medium. Maxwell's theory is



FIGURE 1.1 Optical TEM wave.

based on the four equations shown in Eqs. (1.6) to (1.9) in differential form (point form).

$$\nabla \cdot \vec{D} = \rho_n \tag{1.6}$$

$$\nabla \cdot \vec{B} = 0 \tag{1.7}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1.8}$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$
(1.9)

- where  $\vec{D} =$  electric-flux density vector, C/m<sup>2</sup>. In any medium  $\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$  where  $\vec{P}$  is the electric polarization vector.
  - $\vec{B}$  = magnetic-flux density vector H/m. In any medium  $\vec{B}$  =  $\mu_0(\vec{H} + \vec{M})$ .  $\vec{M}$  is the magnetic polarization of the medium. Silica is nonmagnetic, therefore  $\vec{M} = 0$ .
  - $\overline{E}$  = electric-field amplitude vector, V/m
  - $\overline{H}$  = magnetic-field amplitude vector, A/m
  - $\vec{J}$  = current density vector, A/m<sup>2</sup>. For fiber  $\vec{J} = \sigma \vec{E}$ , where  $\sigma$  is the conductivity of the medium. For silica it is very low, therefore  $\sigma \approx 0$  and assume  $\vec{J} = 0$ , therefore no current flow in a fiber.
  - $\rho_v$  = charge density and we can assume there are no free charges in the medium so that  $\rho_v$  = 0.
  - $\nabla \cdot$  = divergence of the vector field

 $\nabla \times =$  curl of the vector field

Simplification of the above results in two wave equations [Eqs. (1.10) and (1.11)] that describe how the electric and magnetic fields of light behave in a fiber. Each wave equation represents three equations, one for each field vector x, y, and z.

$$\nabla^2 \vec{E} + \frac{\omega^2 n^2}{c^2} \vec{E} = 0 \tag{1.10}$$

$$\nabla^2 \vec{H} + \frac{\omega^2 n^2}{c^2} \vec{H} = 0 \tag{1.11}$$

where  $\nabla^2$  = Laplacian operator, where  $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$  $\omega$  = angular frequency of an optical wave, rad/s

- c = speed of light in a vacuum, m/s
- n = material's refractive index in which the light is propagating. It is defined as the ratio of the speed of light in a vacuum to the speed of light in the material.

The propagation parameter  $\omega n/c$  can be expressed as the wave number *k* as shown in Eq. (1.12).

$$kn = \frac{\omega n}{c} \tag{1.12}$$

The index of refraction is defined for both core and cladding as  $n_R$  and  $n_L$ . Therefore, for a wave propagating only in the core, the propagation parameter is  $kn_R$ . If it is propagating only in the cladding, the propagation parameter is in  $kn_L$ . However, the wave propagates partly in both core and cladding; therefore, a new propagation parameter  $\beta$  is defined, see Eq. (1.13).

$$kn_{L} < \beta < kn_{R} \tag{1.13}$$

An effective index of refraction  $n_{\rm eff}$  between the core and cladding values can be defined by Eq. (1.14).

$$n_{\rm eff} = \frac{\beta}{k} \tag{1.14}$$

The velocity of the monochromatic wave in a fiber can now be defined as Eq. (1.15).

$$v = \frac{c}{n_{\text{eff}}} \tag{1.15}$$

Substituting Eqs. (1.1) and (1.2) into Eqs. (1.10) and (1.11) and solving results in wave equations Eqs. (1.16) and (1.17).

$$E_x(z,t) = E_{x0} e^{-\alpha z} e^{j(\omega t - \beta z)}$$
(1.16)

$$H_{y}(z,t) = H_{y0}e^{-\alpha z}e^{j(\omega t - \beta z)}$$
(1.17)

The real part of these equations can be expressed as wave equations Eqs. (1.18) to (1.20).

$$E_x(z,t) = E_{x0}\cos(\omega t - \beta z)e^{-\alpha z/2}$$
(1.18)

$$H_{y}(z,t) = H_{y0} \cos(\omega t - \beta z) e^{-\alpha z/2}$$
(1.19)

$$\beta = \frac{\omega}{v} \tag{1.20}$$

where  $\beta$  = propagation parameter, rad/m

 $\alpha$  = fiber's attenuation coefficient, m<sup>-1</sup>

 $\omega$  = angular frequency, rad/s

z = propagation distance in the fiber, m

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v = phase velocity of the propagating wave, m/s t = time, s

The exponential part of Eq. (1.18) shows that a TEM wave propagating in a fiber diminishes in amplitude determined by the  $e^{-\alpha z/2}$ term at distance *z*. The fiber's attenuation coefficient  $\alpha$  determines how fast the amplitude dies out. The wave propagates at an angular frequency of  $\omega$ , where  $\omega = 2\pi f$ , with a propagation parameter of  $\beta$ .

#### 1.3 Information Signal

In the electrical domain the information signal is transmitted over a wire to a laser or LED in a digital format or analog format. The digital format consists of a sequence of high- and low-voltage pulses, which is well suited for data transmission. The high pulse represents a data logical 1 and the low pulse (no pulse) represents a data logical zero. The digital signal transmission rate, also known as bit rate R, has units bits per second (bps). Each bit time slot has the period *T* with unit seconds, where T = 1/R. The width of the data bit is some fraction, called duty cycle  $d_{d}$ , of the time slot period, where  $d_c = T_b/T$ . Two common methods of coding data information in a digital signal are non-return to zero (NRZ) and return to zero (RZ) coding, see Fig. 1.2. Figures 1.2a and c shows unipolar coding with a DC component and Figs. 1.2b and d shows polar coding with no DC component. NRZ signal coding is the standard used for many transmission systems including SONET/SDH and GigE. The baseband signal power spectral density (PSD) of an NRZ signal can be calculated<sup>2</sup> using Eq. (1.21) assuming that the bit width is the same as the time slot width  $T = T_{h}$  and  $d_{c} = 1$ . For the polar format, where the DC component is zero,  $\delta(f) = 0$ , see Fig. 1.3*a*. Equation (1.22) provides the PSD of the RZ signal format assuming the bit width is half the time slot width  $T_{b} = T/2$  and  $d_{c} = 0.5$ . The RZ spectral density has a similar sin *c* function shape but wider spectral width.

$$S_{\text{NRZ.bb}} = \frac{A^2 T}{4} \sin c^2 (Tf) + \frac{A^2}{4} \delta(f)$$
(1.21)

$$S_{\text{RZ.bb}} = \frac{A^2 T}{4} \sin c^2 \left(\frac{Tf}{2}\right) \times \left[1 + \frac{1}{T} \sum_{n = -\infty}^{\infty} \delta\left(f - \frac{n}{T}\right)\right]$$
(1.22)

where  $S_{_{NRZ,bb}}$  = baseband NRZ power spectral density assuming a 1  $\Omega$  load, W/Hz

 $S_{\rm RZ,bb}$  = baseband RZ power spectral density assuming a 1  $\Omega$  load, W/Hz

A = voltage of the signal in data one bit state, V

T = signal time slot width, s  $T_b$  = signal full pulse width, s f = frequency of the signal, Hz  $\delta(f)$  = DC component of the signal, V/Hz n = an integer

The spectral width of an NRZ signal to the first null is  $\Delta f_{null} = 1/T$ , see Fig. 1.3*a*. For an RZ signal (where  $T_b = T/2$ ) the spectral width to the first null is  $\Delta f_{null} = 2/T$  much wider than NRZ, see Fig. 1.3*b*. This



FIGURE 1.2 NRZ and RZ signals.



FIGURE 1.3 Power spectral density of baseband NRZ and RZ signals.

is because the RZ pulse width is half the NRZ pulse width. This results in the RZ pulse spectral width being much wider than the NRZ spectral width. Equations (1.21) and (1.22) assume that the signal bit pulses are rectangular. However, in actual transmission systems they are more rounded, which changes their spectral density.

Analog format transmission over a wire is typically used for analog signals such as video, CATV, or RF systems. Often the analog signal does not remain analog during the entire transmission but is converted to a digital signal using a technique called pulse-code modulation (PCM). Because most fiber communication networks consist of digital optical transmission, this book will concentrate on this type of communication. Analog transmission systems have similar design parameters but different design and acceptance criteria.

#### 1.4 Modulation

The information signal is combined with the optical carrier in the transceiver using a technique called modulation, see Fig. 1.4*a*. Modulation is the process of encoding signal information onto the carrier by changing the carrier's amplitude *A*, frequency  $\omega_c$ , or phase  $\phi$ . In radio frequency communications, this is referred to as amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM).



FIGURE 1.4 NRZ modulation.

In optical communications, most transmission systems use a form of amplitude modulation that is actually light intensity modulation. For digital signals this is called amplitude-shift keying (ASK). The simplest and most common form of ASK is on-off keying (OOK). This is where information is represented by the carrier as a sequence of high and low light intensities. A high light intensity (pulse) represents a logic 1 and a low or extinguished light intensity (no pulse) represents a logic 0 (or vice versa depending on the line coding). Two common methods of coding the information onto the carrier are NRZ and RZ coding. This results in a modulated pulsating optical carrier signal as shown in Fig. 1.4*c*. The modulated optical carrier launched into a fiber consists of the optical carrier at center frequency  $f_c$ . If the modulating signal format is NRZ, then the modulated optical signal spectral density<sup>2</sup> can be shown by Eq. (1.23)

q



FIGURE 1.5 NRZ modulated optical spectrum.

assuming an ideal rectangular modulating signal and a monochromatic carrier ( $\Delta f_{null} >> \Delta f_c$ ), which is not realistic. The NRZ modulated optical signal spectral width between the first nulls is  $\Delta f_{mc.null} = 2/T$ , see Fig. 1.5.

$$S_{\text{NRZ.c}} = \frac{A^2 T}{8} [\sin c^2 ((f - f_c)T) + \sin c^2 ((f + f_c)T)] + \frac{A^2}{8} [\delta(f - f_c) + \delta(f + f_c)]$$
(1.23)

Assume that the optical carrier wave is monochromatic (consists of only one optical frequency  $\omega_c$ ) and it is propagating in a fiber that has no optical loss,  $\alpha = 0$ . The electric field component of this optical carrier wave at distance *z* in the fiber can be shown by Eq. (1.18). In Eq. (1.24) the propagation parameter is shown as a function of frequency.

$$E_{x}(z,t) = E_{x0}\cos(\omega_{c}t - \beta(\omega_{c})z)$$
(1.24)

where  $E_{x}(z, t)$  = electric field amplitude at location z and time t, V/m

- $E_{x0}$  = peak electric field amplitude, V/m
- $\omega_c$  = angular optical frequency where  $\omega_c = 2\pi f_c$ , s<sup>-1</sup>

$$t = time, s$$

- $\beta(\omega_c)$  = propagation parameter, which is a function of carrier frequency, rad/m
  - z = distance along the fiber length, m

This wave propagates in the fiber at a phase velocity v defined by Eq. (1.25) and as shown in Fig. 1.6.

$$v = \frac{\omega_c}{\beta} \tag{1.25}$$



FIGURE 1.6 Wave phase propagation.

For on-off key modulation of this optical carrier wave with a digital signal that has a spectral width of  $\Delta \omega$ , the modulated carrier spectrum would span frequencies shown in Eq. (1.26).

$$\omega_c - \Delta \omega < \Delta \omega_{\rm mc} < \omega_c + \Delta \omega \tag{1.26}$$

where  $\Delta \omega_{mc}$  = spectral width of a modulated carrier, rad/s  $\omega_c$  = carrier frequency, rad/s  $\Delta \omega$  = baseband signal spectral width, rad/s

Assuming that  $\Delta \omega$  spectral width is much less than the carrier frequency  $\Delta \omega \ll \omega_c$ , then the modulating signal spectral width can be included in the carrier Eq. (1.24) resulting in modulated carrier Eqs. (1.27) and (1.28). It is seen in time *t* and propagating in the fiber at length location *z*, where  $\cos(\omega_c t - \beta(\omega_c)z)$  describes the phase of the optical carrier wave and  $\cos(\Delta \omega t - \beta(\Delta \omega)z)$  describes the slower varying signal envelope of the carrier wave,<sup>3</sup> see Fig. 1.4*c*.

$$E_{x}(z, t) = E_{x0}[\cos((\omega_{c} + \Delta\omega)t - \beta(\omega_{c} + \Delta\omega)z) + \cos((\omega_{c} - \Delta\omega)t - \beta(\omega_{c} - \Delta\omega)z)]$$
(1.27)

$$E_{x}(z,t) \approx E_{x0}\cos(\Delta\omega t - \beta(\Delta\omega)z)\cos(\omega_{c}t - \beta(\omega_{c})z)$$
(1.28)

From Eq. (1.28) the modulated carrier phase velocity is given by Eq. (1.29) and the group velocity (the velocity of information or pulse envelope in the fiber) is given by Eq. (1.30), see Fig. 1.4*c*.

$$v = \frac{\omega_c}{\beta(\omega_c)} \tag{1.29}$$

$$v_g = \left(\frac{d\beta}{d\omega}\right)^{-1} \tag{1.30}$$

The propagation parameter  $\beta$  depends on the frequency and can be expanded as a Taylor series around the center wavelength  $\omega_c$  of modulated carrier spectrum  $\omega_{mc'}$  where  $\Delta \omega \ll \omega_c$  [see Eq. (1.31), which provides useful wave parameters  $\beta_{0'}\beta_{1'}$ ,  $\beta_{2'}$  and  $\beta_{3'}$  see Eqs. (1.32) to (1.38)].

$$\beta(\omega) = \beta_0 + \beta_1(\Delta\omega) + \frac{1}{2}\beta_2(\Delta\omega)^2 + \frac{1}{6}\beta_3(\Delta\omega)^3 + \cdots$$
(1.31)

$$\beta_n = \frac{d^m \beta}{d\omega^m} \qquad \text{where } \omega = \omega_c \tag{1.32}$$

$$\beta_0 = \beta(\omega_c) \tag{1.33}$$

$$\beta_1 = \frac{d\beta}{d\omega} = \frac{1}{v_g} \tag{1.34}$$

$$\beta_2 = \frac{d^2\beta}{d\omega^2} = \frac{dv_g^{-1}}{d\omega} = -\frac{\lambda^2}{2\pi c} CD_c$$
(1.35)

$$\beta_3 = \frac{d\beta_2}{d\omega} = \frac{\lambda^3}{(2\pi c)^2} (\lambda S + 2CD_c)$$
(1.36)

$$CD_c = -\frac{2\pi c}{\lambda^2} \beta_2 \tag{1.37}$$

$$S = \frac{dCD_c}{d\lambda} = \frac{(2\pi c)^2}{\lambda^3} \left( \frac{\beta_3}{\lambda} + \frac{\beta_2}{\pi c} \right)$$
(1.38)

where  $v_{o}$  = group velocity of the signal envelope, m/s

- $CD_c = fiber$  chromatic dispersion coefficient at wavelength  $\lambda$ , s/(m.m)
  - v = phase velocity of an optical wavelength, m/s
  - c = speed of light in a vacuum, m/s
  - $\beta$  = propagation parameter, rad/m
  - $\beta_0$  = propagation parameter at  $\omega_c$ , rad/m
  - $\beta_1$  = inverse of the envelope velocity of the pulse, s/m
  - $\beta_2$  = signal pulse broadening parameter, known as the groupvelocity dispersion (GVD), s<sup>2</sup>/m
  - $\beta_3$  = slope of GVD, or second-order GVD, considered when  $\beta_2\approx 0,\,s^3/m$
  - $\omega_c$  = center angular frequency of an optical carrier, rad/s
  - $\Delta \omega$  = spectral width of baseband optical pulse,  $\Delta \omega = (-2\pi c/\lambda^2)$  $\Delta \lambda$ , rad/s
    - $S = \text{slope of } CD_c, s/m^3$
    - m = constant
    - n = 0, 1, 2, 3

The modulated optical carrier, described by Eq. (1.28), that is launched into a fiber can be shown in exponential form as in Eq. (1.39). Here  $A_x(z, t)$  is the varying signal amplitude of the optical carrier and the first exponential term represents the carrier, see Fig. 1.4*a*. The last exponential term represents fiber's attenuation effect on the signal.

$$E_{\nu}(z,t) = A_{\nu}(z,t)e^{j(\omega_{c}t - \beta(\omega)z)}e^{-\alpha z/2}$$
(1.39)

Using Fourier transform on Eq. (1.39) and substituting the Taylor series expansion for  $\beta(\omega)$  in Eq. (1.31), the partial differential equation that governs pulse propagation of an optical electric field in a single polarization state is derived, see Eqs. (1.40) and (1.41). It is referred to as the nonlinear Schrödinger equation<sup>4</sup> (NLSE) and is used to accurately determine fiber linear and nonlinear effects on a

propagating optical signal with pulse widths as short as 5 ps. The terms to the right of the equal sign are responsible for nonlinear effects, the Kerr effect, Raman scattering, and self-steepening. When there are no nonlinear effects to consider, the right side equals 0. The left side consists of fiber attenuation and chromatic dispersion terms.

$$\frac{\partial A}{\partial z} + \underbrace{\beta_1 \frac{\partial A}{\partial t}}_{\text{Group velocity}} + \underbrace{\frac{j\beta_2}{2} \frac{\partial^2 A}{\partial t^2}}_{\text{CD effect}} - \underbrace{\frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3}}_{\text{CD slope}} + \underbrace{\frac{\alpha}{2} A}_{\text{Attenuation}}$$
$$= \underbrace{j\gamma |A|^2 A}_{\text{Kerreffect}} - \underbrace{j\gamma_R A \frac{\partial (|A|^2)}{\partial t}}_{\text{SRS}} - \underbrace{\gamma_S \frac{\partial (|A|^2 A)}{\partial t}}_{\text{Self-steepening}}$$
(1.40)
$$2\pi n_2$$

$$\gamma = \frac{2\lambda n_2}{\lambda A_{\rm eff}} \tag{1.41}$$

- where A = modulating electric field signal which is a function of distance and time A(z, t), V/m
  - $|A|^2 = optical intensity, W/m^2$ 
    - $\gamma$  = nonlinear coefficient, (Wm)<sup>-1</sup>
    - $\gamma_{R} = stimulated$  Raman scattering nonlinear coefficient,  $(Wm)^{-1}$
    - $\gamma_{\rm s}$  = self-steepening nonlinear coefficient, (Wm)<sup>-1</sup>
    - $n_2$  = fiber nonlinear refractive index which varies for different fibers between 2.0 × 10<sup>-20</sup> and 3.5 × 10<sup>-20</sup> m<sup>2</sup>/W, (typical is 3.0 × 10<sup>-20</sup> m<sup>2</sup>/W)
    - $\alpha$  = fiber's attenuation coefficient, m<sup>-1</sup>

As mentioned at the beginning of this section, the actual modulated optical pulses propagating in a fiber are not perfectly rectangular,<sup>5</sup> but have rounded edges with pulse shapes that can approximate a Gaussian<sup>6</sup> or super-Gaussian distribution.<sup>7</sup> An optical Gaussian pulse electric field at z = 0 can be defined as Eqs. (1.42) and (1.43).<sup>8</sup> The phase of the pulse can be seen in the cosine term part of Eq. (1.43) as shown in Eq. (1.44). The Gaussian pulse envelope A(z,t), without the optical carrier  $\omega_c$  see Fig. 1.9*a*, as a function of time and distance is described by Eq. (1.45). For a Gaussian pulse the shape parameter  $m_s = 1$  and for a super-Gaussian shape  $m_s > 1$ , see Fig. 1.7. RZ modulation transmissions can be evaluated by assuming the optical pulses have an approximate Gaussian shape. NRZ pulse can be better represented by a super-Gaussian shape.

$$G(t) = \Re \left[ A_0 \exp \left( -\frac{1+jC_0}{2} \left( \frac{t}{T_{\text{HWEM}}} \right)^2 \right) \exp(-j\omega_c t) \right]$$
(1.42)



FIGURE 1.7 Gaussian pulse shape for different values of the shape parameter.

$$G(t) = A_0 \exp\left(-\frac{1}{2}\left(\frac{t}{T_{\text{HWEM}}}\right)^2\right) \cos\left(\omega_c t + \frac{C_0}{2}\left(\frac{t}{T_{\text{HWEM}}}\right)^2\right)$$
(1.43)

$$\phi(t) = \omega_c t + \frac{C_0 t^2}{2T_{\text{HWEM}}^2} \tag{1.44}$$

$$A(0, t) = A_0 \exp\left(-\frac{1+jC_0}{2} \left(\frac{t}{T_{\text{HWEM}}}\right)^{2m_s}\right)$$
(1.45)

$$T_{\rm FWHM} = 2\sqrt{\ln 2} \times T_{\rm HWEM} \approx 1.665 T_{\rm HWEM} \tag{1.46}$$

$$C_0 = \frac{T_{\rm HWEM}^2}{t} \delta\omega(t) \tag{1.47}$$

where G(t) = chirped optical Gaussian pulse electric field amplitude at z = 0 amplitude, V/m

A(0, t) = pulse launch electric field amplitude at time t, V/m

- $A_0$  = peak pulse electric field amplitude, V/m
- $C_0$  = initial pulse chirp parameter

$$T = time, s$$

- $m_s$  = shape parameter, where  $m_s$  = 1 is for Gaussian pulse; as  $m_s$  increases pulse shape becomes more rectangular
- $T_{\text{HWEM}}$  = half pulse width at 1/*e* amplitude point, s
- $T_{\text{FWHM}}$  = full pulse width at half maximum amplitude point (-3 dB), s
- $\delta\omega(t)$  = time-dependent instantaneous frequency shift from the center optical carrier frequency  $\omega_c$ , rad/s
  - $\phi$  = phase of the pulse, rad
  - $\omega_c$  = optical carrier angular frequency, rad/s

Optical pulses generated by directly modulated laser and certain externally modulated lasers will contain frequency chirp. Frequency chirp is the change of the pulse's optical carrier frequency due to carrier modulation as shown in Fig. 1.9b and 1.9c. The chirp parameter can be calculated by differentiating the phase of the output optical field in Eq. (1.44) with respect to time resulting in Eq. (1.48). A model for chirp frequency shift<sup>9</sup> established to be accurate for DFB lasers is shown in Eq. (1.49). It is made up of a transient component (the equation's differential term) and adiabatic component ( $\chi \Delta P$  term). The former is caused by the pulse's rapid rise and fall times. The latter is caused by the difference in power levels between the optical 1 and zero states of the signal. Transient chirp is most detrimental in pulse propagation because it hastens pulse broadening and is the dominant term for directly modulated semiconductor lasers (DML). Figure 1.8a is an example of an RZ modulation DML optical pulse and Fig. 1.8b represents the frequency chirp associated with the pulse. The leading edge of the pulse's carrier frequency is shifted to a higher frequency and the falling edge shifts to a lower frequency. DML frequency shift  $\delta f(t)$  typically can range from ~100 MHz to ~10 GHz, which is about 0.005% of the carrier frequency  $f_0$  at 193 THz. This is



FIGURE 1.8 Transient and adiabatic chirp.

quite small as a percentage but does impact transmission distance significantly.

$$\delta\omega(t) = -\frac{\partial\phi}{\partial t} = \frac{C_0}{T_{\rm HWEM}^2}t$$
(1.48)

$$\delta f(t) = \frac{\alpha_c}{4\pi} \left[ \frac{d \ln(\Delta P)}{dt} + \chi \Delta P \right]$$
(1.49)

- where  $\delta f(t)$  = time-dependent instantaneous frequency shift from the center optical carrier frequency  $f_{0'}$  Hz [note:  $\delta \omega(t) = 2\pi \delta f(t)$ ]
  - $\alpha_c$  = chirp  $\alpha_c$  parameter also known as line width enhancement factor
  - $\Delta P$  = change in optical power when switching between high pulse level (1) and low level (0), W
    - $\chi$  = laser damping constant, s<sup>-1</sup>

Due to the fiber dispersion, frequency chirping results in the pulse compression or expansion as it propagates in the fiber. This increases or decreases the system's chromatic dispersion limit. Therefore, adding frequency chirp to a pulse can be beneficial or detrimental to the transmission system. In Eq. (1.45) the chirp parameter  $C_0$ determines how much frequency chirp is added to the pulse. When  $C_0 = 0$  there is no pulse chirp, see Fig. 1.9*a*. If  $C_0$  is positive the chirped pulse looks like Fig. 1.9b with higher optical frequency at the trailing end of the pulse. If  $C_0$  is negative the chirped pulse looks like Fig. 1.9*c* with higher optical frequency at the beginning of the pulse. The chirp parameter  $C_0$  is determined by measuring the amount of frequency shift  $\delta\omega(t)$  in the pulse's time span, away from the carrier frequency  $\omega_{a'}$  see Eq. (1.47). The frequency shift can be modeled by Eq. (1.49) for DFB lasers. Note, this chirp parameter  $C_0$  is related to but not the same as the chirp alpha parameter  $\alpha$  seen in some publications and laser specifications. It is defined<sup>10</sup> as the ratio of the rate of change of the laser's refractive index  $n_{r}$  as a function of the electron density  $n_{r}$ and the differential gain  $dg/dn_{s}$ , see Eq. (1.50). Given the  $\alpha_{s}$  parameter, the chirp parameter  $C_0$  can be approximated by Eq. (1.51).

$$\alpha_c = -\frac{4\pi}{\lambda} \frac{dn_r/dn_e}{dg/dn_e}$$
(1.50)

$$C_0 \approx -\alpha_c \tag{1.51}$$

The spectrum of a Gaussian pulse, where  $m_s = 1$ , can be determined by taking the Fourier transform of Eq. (1.45) at z = 0, which results in Eq. (1.52).

$$A(0, \omega) = A \left[ \frac{2\pi T_{\text{HWEM}}^2}{1+jC_0} \right]^{1/2} \exp\left[ -\frac{(\omega T_{\text{HWEM}})^2}{2(1+jC_0)} \right]$$
(1.52)



Note: Optical wavelength greatly exaggerated for illustrative purposes.



The spectral shape is Gaussian and the spectral half width at the 1/e intensity point is given by Eq. (1.53).

$$\Delta \omega_{\rm HWEM} = \frac{(1+C_0^2)^{1/2}}{T_{\rm HWEM}}$$
(1.53)

The pulse broadening factor given by Eq.  $(1.54)^{11}$  can be derived by solving Eq. (1.40), assuming nonlinear effect is zero, with Eq. (1.45) assuming a chirped Gaussian pulse ( $m_s = 1$ ) with very narrow optical carrier spectral width ( $\Delta \omega_{HWEM} >> \Delta \omega_c$ ). It shows the relationship between initial pulse width and pulse width after propagating fiber distance *z* for various chirp parameters. Refer to Chap. 4 for more information about fiber pulse broadening limiting effects and fiber dispersion.

$$\frac{T_{\rm HWEM.z}}{T_{\rm HWEM.0}} = \sqrt{\left(1 + \frac{C_0 \beta_2 z}{T_{\rm HWEM.0}^2}\right)^2 + \left(\frac{\beta_2 z}{T_{\rm HWEM.0}^2}\right)^2}$$
(1.54)

$$L_D = \frac{T_{\rm HWEM.0}^2}{\left|\beta_2\right|} \tag{1.55}$$

where  $T_{\text{HWEM},z}$  = half pulse width at 1/*e* amplitude point at distance *z*, s

 $T_{\text{HWEM.0}}$  = half pulse width at 1/*e* amplitude point at launch into the fiber, s

- $\beta_2$  = group-velocity dispersion (GVD) parameter, s<sup>2</sup>/m
- z = distance along the fiber length, m
- $L_D$  = dispersion length, m

The dispersion length parameter  $L_{\rm p}$  obtained from Eqs. (1.54) and (1.55) is useful in quickly assessing the effects of chromatic dispersion on a propagating Gaussian pulse. It represents the maximum fiber length possible for transmission before chromatic dispersion begins to degrade the signal below specifications for a chirpless pulse. If the fiber length z is much shorter than the dispersion length  $L_{D}$ , then the chromatic dispersion effects can be neglected; if the fiber length equals the dispersion length, then pulse spread is increased by a factor of  $\sqrt{2}$ . Figure 1.10 plots the broadening effect of chirped and chirpless 10 Gbps NRZ transmission with  $T_{\text{HWEM.0}} = 50$  ps Gaussian pulses respect to normalized fiber distance (fiber distance divided by dispersion length  $L_{\rm p}$ ). The dispersion length parameter is calculated to be 155 km. The fiber type is standard G.652 fiber, which has positive chromatic dispersion of 17  $ps/(nm \cdot km)$ . For the chirpless pulse case  $C_0 = 0$ , the broadening factor is 2.2, when the normalized distance is 2.0. The pulse constantly expands in width as it propagates in the fiber. However, if frequency chirp is introduced to the pulse with a positive chirp parameter of  $C_0 = 2$ , the pulse initially compresses up to a normalized distance of 0.4 and then expands more rapidly than



FIGURE **1.10** Chirped pulse broadening as a function of normalized fiber distance for G.652 fiber.

the chirpless case. At a normalized distance of approximately 1, where the dispersion length equals the distance, the pulse width begins to exceed that of the chirpless case. Therefore, positive frequency chirp can be beneficial up to distance  $L_D$  for fibers with positive chromatic dispersion. For a negative chirp parameter, the pulse expands much more rapidly than both chirpless and positive chirp cases right after launch. This is the worst-case chirp scenario for the transmission system. Unfortunately, directly modulated semiconductor lasers (DML) produce a negative chirp parameter  $C_0$ , which significantly limits propagation distance due to accelerated pulse broadening. This can be overcome by using externally modulated semiconductor lasers that exhibit little or no chirp.

As the Gaussian pulse propagates in the fiber it lengthens and distorts losing its original Gaussian shape. It can no longer can be well represented by FWHM or HWEM points. A better representation of these pulses is by the root means square (RMS) pulse width,<sup>12</sup> defined by Eqs. (1.56) to (1.58). RMS pulse width  $\sigma$  at distance *z* can be defined by Eq. (1.58).

$$\boldsymbol{\sigma} = \left[ \left\langle t^2 \right\rangle - \left\langle t \right\rangle^2 \right]^{1/2} \tag{1.56}$$

$$\left\langle t^{n}\right\rangle = \frac{\int\limits_{-\infty}^{+\infty} t^{n} \left|f(t)\right|^{2} dt}{\int\limits_{-\infty}^{+\infty} \left|f(t)\right|^{2} dt}$$
(1.57)

$$\sigma(z) = \begin{bmatrix} \int_{-\infty}^{+\infty} t^2 |A(z,t)|^2 dt \\ \int_{-\infty}^{-\infty} |A(z,t)|^2 dt \\ \int_{-\infty}^{+\infty} |A(z,t)|^2 dt \end{bmatrix}^{-\infty} - \begin{bmatrix} \int_{-\infty}^{+\infty} t |A(z,t)|^2 dt \\ \int_{-\infty}^{+\infty} |A(z,t)|^2 dt \end{bmatrix}^{2} \end{bmatrix}^{1/2}$$
(1.58)

where  $\sigma(z)$  is the RMS optical power pulse width at distance *z*, s.

For a Gaussian pulse that is launched into the fiber the relationship between RMS pulse width<sup>13</sup>  $\sigma_0$  and  $T_{HWEM0}$  is defined in Eq. (1.59).

$$T_{\rm HWEM.0} = \sigma_0 \sqrt{2} \tag{1.59}$$

. . .

The broadening factor shown in Eq. (1.54) can now be represented by the pulse RMS width as Eq. (1.60). Also included in this equation is the higher order  $\beta_3$  term that increases equation accuracy for values near zero dispersion.

$$\frac{\sigma(z)}{\sigma_0} = \sqrt{\left(1 + \frac{C_0 \beta_2 z}{2\sigma_0^2}\right)^2 + \left(\frac{\beta_2 z}{2\sigma_0^2}\right)^2 + \left(1 + C_0^2\right) \frac{1}{2} \left(\frac{\beta_3 z}{4\sigma_0^3}\right)^2}$$
(1.60)

All of the above equations assume that the optical carrier spectral width is monochromatic. In practice however, laser light does occupy a spectral width  $\sigma_{\omega c'}$ , which can be included in Eq. (1.60) as shown in Eq. (1.61).

$$\frac{\sigma(z)}{\sigma_0} = \sqrt{\left(1 + \frac{C_0 \beta_2 z}{2\sigma_0^2}\right)^2 + \left(1 + 4\sigma_{\omega c}^2 \sigma_0^2\right) \left(\frac{\beta_2 z}{2\sigma_0^2}\right)^2 + \left(1 + C_0^2 + 4\sigma_{\omega c}^2 \sigma_0^2\right) \frac{1}{2} \left(\frac{\beta_3 z}{4\sigma_0^3}\right)^2} \quad (1.61)$$

where  $\omega_{\omega c}$  is the optical carrier's RMS spectral width, rad/s.

This equation describes Gaussian pulse broadening as it propagates in a fiber, for super Gaussian pulse where the pulse is more rectangular with sharper leading and trailing edges. The broadening factor can be determined by solving Eq. (1.40) with Eq.(1.45) using m > 1. The super Gaussian pulse broadens more rapidly than Gaussian pulse as it propagates down the fiber and therefore the dispersion limit is shorter. Refer to Chap. 4 for more information regarding bandwidth limiting effects due to pulse broadening.

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## CHAPTER 2 Optical Power and Loss

#### 2.1 Description

Signal loss is the reduction of signal power along a transmission path. For fiber optic communications the transmission path is optical and consists of fibers, connectors, splices, and other optical components. The total link loss, which is the optical transmission path loss measured from the transceiver laser output to the receiver input, is the most important planning parameter to consider for all fiber systems.

Optical loss is defined as a dimensionless ratio of optical output power to input power for a fiber or component at a specific wavelength, see Eq. (2.1) and Fig. 2.1. It represents the amount an optical signal is diminished in power (intensity) after it propagates through a passive component or fiber. In more general terms, this ratio is also referred to as transmittance because it represents the amount of optical power that is transmitted through a fiber or component.

$$LossRatio = T_r = \frac{P_{out}}{P_{in}}$$
(2.1)

where LossRatio = optical power loss ratio at a specific wavelength

- $T_r$  = transmittance
- *P*<sub>out</sub> = fiber or component average output power at a specific wavelength, mW
- *P*<sub>in</sub> = fiber or component average input power at a specific wavelength, mW

Optical output power will always be less than or equal to the input power in any passive optical path (no optical amplifiers) and therefore the loss ratio will always be equal to or less than 1. For optical amplifiers the  $P_{out}/P_{in}$  ratio is greater than 1 and is referred to as *Gain*.

To conveniently represent very small and large numbers often encountered in loss calculations and to be able to easily calculate total link loss by addition instead of ratio multiplication, the industry


FIGURE 2.1 Optical loss.

has accepted the decibel logarithmic scale with unit dB as a standard for loss measurement. Equations (2.2) and (2.3) are the conversions between the linear and logarithmic loss units. Since the loss ratio is always less than 1, output power is always less than input power, then optical loss in dB units is represented as a positive number or 0.

$$\Gamma = -10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)$$
(2.2)

$$\frac{P_{\rm out}}{P_{\rm in}} = 10^{-\Gamma/10}$$
(2.3)

where  $\Gamma$  is the optical power loss at a specific wavelength, dB.

Loss is a relative measure and therefore the output and input powers need to be known before loss can be calculated. For example, if a system transceiver's optical output power is 1 mW and the measured receive power is 0.025 mW, what is the loss? Using Eq. (2.2) we calculate link loss as follows:

$$\Gamma = -10 \log \left( \frac{0.025}{1} \right)$$
$$\Gamma = 16.02$$

Therefore the optical loss is 16.02 dB.

Optical power loss is wavelength dependent and cumulative in an optical fiber. It increases exponentially with fiber length, refer to wave equation Eq. (1.16). The main mechanism causing about 96% of signal loss in a silica fiber is Rayleigh scattering. Material absorption and bend loss accounts for the rest of the loss. Rayleigh scattering is the scattering of light along the entire length of the fiber, which is caused by elastic collisions between the light wave and fiber molecules. This results in some of the light escaping the fiber

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waveguide and some of the light reflecting back to the source. Note that Rayleigh scattering is responsible for scattering of sunlight in the atmosphere, which results in a blue sky. The effect decreases with increasing signal wavelength. Two other types of scattering effects, called Brillouin and Raman scattering, occur at higher optical powers (>5 dBm) and are discussed in detail in Chap. 7. Material absorption is the absorption of light energy by fiber impurities such as water (OH<sup>-</sup>) molecules. The main water absorption band is centered at 1383 nm, which in newer G.652.c/d fiber is significantly reduced. Figure 2.2 shows fiber attenuation dependence on wavelength of a typical standard G.652.a/b fiber and reduced water absorption G.652.c/d fiber.

Micro- and macrobending loss is the third effect that can result in power loss in a fiber. Microbending loss is due to small fiber imperfections caused in the manufacturing process. It also can be due to small fiber distortions caused by pressure points on the fiber created during or after the installation process. Loose tube-type cable helps in reducing this loss due to installation. Macrobending loss occurs when the fiber is bent past its minimum bend radius, which results in light escaping its waveguide confines. Careful installation practices help to avoid this type of loss.



FIGURE 2.2 Fiber attenuation dependence on wavelength.

Optical power loss in a fiber can be specified by an attenuation coefficient (often referred to as attenuation) term  $\alpha$  which represents the power loss per 1 km unit length of fiber, see Eq. (2.4). As shown in wave equation Eq. (1.16), power loss in a fiber is exponential.

$$\frac{P_{\text{out}}}{P_{\text{in}}} = e^{-\alpha L} \tag{2.4}$$

where  $P_{out}$  = fiber's average optical power at length *L* at a specific wavelength, mW

- $P_{in}$  = fiber's average input power where L = 0 at a specific wavelength, mW
  - L = fiber length, km
  - $\alpha$  = fiber attenuation coefficient, km<sup>-1</sup> or m<sup>-1</sup>

The  $\alpha$  term is more commonly represented in a logarithmic decibel form with units dB/km. The conversion from linear to decibel attenuation is shown in Eqs. (2.5) and (2.6).

$$\alpha_{\rm dB} = \alpha 10 \log e \tag{2.5}$$

$$\alpha_{\rm dB} \approx 4.343\alpha \tag{2.6}$$

where  $\alpha_{dB}$  is the fiber attenuation at a specific wavelength, dB/km.

Often used to determine fiber length or loss, the formula for attenuation in dB format is shown as Eq. (2.7).

$$\alpha_{\rm dB} = \frac{\Gamma}{L} \tag{2.7}$$

Maximum fiber attenuation values for different wavelengths are provided in all fiber cable manufacturer specifications. These values are typically guaranteed only while the cable is still on the cable reel. After the cable is installed, the attenuation often increases due to various effects including bend and splice loss.

Attenuation calculated or measured for a fiber link also provides for a quick link loss quality assessment. Typically, for a low loss fiber link the attenuation is 0.22 dB/km or less measured at 1550 nm.

Any other passive component such as WDMs (wavelength division multiplexing), DCMs (dispersion compensation module), jumpers, connectors, and splices inserted into the fiber signal path will increase the total link loss to some degree. Their insertion loss is also specified in dB units. The total link loss (in dB units) is equal to the total fiber loss plus all individual component losses in the optical transmission path (fiber link), see Eq. (2.8).

$$\Gamma_{\text{total}} = \Gamma_{\text{fiber}} + \sum \Gamma_{\text{com}.i}$$
(2.8)

where  $\Gamma_{\text{total}} = \text{total link loss, dB}$   $\Gamma_{\text{fiber}} = \text{total fiber loss, dB}$  $\Gamma_{\text{com.}i} = \text{component } i \text{ loss, dB}$ 

# 2.2 Optical Signal Power Unit

Optical signal power can also be represented in the logarithmic decibel scale. Because it is an absolute measure, it needs to be referenced to a specific power value. The standard reference value for optical communications is one milliwatt (1 mW), see Eqs. (2.9) and (2.10). Absolute measurements that are referenced to the milliwatt are denoted by the unit dBm.

$$P_{\rm dBm} = 10 \log\left(\frac{P_{\rm mW}}{1_{\rm mW}}\right) \tag{2.9}$$

$$P_{\rm mW} = 10^{P_{\rm dBm}/10} \tag{2.10}$$

where  $P_{dBm}$  = decibel average optical power referenced to 1 mW, dBm  $P_{mW}$  = linear average optical power, mW

Therefore an optical power level of 1 mW is 0 dBm and 5 mW is 7 dBm. It should be noted that dBm units can be positive or negative. A negative dBm value simply means that the power is less than 1 mW. Table 2.1 shows a few common milliwatt-to-dBm conversions.

Power in mW	Power in dBm
31.6	15
10	10
7	8.5
5	7
2	3
0	1
0.5	-3
0.32	-5
0.1	-10
0.01	-20
0.0032	-25

 TABLE 2.1
 Common milliwatt-to-decibel

 Conversions
 Conversions

## 2.3 Link Power Budget

The planning of a fiber optic link often requires a detailed link power budget to be completed. The goal of this budget is to ensure that the total link loss does not exceed the transceiver's operating specifications. It is a simple tabulation of all fiber link losses that are obtained from field measurement or calculation using fiber and equipment specifications. If the sum of all the link losses is greater than the transceiver's specified optical budget, then the transmission system is not likely to work properly and/or it may experience high bit errors. Figure 2.3 illustrates the link power budget diagram. Table 2.2 is an example of a typical link loss budget table.

This budget table has two entry columns: specification values and measurement values. If loss measurements are available, they are entered in the measurement values column. Properly measured parameters provide more realistic results than values calculated from fiber specifications. If field measurements are not available, then the loss can be estimated by using manufacturer worst-case specifications, which are entered in the specification values column. Typically, field measurements are performed to obtain realistic fiber loss values and worst-case equipment specifications are used for all other link component losses. This method provides a good worst-case link design for BoL (beginning of life) operation.



FIGURE 2.3 Link power budget diagram.

	Link Power Budget for Fiber Number		Specificatio	n Valuesat _	nm	Measurement Values
Line #	for Tx to Rx	Unit	Unit Value	Quantity	Line Totals	at nm
1	Fiber loss	dB/km				
2	Splice loss	dB				
3	Connector loss	dB				
4	Other fiber loss	dB				
5	Fiber loss (sum L1 to L4)	dB				
6	WDM insertion loss	dB				
7	DCM insertion loss	dB				
8	Amplifier gain (show as neg.)	dB				
9	Other component loss	dB				
10	Link loss (sum L5 to L9)	dB				
11	CD penalty	dB				
12	PMD penalty	dB				
13	PDL <sub>Tmax</sub> penalty	dB				
14	Nonlinear penalties total	dB				
15	Extinction ratio penalty	dB				
16	<b>Total link loss</b> with penalties (sum L10 to L15)	dB				

 TABLE 2.2
 Link Power Budget (Continued)

	Link Power Budget for Fiber Number		Specificatio	n Valuesat _	nm	Measurement Values
Line #	for Tx to Rx	Unit	Unit Value	Quantity	Line Totals	at nm
17	Maximum transmit power	dBm				
18	Minimum transmit power	dBm				
19	Receiver overload power	dBm				
20	Receiver sensitivity at BER, & OSNR	dBm				
21	Minimum transceiver budget (L18 – L20)	dB				
22	Minimum measurable receive power (L18 – L10 )	dBm				Measured Rx power
23	Maximum measurable Rx power < L19 (L17 – L10 )	dBm				
24	<b>Remaining margin BoL</b> must be > 0 (L21 – L16)	dB				
25	System aging	dB				
26	Cable repair	dB				
27	<b>Remaining margin EoL</b> must $be > 0$ (L24 – L25 – L26)	dB				

 TABLE 2.2
 Link Power Budget (Continued)

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Because power loss is dependent on signal wavelength, all loss measurements and specification calculations are performed at the operating signal wavelength. For single-channel non-WDM systems, measurements and calculations are typically performed at 1310 and/or 1550 nm. For WDM systems the link loss budget is completed for the individual WDM channels. Typically, budgets are completed for both the first and last WDM channels to ensure the budget is not exceeded at the WDM channel edges. The exception to this rule is for CWDM multiplexer systems with greater than 8 channels (1471 to 1611 nm). Because of high power loss near the water peak wavelength of 1383 nm, for some fiber types, loss measurements are taken for every channel below 1471 to ensure they are all within budget.

Explanation of the link power budget individual lines are as follows:

- The first line, fiber loss, represents the signal power loss due only to the fiber. To estimate this loss, the specified fiber attenuation is entered in the Unit Value column and fiber length is entered in the Quantity column. The product of these two entries is the fiber loss. If the fiber link loss is measured then it is entered in the Measurement column.
- 2. The splice loss line accounts for all fiber splice losses in the link. A typical good splice loss is less than 0.1 dB. The number of times a cable is spliced during installation depends on the fiber cable reel size and other route factors.
- 3. The connector loss line accounts for all connection losses in the link. Typically there will be at least two fiber connections in a link, at the fiber distribution panel, at each end of a link. Connection loss (two connectors and an adapter) is typically less than 0.5 dB for good quality connectors. Note that the connection loss at the transmission equipment is not included in any loss calculations.
- 4. The other fiber loss line includes any other fiber losses, such as bad fiber bends.
- 5. Fiber loss represents the total end-to-end optical power loss in the fiber link. It is calculated by summing lines L1 through L4. This value can be referred to as the dark fiber loss.
- 6. If passive WDMs are in the link, then their insertion loss at both cable ends is entered here. The WDM insertion loss is available from the manufacturer.
- 7. If DCMs are included in the link, their insertion loss is entered here. This information is available from the manufacturer.
- 8. If optical amplifiers are used in the link, enter their total gain of all amplifiers in the link as a negative dB value here.

- 9. Any other components in the link that contribute to the link loss are entered on this line.
- 10. The link loss line is the summation of lines L5 to L9 and represents all losses and gains in the fiber link. This is the value that is measured with an optical power meter during testing and turn-up. A positive value represents an overall link loss and negative is a gain.
- 11. The chromatic dispersion (CD) penalty is entered in this line. Typically, 1 or 2 dB is specified for a transceiver's CD penalty by the manufacturer.
- 12. The polarization mode dispersion (PMD) penalty is entered in this line for only 10 Gbps and higher transmission rates. It is specified by the manufacturer and is typically 1 dB.
- 13. Maximum link polarization dependent loss (PDL) is entered here. The value is obtained by summing individual component PDL values, refer to Eq. (5.30).
- 14. The total of all nonlinear penalties (if applicable) is entered on this line. This information is determined mainly from calculation and is described in this book.
- 15. The extinction ratio penalty is the power penalty due to a nonideal transmitter extinction ratio. This is when the optical zero bit has some low level of optical power associated with it. The penalty value can be calculated using Eq. (3.71) from Chap. 3 knowing the transmitter's extinction ratio.

$$\delta_{\text{ex.dB}} = 10 \log \left( \frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1} \right)$$

- 16. The total link loss line is the sum of lines L10 to L15 and represents all link losses and gains including penalties. This value cannot be measured with an optical power meter test set.
- 17. The maximum transmit power line represents the transmitter's maximum optical output (average,  $P_{ave}$ ) power specified by the manufacturer.
- 18. The minimum transmit power line represents the minimum optical output (average,  $P_{ave}$ ) power specified by the manufacturer.
- This line represents the receiver's overload power or maximum receiver (average, P<sub>ave</sub>) power. The received optical signal must be kept below this value for the receiver to work properly.
- 20. The receiver's sensitivity is entered on this line. It is specified by the manufacturer for a given BER and OSNR value. Typically, the larger the OSNR value, the lower the receiver sensitivity.

- 21. This line represents the transceiver's minimum optical budget and is equal to L18 L20.
- 22. This line represents the minimum measurable optical (average,  $P_{ave}$ ) power at the receiver and is equal to L18 L10. The actual measured power at the receiver should fall between the minimum receive power and maximum receive power. If it does not there is likely a problem with the link or design budget.
- 23. This line represents the maximum measurable optical (average,  $P_{ave}$ ) power at the receiver. It is equal to L17 L10. This value must remain less than the receiver overload power on line L19.
- 24. The remaining margin BoL line is equal to L21 L16 and represents the remaining optical budget after all losses and penalties have been subtracted at the beginning of life (BoL) operation. A value greater than 0 can be considered as a buffer or safety margin. A value less than 0 means that the receiver signal power may be below manufacturer specifications and the link may not work properly.
- 25. The system aging line accounts for fiber link aging. Typically all fiber link components will be replaced as they fail except for the outside plant fiber optic cable. Therefore, the main aging component that remains for the entire life span is the fiber optic cable. Typical values used fiber aging<sup>1</sup> over a 25-year life span are 0.003 dB/km for hydrogen degradation plus 0.002 dB/km for gamma radiation degradation (if applicable).
- 26. The cable repair margin is the estimated loss of all repair cable lengths spliced into the link over the life span of the link.
- 27. The remaining optical margin at system end of life (EoL) is equal to L24 L25 L26. A value greater than 0 can be considered as a buffer or safety margin. A value less than 0 means that the receiver signal power may be below manufacturer specifications and the link may not work properly at system end of life stage.

Although not noted in this budget table, the completion date, type of measurement equipment, and technician's/engineer's name are often recorded with this table.

**Example 2.1** A single-channel 10 Gbps transmission system is planned to be installed on an existing dark fiber link. The link consists of 66.4 km of standard G.652 fiber with specified attenuation of 0.21 dB/km @1550 nm, see Table 2.3. Its link is known to have nine splices of 0.1 dB and three connections of 0.3 dB. The total fiber loss was also measured and a value of 16.5 dB was recorded. The 10-Gbps transceiver operates at 1550 nm and has a minimum transmit power

	Link Power Budget for Fiber Number 3.		Specification Values at 1550 nm		Measurement Values at	
Line #	for Tx <u>site A t</u> o Rx <u>site B</u>	Unit	Unit Value	Quantity	Line Totals	<u>1550</u> nm
1	Fiber loss	dB/km	0.21	66.4	13.9	
2	Splice loss	dB	0.1	9	0.9	
3	Connector loss	dB	0.3	3	0.9	
4	Other fiber loss	dB			0.0	
5	Fiber loss (sum L1 to L4)	dB			15.7	16.5
6	WDM insertion loss	dB			0.0	
7	DCM insertion loss	dB			0.0	
8	Amplifier gain (show as neg.)	dB			0.0	
9	Other component loss	dB			0.0	
10	Link loss (sum L5 to L9)	dB			15.7	16.5
11	CD penalty	dB			2.0	
12	PMD penalty	dB			1.0	
13	PDL <sub>Tmax</sub> penalty	dB			0.0	
14	Nonlinear penalties total	dB			0.0	
15	Extinction ratio penalty	dB			0.4	
16	<b>Total link loss</b> with penalties (sum L10 to L15)	dB			19.9	

17	Maximum transmit power	dBm	2.0	
18	Minimum transmit power	dBm	-1.0	
19	Receiver overload power	dBm	-12.0	
20	Receiver sensitivity at BER <u>10<sup>-12</sup></u> , & OSNR <u>28 dB</u>	dBm	-24.0	
21	Minimum transceiver budget (L18 – L20)	dB	23.0	
22	$\begin{array}{l} \mbox{Minimum measurable receive power} \\ (L18-L10) \end{array}$	dBm	-17.5	Measured Rx power -15.7
23	<b>Maximum measurable Rx power</b> <l19 (l17="" )<="" l10="" td="" –=""><td>dBm</td><td>-14.5</td><td></td></l19>	dBm	-14.5	
24	<b>Remaining margin BoL</b> must be >0 (L21 – L16)	dB	3.1	
25	System aging	dB	0.2	
26	Cable repair	dB	2.4	
27	<b>Remaining margin EoL</b> must be >0 (L24 – L25 – L26)	dB	0.5	

 TABLE 2.3
 Power Budget Example

of -1.0 dBm, maximum transmit power of 2.0 dBm, receiver sensitivity of -24.0 dBm at BER of  $10^{-12}$  with 28 dB OSNR, and receiver overload at -12.0 dBm. The specified CD penalty is 2.0 dB and PMD penalty is 1.0 dB. Its extinction ratio is 13.0 dB. PDL in this link is negligible. Create a power budget to determine if the link loss is within acceptable limits for this transceiver at BoL and EoL 25-year operation.

Line item explanation as follows:

- 1–5. Both calculated and measured values are entered in the table to illustrate their use. In this case the calculated fiber loss is less than the measured loss. The measured loss is the more accurate value and therefore will be used for the rest of the calculations. Note that the measurement direction is indicated in the link loss budget cell laser at site A and receiver at site B. This is to increase repeatability since loss differs slightly for each direction.
- 6–9. The link does not contain any DWDM, DCM, or amplifier components and therefore these values are 0.
  - 10. The total measured link loss is the same as the total measured fiber loss. The total calculated link loss is not used.
- 11–14. Power penalties due to CD and PMD are entered as listed in transceiver specifications. There is no penalty associated with nonlinear distortions.
  - 15. The extinction ratio penalty is calculated to be 0.4 dB.
  - 16. The total link loss including all penalties is calculated to be 19.9 dB by summing lines L10 to L15.
- 17–20. This transceiver information is available from manufacturer specifications.
  - 21. The transceiver's minimum optical budget can be calculated by subtracting L20 from L18, or often the manufacturer will specify the value.
- 22–23. The actual field measured power should fall between the minimum receive power and maximum receive power. For this budget the range is between –17.5 dBm and –14.5 dBm. The actual receive power was measured and recorded at –15.7 dBm, which is within this range.
  - 24. The remaining optical margin at BoL operation is determined by subtracting the total loss with penalties from the transceiver's optical budget. The positive value indicates that there is 3.1 dB of buffer (safety margin) available in this link.
  - 25. Fiber loss degradation of 0.003 dB/km over a 25-year period is used for this value.
  - 26. It is estimated that 10 repairs will be required for this link over a 25year life span. Each repair will add an additional 200 meter length of cable at 0.21 dB/km and two splices of maximum loss of 0.1 dB per splice. Total loss per repair is 0.24 dB.
  - 27. The remaining margin at EoL is calculated by subtracting lines L25 and L26 from L24. This value indicates that there is still 0.5 dB buffer remaining after 25 years of operation.

This optical power loss budget is within acceptable limits for this transceiver.

#### 2.4 Link Budget with Optical Modulation Amplitude

Ethernet transceiver optical power parameters (such as for 10 GigE transceivers) may be specified using IEEE 802.3ae standard called optical modulation amplitude (OMA) power instead of average power. This standard defines the OMA power parameter as the difference between the high optical power  $P_1$  that represents a binary 1 and the low optical power  $P_0$  that represented the binary 0, see Eq. (3.75) and Fig. 3.17.

$$OMA = P_1 - P_0$$

It is closely related to the extinction ratio, which is the ratio of the high optical power level  $P_1$  and the low optical power  $P_0$ . OMA power is defined for both multimode and single mode transmission systems. Only single-mode systems are discussed in this text.

OMA power can be thought of as the peak signal power if the modulated laser power during binary zero bit transmission is zero (off)  $P_0 = 0$ , or the extinction ratio is infinity  $R_{ox} = \infty$ . For this case, the average signal power would be half of the peak power, see Eq. (3.82). However, turning optical power completely off during zero bit transmissions is not practical; therefore most transceivers operate with some level of zero bit optical power. Zero bit optical power is wasted power and contains no information since the optical receiver is interested only in signal transitions and the  $P_0$  level is continuous during both zero and one bit transitions. Therefore this level is treated as an optical power penalty. The OMA power level represents only the modulated information (data), which excludes the  $P_0$  power level. The signal  $P_0$  power varies for different manufacturer transceivers and is typically represented as the extinction ratio with  $P_1$  between  $R_{ex} = 3 \text{ dB}$ and 11 dB. An extinction ratio of  $R_{ex} = 3$  dB means that half the signal power is  $P_0$  power that contains no information and therefore is wasted.

OMA power and extinction ratio parameters are related but are not the same. The extinction ratio does not change as a signal is linearly attenuated during its propagation in a fiber. However, OMA does decrease during signal propagation by the same amount as the attenuation. For example, if at the beginning of a 10 km length of fiber  $P_1 =$ 1 mW and  $P_0 = 0.1$  mW then  $R_{ex} = 1/0.1 = 10$ , see Eq. (3.68). Calculation with Eq. (3.75) gives a beginning OMA = 0.9 mW. After the signal propagates the length of the fiber and assuming the fiber attenuation is 0.2 dB/km, the signal's power loss is 2 dB or a factor of 0.63. At the end of the fiber  $P_1 = 0.63$  mW and  $P_0 = 0.063$  mW. Therefore, the extinction ratio is still 10,  $R_{ex} = 0.63/0.063$ . However, the OMA has now changed to OMA = 0.63 – 0.063 = 0.567 mW, a decrease by a factor of 0.63 times the beginning OMA. OMA power cannot be measured directly with conventional field test instruments such as an optical power meter or optical spectrum analyzer (OSA). In order to determine if planned optical power levels are being received, OMA needs to be converted to average power using Eq. (3.78), Eq. (3.80), or Eq. (3.81). Transceiver specifications typically include extinction ratio and/or zero bit power level  $P_0$  to allow for this calculation.

$$P_{\text{ave}} \approx \frac{1}{2} \text{OMA} \left( \frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1} \right)$$
$$P_{\text{ave}} \approx P_0 + \frac{1}{2} \text{OMA}$$
$$P_{\text{ave}} \approx P_1 - \frac{1}{2} \text{OMA}$$

OMA power is often expressed in dBm units instead of linear units using Eq. (3.83) for the conversion.

$$OMA_{dBm} = 10 \log(OMA)$$

Average power can be converted to dBm units using Eq. (2.11) and Eq. (3.71). This formula assumes that the modulating NRZ waveform is rectangular.

$$P_{\text{ave.dBm}} \approx \text{OMA}_{\text{dBm}} + \delta_{\text{ex.dB}} - 3.01$$
 (2.11)

where  $P_{\text{ave.dBm}}$  = average measurable power, dBm OMA<sub>dBm</sub> = optical modulation amplitude power, dBm  $\delta_{\text{ex.dB}}$  = extinction ratio penalty, dB

Table 2.4 lists average optical powers for various OMA values and extinction ratios.

		OMA Power (dBm)						
		0	2	3	5	7		
P <sub>ave</sub> (dBm)	$R_{\rm ex} = 4$	-0.79	1.21	2.21	4.21	6.21		
	$R_{\rm ex} = 9$	-2.04	-0.04	0.96	2.96	4.96		
	$R_{\rm ex} = \infty$	-3.01	-1.01	-0.01	1.99	3.99		

TABLE 2.4	OMA and Average Optical Power
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Many OMA power parameters defined by IEEE 803ae are listed in transceiver specifications, as follows:

- *P*<sub>TXOMA</sub> is the minimum OMA transmit power in dBm units. This value cannot be measured with a power meter or OSA.
- 2. SRS<sub>OMA</sub> is the OMA stressed receiver sensitivity for a nonideal signal (includes jitter, noise, chromatic dispersion) at the specified BER rate. This value cannot be measured with a power meter or OSA.
- 3.  $S_{\text{OMA}}$  is the OMA receiver maximum sensitivity for an ideal signal at the specified BER rate. This value cannot be measured with a power meter or OSA.
- 4.  $P_{\text{TX}}$  is the average laser output power, which can be measured by a power meter or OSA.
- 5.  $P_s$  is the average receiver signal power sensitivity at the specified BER rate. This value can be measured by a power meter or OSA.
- 6.  $P_{\text{OFF}}$  or  $P_0$  is the optical power for a digit zero transmission. This value cannot be measured with a power meter or OSA.
- 7. TDP is the transmitter and dispersion penalty. This value includes transmitter impairments such as jitter and laser noise as well as the chromatic dispersion penalty for standard single-mode fiber (G.652).

These parameters are used to create an OMA budget table, see Table 2.5. Refer to Fig. 2.4 for the OMA budget diagram.

**Example 2.2** A single-channel 10 GE transmission system is planned to be installed on an existing dark fiber link. The link consists of 11.0 km of standard G.652 fiber with specified attenuation of 0.35 dB/km @1310 nm. Its link is known to have nine splices of 0.1 dB and two connections of 0.3 dB. The total fiber loss was also measured and a value of 10.0 dB was recorded. The 10 GE transceiver operates at 1310 nm and has a minimum transmit OMA of -5.2 dBm, maximum transmit average power of 2.0 dBm, receiver sensitivity in OMA of -12.6 dBm at BER of  $10^{-12}$ , receiver overload at 0.0 dBm, and optical extinction ratio of 3.5 dB. The maximum TDP is 1.0 dB. Create a power budget to determine if the link loss is within acceptable limits for this transceiver at BoL and EoL 25-year operation.

Refer to example results in Table 2.6, the remaining margins at both BoL and EoL periods are positive, which indicates that this system has sufficient optical power budget for its life span.

# 2.5 Optical Loss Measurement

Optical loss measurement is performed with a laser source tuned to the required wavelength and with an optical power meter. If a test laser source is not available, a transmission equipment transceiver

	OMA Budget for Fiber Number . for		Specification	n Values at _	nm	Measurement Values
Line #	Tx to Rx	Unit	Unit Value	Quantity	Line Totals	at nm
1	Fiber loss	dB/km				
2	Splice loss	dB				
3	Connector loss	dB				
4	Other fiber loss	dB				
5	Fiber loss (sum L1 to L4)	dB		·		
6	WDM insertion loss	dB				
7	DCM insertion loss	dB				
8	Amplifier gain (show as neg.)	dB				
9	Other component loss	dB				
10	Link loss (sum L5 to L9)	dB				
11	TDP/CD penalty	dB				
12	PMD penalty	dB				
13	PDL <sub>Imax</sub> penalty	dB				
14	Nonlinear penalties total	dB				
15	<b>Total link loss</b> with penalties (sum L10 to L14)	dB				
16	Maximum transmit power	dBm				

17	Minimum Tx OMA, P <sub>TXOMA</sub>	dBm	n/a
18	Minimum Tx power, $P_{TX}$ use [Eq. (2.11)]	dBm	
19	Optical extinction ratio, $R_{ex}$	dB	n/a
20	Optical extinction ratio penalty, $\delta_{_{ex}}$ [Eq. (3.64)]	dB	
21	Receiver overload power	dBm	
22	Rx sensitivity OMA S <sub>OMA</sub> @ BER & OSNR	dBm	n/a
23	Minimum transceiver budget (L17 – L22)	dB	
24	Minimum measurable Rx receive power (L18 – L10 )	dBm	Measured Rx power
25	Maximum measurable Rx power <l21 (l16="" )<="" l10="" td="" –=""><td>dBm</td><td></td></l21>	dBm	
26	<b>Remaining margin BoL</b> must be >0 (L23 – L15)	dB	
27	System aging	dB	
28	Cable repair	dB	
29	<b>Remaining margin EoL</b> must be >0 (L26 – L27 – L28)	dB	

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 TABLE 2.5
 OMA Budget



FIGURE 2.4 OMA budget power diagram.

laser can be used instead (note this test is traffic affecting). The convention for fiber loss measurement is to perform span measurements in both directions in a fiber and then to average the results. This is because the measurements will differ slightly in each direction, primarily due to core mismatches at connections and splices. A large difference in measurement can mean a bad fiber splice or connector. If the transmission direction for the fiber is known, then one measurement can be performed in the same direction as the signal transmission. Typical measurement precision for most network designs is 0.1 or 0.01 dB.

A simple loss measurement procedure is shown in Fig. 2.5 using two fiber jumpers, laser source at proper wavelength, and calibrated power meter. The First step as shown in Fig. 2.5*a* is to measure the loss with only test jumpers. This value is recorded as the reference value. If the power meter can measure loss in dB, then the zero button on the meter is pressed. This sets the meter reading to 0 dB. Next the fiber under test is added as shown in Fig. 2.5*b*. If the power meter reading is in dB, then the loss of the fiber under test is displayed. If the power meter reading is only dBm, subtract the reference value from the fiber under test value to obtain the fiber loss.

Fiber link loss measurement can also be performed using an OTDR but is less accurate than a power meter measurement. This is because the OTDR determines fiber loss indirectly by estimating the

	OMA Budget for Fiber Number 3. for		Specification Values at <u>1310</u> nm			Measurement Values
Line #	Tx <u>site A</u> to Rx <u>site B</u>	Unit	Unit Value	Quantity	Line Totals	at <u>1310</u> nm
1	Fiber loss	dB/km	0.35	11.0	3.85	
2	Splice loss	dB	0.1	9	0.9	
3	Connector loss	dB	0.3	2	0.6	
4	Other fiber loss	dB			0.0	
5	Fiber loss (sum L1 to L4)	dB			5.4	5.8
6	WDM insertion loss	dB			0.0	
7	DCM insertion loss	dB			0.0	
8	Amplifier gain (show as neg.)	dB			0.0	
9	Other component loss	dB			0.0	
10	Link loss (sum L5 to L9)	dB			5.4	5.8
11	TDP/CD penalty	dB			1.0	
12	PMD penalty	dB			0	
13	PDL <sub>Imax</sub> penalty	dB			0	
14	Nonlinear penalties total	dB			0	
15	<b>Total link loss</b> with penalties (sum L10 to L14)	dB			6.8	
16	Maximum transmit power	dBm			2.0	

 TABLE 2.6
 OMA Budget Example (Continued)

	OMA Budget for Fiber Number 3. for		Specification Values at <u>1310</u> nm Measu			Measurement Values
Line #	Tx <u>site A</u> to Rx <u>site B</u>	Unit	Unit Value	Quantity	Line Totals	at <u>1310</u> nm
17	Minimum Tx OMA, P <sub>TxOMA</sub>	dBm			-5.2	n/a
18	Minimum Tx power, $P_{Tx}$ [Eq. (2.11)]	dBm			-4.0	
19	Optical extinction ratio, $R_{ex}$	dB			3.5	n/a
20	Optical extinction ratio penalty, $\delta_{_{ex}}$ [Eq. (3.64)]	dB			4.2	n/a
21	Receiver overload power	dBm			0.0	
22	Rx sensitivity OMA S <sub>OMA</sub> @ BER & OSNR	dBm			-12.6	n/a
23	Minimum transceiver budget (L17 – L22)	dB			7.4	
24	$\begin{array}{l} \mbox{Minimum measurable Rx receive power} \\ (L18-L10 \ ) \end{array}$	dBm			-9.4	Measured Rx power
25	<b>Maximum measurable Rx power</b> <l21 (l16="" )<="" l10="" td="" –=""><td>dBm</td><td></td><td></td><td>-3.4</td><td></td></l21>	dBm			-3.4	
26	<b>Remaining margin BoL</b> must be >0 (L23 – L15)	dB			0.6	
27	System aging	dB			0	
28	Cable repair	dB			0.5	
29	<b>Remaining margin EoL</b> must be >0 (L26 – L27 – L28)	dB			0.1	

 TABLE 2.6
 OMA Budget Example (Continued)

₽



FIGURE 2.5 Fiber loss measurement.

fiber attenuation from backscattering of optical pulses that are embedded in noise.<sup>2</sup> Also, fiber loss measurement is not available in the OTDR's dead zone and for the fiber's end connectors. Better accuracy can be obtained if OTDR measurements are taken from both fiber ends and then averaged.

# 2.6 Optical Return Loss

Optical return loss (ORL) is the logarithmic ratio of the launch (incident) power divided by the total reflected power seen at the launch point, see Eq. (2.12). The total reflected power is the total accumulated reflected optical power measured at the launch caused by fiber Rayleigh scattering and Fresnel reflections. Rayleigh scattering is the scattering of light along the entire length of the fiber, caused by elastic collisions between the light wave and fiber molecules. This results in some of the light to be reflected back to the source. Rayleigh scattering is intrinsic to the fiber and therefore cannot be eliminated. Fresnel reflections occur in the light path where there is an abrupt change in the refractive index such as at connections and splices. The further away a reflective event is from the fiber launch point the less it contributes to the total reflected power. Therefore, fiber connections and splices closest to the laser contribute the most to the ORL. ORL is always expressed as a positive decibel. The higher the ORL the lower the reflected power.

$$ORL = 10 \log\left(\frac{P_i}{P_R}\right)$$
(2.12)

where ORL = optical return loss, dB

 $P_R$  = total reflected power seen at the launch point, mW  $P_i$  = launch or incident power, mW

Because of Rayleigh scattering, as fiber length increases so does the amount of reflected power. This relationship is logarithmic and reaches an asymptote at approximately 31 dB for a 1550 signal. This assumes an ideal fiber with no splices, no connections and a nonreflective end of the fiber, see Eq. (2.13).<sup>3</sup>

$$ORL = -10 \log \left[ \frac{S}{2} (1 - e^{-2\alpha L}) \right]$$
(2.13)

where *S* = backscattering capture coefficient, approximately 0.0015 for standard fiber at 1550 nm

- L = fiber length, km
- $\alpha$  = attenuation coefficient, 1/km

Figure 2.6 plots the dependence of ORL on fiber length assuming fiber attenuation is 0.22 dB/km at 1550 nm, S = 0.0015 with a non-reflective end. As can be seen from the plot, for fiber lengths greater than 20 km, the best possible achievable ORL is approximately 31 dB. If a reflective end is added to the fiber, then the ORL for L = 0 begins at the fiber end boundary reflectance, typically 15 dB for fiber-to-air boundary, and then increase to 31 dB.



FIGURE 2.6 ORL as a function of fiber length at 1550 nm.

ITU-T G.959.1 recommends a minimum ORL of 24 dB for 2.5, 10, and 40 Gbps fiber links.

#### 2.6.1 Reflectance

The portion of optical power reflected back to the source by a discrete component is referred to as reflectance. It is due to the Fresnel reflection effect, which occurs at any fiber boundary where a change of refractive index, such as between glass and air, exists. Reflectance is defined as the logarithmic ratio of the reflected power divided by the incident power, see Eq. (2.14). It is always expressed as negative decibel value. The more negative the component's reflectance, the less power it reflects back to the source.

$$RF = 10 \log\left(\frac{P_r}{P_i}\right)$$
(2.14)

where RF = component reflectance, dB

 $P_r$  = average reflected optical power, mW

 $P_i$  = average incident optical power, mW

Examples of components with reflectance values include connectors, splices, and unterminated fiber. Fiber connectors are classified into four reflectance polish grades: physical contact (PC), super physical contact (SPC), ultra physical contact (UPC), and angled physical contact (APC). Each polish grade represents the maximum amount of reflectance the connector will exhibit when mated properly. Table 2.7 lists typical maximum values for these grades. Refer to connector manufacturer specifications for actual values. The polish grade abbreviation is typically placed immediately after the type of connector such as FC-SPC.

If the connector is not mated properly or if its contact surface is dirty, these reflectance values can increase substantially over manufacturer specifications. These connector types (PC) all require physical contact with the mating connector, any air gap will significantly increase the connector's reflectance and insertion loss.

Reflectance can be estimated knowing the refractive index for both media, see Eq. (2.15). For example, the ideal reflectance for an

Group Name	Maximum Reflectance (dB)
Physical contact (PC)	-30
Super physical contact (SPC)	-40
Ultra physical contact (UPC)	-50
Angled physical contact (APC)	-60

TABLE 2.7 Single-Mode Fiber Connector Ty	pical Reflectance Values
--	--------------------------

unterminated fiber with a perpendicular flat face is -14.6 dB. This assumes the fiber core's refractive index is  $n_1 = 1.46$  and the air refractive index is  $n_2 = 1$ .

$$RF = 10 \log \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$
(2.15)

where RF = reflectance, dB

 $n_1$  = fiber core refractive index

 $n_2$  = other medium refractive index

ITU-T G.959.1 recommends<sup>4</sup> single component reflectance not to exceed –27 dB for single-mode fiber.

#### 2.6.2 Detrimental Effects due to Low ORL

High reflected power back into a laser can result in undesirable effects. This includes laser instability, wavelength drift, and an increase in laser noise, which all can lead to a less desirable BER. If the reflective power is high enough, the laser itself can be permanently damaged.

High fiber link reflectance can also cause interferometric noise that is seen by the receiver. This also degrades BER performance. Interferometric noise is signal amplitude variations due to the interference caused by a single reflection or multiple reflections in a fiber. It is analogous to radio frequency standing waves in a mismatched transmission cable. Interferometric noise is significant<sup>5</sup> only for 10 Gbps systems operating at 1300 nm over a low loss link of less than 7 dB. Penalties at 1550 nm are insignificant. Interferometric noise penalty can be kept to a minimum by ensuring reflectance values at both the receiver and the laser source (or anywhere else in the link) are less than –20 dB and the laser source has a minimum extinction ratio of 4 dB. Table 2.8 lists interferometric noise penalties with various fiber end reflectance and loss between reflective events estimated by Fröjdh.<sup>6</sup>

Methods to help improve ORL are as follows:

- Use ultra polish connectors that have low reflectance such as UPC type. APC type connectors have even better reflectance values but are not compatible with other non-APC connectors. Connection to a non-APC connector can damage the APC connector.
- 2. Use fusion splices instead of mechanical connectors or mechanical splices where possible.
- 3. Redo fusion splices that are shown to have reflectance. A good fusion splice should have no reflectance.
- 4. Install optical isolators at the laser to reduce back reflectance.

	Interferometric Noise Penalty (dB)					
	Link with both Ends —20 dB Reflectance	Link with –12 and –20 dB End Reflectance	Link with both Ends –12 dB Reflectance			
Extinction	Link Loss of	Link Loss of	Link Loss of			
Ratio (dB)	7 dB	7 dB	7 dB	5 dB	3 dB	
3.5	0.04	0.13	0.45	0.8	1.5	
4	0.04	0.1	0.35	0.62	1.2	
6	0.03	0.8	0.27	0.5	0.9	
8	0.02	0.7	0.23	0.41	0.8	
10	0.02	0.6	0.21	0.4	0.7	
12	0.02	0.05	0.2	0.38	0.7	

TABLE 2.8 Interferometric Noise Penalties at 1300 nm

#### 2.6.3 ORL Measurement

ORL can be measured with an ORL test set or an OTDR. The test set typically uses the optical continuous wave reflectometer (OCWR) method for determining ORL. It basically consists of an optical 3 port circulator, a continuous wave laser source (fixed or tunable), and power meter, see Fig. 2.7. A tunable laser source is used if ORL is measured in a WDM channel. The technique involves a three-step measurement process. The first step is to determine the circulator's insertion loss port X to Y and fiber launch power at port Y, see Fig. 2.7a. The second step is to determine the leaked power between isolated ports X and Z, see Fig. 2.7b. A nonreflective end is attached to port Y so that reflections from this port are not measured. The last measurement is completed when the fiber under test is attached to port Y, see Fig. 2.7c. If the far end connector is unterminated, a non-reflective end may be required for short fiber lengths, less than 20 km. This is to ensure the far end connector does not affect the ORL measurement. The fiber's total reflected power can be determined by accounting for the circulator's insertion loss and subtracting any measured isolation power, see Eqs. (2.16) to (2.19).

$$P_Z^{\rm mW} = P_{YZ}^{\rm mW} + P_{XZ}^{\rm mW} \tag{2.16}$$

$$P_{\text{ORL}}^{\text{dBm}} = P_Z^{\text{dBm}} + \Gamma_{YZ}^{\text{dB}}$$
(2.17)

$$ORL = 10 \log \left(\frac{P_i^{mW}}{P_{ORL}^{mW}}\right)$$
(2.18)

$$ORL = P_i^{dBm} - P_{ORL}^{dBm}$$
(2.19)

where ORL = fiber's optical return loss, dB

- $P_i$  = incident or launch optical power into fiber under test, mW or dBm
- $P_{z}$  = reflected optical power at port Z, mW or dBm
- $P_{xz}$  = power transferred between isolated ports X and Z, mW
- $P_{ORL} =$  fiber under test total reflected power
- $\Gamma_{\gamma\gamma}$  = insertion loss of the circulator, dB



FIGURE 2.7 Simple ORL measurement method.

Refer to TIA/EIA-455-107, FOTP  $107^7$  standard for additional measurement details.

An OTDR can also measure ORL but is less accurate than an OCWR.

## 2.7 Average and Peak Optical Power

Optical signal power is specified as an average power or peak power value. This is because on-off keying (OOK) modulated optical signals consist of an optical carrier intensity modulated with a digital signal. The optical signal has a high optical power level representing a one bit pulse and a low optical power level representing a zero bit, see Fig. 2.8. The signal's average power represents the signal power measured over a relatively long time period, which is much longer than the signal's bit time slot width. This results in a power measurement that averages numerous high and low pulse levels over the time period, see Eq. (2.20). Peak power of a modulated optical signal is the power at an instance in time during the one bit's pulse width  $T_b$ . Most field measurement equipment such as power meters and optical spectrum analyzers (OSA) measure average optical signal power. For an unmodulated optical source, peak power is equal to average power.





FIGURE 2.8 NRZ and RZ modulated optical signals.

where  $P_{ave}$  = modulated optical signal's average power, W P(t) = modulated optical signal power at an instance in time t, W T = a long time period until the modulation pattern repeats, s

Assuming that the 1 and 0 information bits are equally distributed in a signal, the equipment extinction ratio is ideal,  $r_{ex} = \infty$  ( $P_L = 0$ ), and the bit pulses are rectangular, then the average power level for an NRZ signal, with a duty cycle of 1, is equal to half its peak value, see Eq. (2.21). These assumptions are used for calculating NRZ signal average power given peak power in this text. The average power level for an RZ signal, with a duty cycle of 0.5, is equal to one quarter its peak value, see Eq. (2.22).

$$P_{\text{ave.NRZ}} = \frac{P_{\text{peak}}}{2} \tag{2.21}$$

$$P_{\text{ave.RZ}} = \frac{P_{\text{peak}}}{4} \tag{2.22}$$

$$d_c = \frac{T_b}{T} \tag{2.23}$$

$$R = \frac{1}{T} \tag{2.24}$$

where  $P_{\text{ave.NRZ}}$  = average power for an NRZ modulate optical signal, W  $P_{\text{ave.RZ}}$  = average power for an RZ modulate optical signal, W  $P_{\text{peak}}$  = optical signal peak power, W  $P_{L}$  = low (0) bit optical power value, W T = time slot width, s  $T_{b}$  = signal bit pulse width (FWHM), s R = signal transmission rate, bps  $d_{c}$  = signal duty cycle

If the extinction ratio is nonideal then Eqs. (2.21) and (2.22) are modified to take into account the extinction ratio penalty, see Eqs. (2.25) and (2.26).

$$P_{\text{ave.NRZ}} = \frac{P_{\text{peak}}}{2} \left( \frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1} \right)$$
(2.25)

$$P_{\text{ave.RZ}} = \frac{P_{\text{peak}}}{4} \left( \frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1} \right)$$
 (2.26)

where  $R_{ex}$  is the optical extinction ratio.

If the signal bit pulses are not rectangular but more resemble a Gaussian curve, then additional adjustment is required for the conversion between peak to average powers.

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# CHAPTER **3** Optical Signal to Noise Ratio

## 3.1 Description

Optical signal to noise ratio (OSNR) is an important figure of merit used in fiber link planning. It is the ratio of signal power to noise power, over a specific spectral bandwidth, at any point in an optical link. Noise power can be defined as any undesirable signal interference. All fiber transmission signals consist of modulated light with some level of background noise. As the noise level increases, the receiver has greater difficulty decoding signal information and consequently errors are introduced into the received transmission. A welldesigned system will have sufficiently high receiver signal power over noise power (the OSNR) to maintain communications within acceptable error limits. This is analogous to trying to listen to a speaker at a conference where many people are talking. The higher the background noise from other people talking, the more difficult it is to discern what the speaker is saying (lower OSNR). Ultimately with increasing noise, words and information are missed to a point where there is so much background noise the listener can no longer understand the speaker. All optical receivers can tolerate a minimum level of noise power below the signal power. This noise power is referenced to the signal power and is specified for the receiver as the minimum required OSNR value for a specific receiver signal power. If it is exceeded, transmission bit errors above the specification level will occur.

Noise sources can be grouped as active and passive. Active sources such as lasers, receivers, and optical amplifiers generate new noise power in the fiber link. Passive sources such as fiber, connectors, splices, and WDMs cause interference by distorting or reflecting the propagating signal power. Below are 10 common noise sources.

1. *Signal-spontaneous noise (si-sp)*: This noise is generated by the signal mixing with amplified spontaneous emission noise generated in an optical amplifier. It is typically the dominant

noise source in an amplified link. It can also be referred to as amplified spontaneous emissions (ASE) noise. The optical noise power<sup>1</sup> is given by Eq. (3.1) and noise RMS photodiode current as Eq. (3.2).

$$P_{\rm si-sp} = 2n_{\rm sp} hf \Delta f(G-1) \tag{3.1}$$

$$\sigma_{\rm si-sp} = \sqrt{4R_p^2 G P_s n_{\rm sp} h f \Delta f (G-1)}$$
(3.2)

2. *Spontaneous-spontaneous noise (sp-sp)*: This noise is generated by ASE mixing with itself. It generally is not consequential. The noise RMS photodiode current is given by Eq. (3.3).

$$\sigma_{\rm sp-sp} = \sqrt{4R_p^2(n_{\rm sp}hf(G-1))^2\Delta f_o\Delta f_e}$$
(3.3)

3. *Shot noise* (*sh*): This is electrical noise produced by the receiver photodiode in both PIN and APD type receivers. APD type receivers have a better signal to noise ratio (SNR) due to their internal multiplication gain mechanism. Receiver noise level and minimum OSNR are established in transceiver design and cannot be controlled by system planning other than by selecting better transceivers. The RMS photodiode noise current is given by Eq. (3.4).

$$\sigma_{\rm sh} = \sqrt{2qI_{\rm dc}\Delta f} \tag{3.4}$$

4. *Shot-spontaneous noise (sh-sp)*: This noise is generated by shot noise mixing with ASE noise in the receiver. It is accounted for in the transceiver's OSNR specifications. The RMS photodiode noise current is given by Eq. (3.5).

$$\sigma_{\rm sh-sp} = \sqrt{4qR_p n_{\rm sp} h f (G-1)\Delta f_o \Delta f}$$
(3.5)

5. *Thermal noise (th)*: This also is noise produced by the front end of the receiver diode due to thermal activity and is accounted for in the transceiver's OSNR specifications. The RMS photodiode noise current is given by Eq. (3.6).

$$\sigma_{\rm th} = \sqrt{4kT_{\rm temp}\Delta f/R_L} \tag{3.6}$$

6. *Multiple path interference noise (MPI)*: This noise is generated by the signal reflecting multiple times in the fiber and interfering with itself. Reflections are due to Rayleigh scattering and other reflective events such as connectors and splices. It is typically a concern for high signal powers and in distributed Raman amplifiers with high gains. This noise source is also known as double Rayleigh scattering (DRS). To keep MPI noise to a minimum, use good-quality and clean ultra polish (UPC) or angle polish (AP) type fiber connectors. Fiber splices that show OTDR reflections should be respliced.

- Source spontaneous emissions (SSE): This noise is due to spontaneous photon emissions during the lasing process. These random photons add to the laser's amplitude and phase causing noise. Typical values for DFB laser relative intensity noise (RIN) is -150 dB/Hz,<sup>2</sup> and OSNR/0.1 nm varies from 40 to 50 dB.<sup>3</sup> Laser noise is constant but can be increased by fiber link reflections (low ORL). This noise is included in OSNR design budgets.
- 8. *Mode partition noise (MPN)*: This noise occurs because of random variations of individual laser modes even though the total laser output power remains constant. The noise is generated in fibers where the signal dispersion wavelength is not zero. The fluctuating modes travel at different group velocities due to chromatic dispersion, which results in mode desynchronization and added receiver noise. MPN occurs for MLM lasers but can also occur for SLM lasers that have significantly large side nodes and where the side mode suppression ratio (SMSR) is less than 20 dB. See Chap. 10 for details.
- 9. *Cross talk noise (CTN)*: WDMs (wavelength-division multiplexing) can cause interference noise as channel cross talk. The signal from one WDM channel appears on another channel resulting in interference. This is because a WDM cannot provide total 100% channel isolation. Typical adjacent channel isolation is approximately 30 dB down from adjacent channel signal power. At this level, the interference is not significant in most systems. However, it can be a concern for high channel launch powers. Refer to Chap. 6 for more information on adjacent channel interference.
- 10. *Nonlinear distortion*: Fiber can also cause noise interference when high power signals interact with the fiber, resulting in nonlinear distortions such as four wave mixing. Maintaining signal power below recommended limits can help keep this interference to a minimal level. Refer to Chap. 7 for further details. Nonlinear penalties are included in OSNR budget calculations.

The receiver's total photodiode current can be shown as the incident optical power times the photodiode's responsivity, see Eq. (3.10). This current is the sum of signal and noise currents, see Eq. (3.9). Total noise current variance, as defined by Eq. (3.8), is equal to the sum of each individual contributing noise variance, see Eq. (3.7).

$$\sigma_N^2 = \sigma_{th}^2 + \sigma_{sh}^2 + \sigma_{sh-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{si-sp}^2 + \sigma_{MPI}^2 + \sigma_{SSE}^2 + \sigma_{other}^2$$
(3.7)

$$\sigma_{\text{noise}}^2 = \left\langle (\Delta i_{\text{noise}})^2 \right\rangle \tag{3.8}$$

$$i_{\text{total}} = i_{\text{signal}} + \Delta i_{\text{noise}} \tag{3.9}$$

$$i = R_p P_{\rm op} \tag{3.10}$$

where  $\sigma_{\rm N}$  = total RMS noise current, A  $\sigma_{xx}$  = xx type of RMS photodiode noise current, A  $R_p$  = photodiode responsivity, A/W  $P_{op}$  = photodiode incident optical power, W  $T_{\text{temp}}$  = absolute temperature, K  $\dot{k}$  = Boltzmann constant, 1.38 × 10<sup>-23</sup> J/K  $\Delta f$  = noise bandwidth, Hz  $\Delta f_{a}$  = optical bandwidth, Hz  $\Delta f_a$  = electrical bandwidth, Hz  $R_{t}$  = photodiode load resistance,  $\Omega$  $I_{dc}$  = average photodiode current, A G = gain $n_{sp}$  = spontaneous emissions factor  $\hat{h}$  = Planck's constant, 6.63 × 10<sup>-34</sup> J/Hz q = electron charge (1.6 × 10<sup>-19</sup> coulomb) times photo detector quantum efficiency i = instantaneous photodiode current, A  $i_{total}$  = instantaneous photodiode total current, A  $i_{signal}$  = instantaneous photodiode signal current, A  $\Delta i$  = instantaneous photodiode noise current, A

With Eqs. (3.10) and (3.7) total optical noise power at the receiver (also referred to as the noise floor) can be determined as shown by Eq. (3.11). Graphically, the optical noise power, signal power, link loss, and OSNR can be shown as Fig. 3.1.

$$P_N = \frac{\sigma_N}{R_p} \tag{3.11}$$

where  $P_N$  is the total RMS optical noise power at the receiver, W.

For most fiber transmission systems, OSNR needs to be considered only if optical amplifiers are included in a transmission link. This is because in links without amplifiers, noise power does not accumulate sufficiently to be a significant limiting factor.



FIGURE 3.1 Noise, signal, and OSNR diagram.

OSNR can be defined as the logarithmic ratio of average optical signal power to average optical noise power over a specific spectral bandwidth measured at the input of an optical receiver<sup>4</sup> photodiode. Figure 3.2 shows a typical optical spectrum analyzer (OSA) signal trace. The signal power  $P_{sig}$  is determined by subtracting the noise power  $P_{noise}$  bound by a spectral width  $B_o$  from the peak amplitude of the signal plus noise curve also bound by  $B_o$ , see Fig. 3.2 and Eq. (3.13).  $B_o$  must be wide enough to include all of the signal power envelope in order to minimize signal measurement error, see Sec. 3.13 resolution bandwidth. The noise power  $P_{noise}$  is the total noise power bound by the same spectral bandwidth  $B_o$ .

$$OSNR = 10 \log \left(\frac{P_{sig}}{P_{noise}}\right)$$
(3.12)

$$P_{\rm sig} = P_{\rm sig+noise} - P_{\rm noise}$$
(3.13)

$$P_{\text{noise}} = P_{\text{noise}}(B_o) \tag{3.14}$$

where OSNR = optical signal to noise ratio bound by bandwidth  $B_o$ , dB  $P_{sig}$  = signal power bound by  $B_o$ , mW  $P_{sig+noise}$  = signal plus noise power bound by  $B_o$ , mW  $P_{noise}$  = noise power bound by  $B_o$ , mW  $P_{noise}(B_o)$  = noise power bound by  $B_o$ , mW  $B_o$  = spectral bandwidth, nm


FIGURE 3.2 Spectral view of a typical signal and OSNR parameters.

### 3.1.1 OSNR Measurement

The optical spectrum analyzer (OSA) is the instrument typically used to measure OSNR. Most OSA units use the method defined by IEC 61280-2-9 standard,<sup>5</sup> and the equation shown in Eq. (3.15). Signal and noise measurement are made over a specific spectral bandwidth  $B_r$ , which is referred to as the OSA's resolution bandwidth (RBW). The RBW filter acts as a band pass filter allowing only the set amount of light spectrum to strike the OSA's photo detector. The photo detector measures the average of all optical power in this spectral width. It cannot discriminate between two separate signals in the RBW spectrum. If there is more than one signal in RBW, it will treat and display them as one. Therefore, the ability of an OSA to display two closely spaced signals as two distinct signals is determined by the RBW setting. Typically, an OSA's RBW range is adjustable between 10 and 0.01 nm with common settings of 1.0, 0.5, 0.1, and 0.05 nm.

The signal power in Eq. (3.15) is the measured signal plus noise power minus the in-band noise power measured at the OSA's RBW as shown in Fig. 3.3 and Eq. (3.16). The RBW setting for the signal measurement must be wide enough to include all of the signal power. If it is not, some signal power will fall outside of the RBW width and will not be measured. Consequently, signal power measurement error will increase.



FIGURE 3.3 OSA view of a typical signal and OSNR parameters.

Noise power at the signal wavelength cannot be measured directly because it is obscured by the signal itself. Therefore, the noise measurement is performed at both sides of the signal, just outside of the signal skirts, using the OSA's noise equivalent bandwidth (NEB) filter. The results are then interpolated to determine the noise power at the signal wavelength, see Eq. (3.17) and Fig. 3.3. The NEB filter has a rectangular passband and provides a more accurate noise measurement than the standard RBW filter.

OSNR is calculated using Eq. (3.15), which is similar to Eq. (3.12) with the exception of the last term. This term is a scaling factor used to adjust the measured noise power bound by the noise equivalent bandwidth, represented by  $B_{\mu}$ , to the signal RBW bandwidth, represented by  $B_{\mu}$ . If the NEB filter width is the same as the signal RBW width, then this term is zero. Scaling noise power is possible assuming that the broad noise level is relatively flat at the signal's RBW. These calculations are automatically performed by most OSAs, resulting in signal power, noise power, and OSNR readouts.

$$OSNR = 10 \log\left(\frac{P_{sig}}{P_{noise}}\right) + 10 \log\left(\frac{B_m}{B_r}\right)$$
(3.15)

$$P_{\rm sig} = P_{\rm sig+noise} - P_{\rm noise}$$
(3.16)

$$P_{\text{noise}} = \frac{P_{\text{noise}}(\lambda_1) + P_{\text{noise}}(\lambda_2)}{2}$$
(3.17)

where OSNR = optical signal to noise ratio bound by RBW, dB  $P_{sig}$  = optical signal power bound by RBW, mW  $P_{sig+noise}$  = optical signal plus noise power bound by RBW, mW  $P_{noise}$  = noise power bound by NEB, mW  $P_{noise}(\lambda_1)$  = noise power at  $\lambda_1$  bound by NEB, mW  $P_{noise}(\lambda_2)$  = noise power at  $\lambda_2$  bound by NEB, mW  $B_m$  = noise equivalent bandwidth NEB, nm  $B_r$  = measurement resolution bandwidth RBW, nm

### 3.1.2 WDM OSNR

IEC 61280-2-9 defines the OSNR measurement method and equation for DWDM systems, which is similar to the single-channel method in the previous section. Each individual DWDM channel is represented by its own OSNR that is calculated with Eq. (3.18). As discussed in the previous section, the first term determines the logarithmic signal to noise ratio and the second term is a scaling factor used to adjust the noise power bandwidth NEB, represented by  $B_m$  if it is not the same as the signal measurement bandwidth RBW. Scaling noise power is possible assuming that the noise level is relatively flat at the signal RBW. For DWDM OSNR measurements, there often is insufficient spectral space between DWDM signals to measure noise power at the RBW. Therefore the NEB bandwidth is adjusted narrower than RBW for noise measurements at both sides of the signal. Therefore it is scaled by the second term in Eq. (3.18). If the reference bandwidth  $B_r$ and noise measurement bandwidth  $B_{m}$  are the same, this second term is zero.

Signal, noise power, and OSNR measurements and calculations are performed at each individual DWDM channel. The signal power in Eq. (3.18) is the measured signal plus noise power minus the in-band noise power measured at the RBW as shown in Fig. 3.4 and Eq. (3.19). The RBW setting for the signal measurement must be wide enough to include all of the signal power. If it is not, some signal power will fall outside of the RBW width and will not be measured. Consequently, signal measurement error will increase.

Noise  $P_{noise,i}$  measurement is required at the channel's signal wavelength bound by RBW. However, the signal power obscures the noise at this wavelength and most OSA's cannot measure the noise power here directly. Therefore, the noise measurement is performed at both sides of the signal, just outside of the signal skirts, using the OSA's noise equivalent bandwidth (NEB) filter. The results are then interpolated to determine the noise power at the signal wavelength, see Eq. (3.20) and Fig. 3.4. Noise measurements for interpolation are made





at 1/2 ITU channel spacing or less on both sides of the signal. The NEB filter has a rectangular passband and provides a more accurate noise measurement than the standard RBW filter. For tightly spaced DWDM channels where noise measurement space, at the signal RBW width on both sides of the signal is insufficient, a tighter width is used. The results are then scaled by Eq. (3.18). Scaling noise power is possible assuming that the noise level is relatively flat at the signal's RBW. These calculations are automatically performed by most OSAs resulting in signal power, noise power, and OSNR readouts.

$$OSNR_{i} = 10 \log\left(\frac{P_{\text{sig.}i}}{P_{\text{noise.}i}}\right) + 10 \log\left(\frac{B_{m}}{B_{r}}\right)$$
(3.18)

$$P_{\text{sig.}i} = P_{\text{sig.}i+\text{noise.}i} - P_{\text{noise.}i}$$
(3.19)

$$P_{\text{noise},i} = \frac{P_{\text{noise}}(\lambda_{i-\Delta \text{ITU}/2}) + P_{\text{noise}}(\lambda_{i+\Delta \text{ITU}/2})}{2}$$
(3.20)

where

OSNR<sub>i</sub> = optical signal to noise ratio at the *i*'th channel bound by RBW, dB

 $P_{\text{sig.}i}$  = average optical signal power at the *i*'th channel bound by RBW, mW

- $P_{\text{noise.}i}$  = average (interpolated) noise power at the *i*'th channel bound by NEB, mW
- $P_{\text{noise}}(\lambda_{i+\Delta ITU/2}) = \text{noise power centered at } \lambda_{i+\Delta ITU/2} \text{ bound by } \text{NEB, mW}$
- $P_{\text{noise}}(\lambda_{i-\Delta ITU/2}) = \text{average noise power centered at } \lambda_{i-\Delta ITU/2} \text{ bound}$ by NEB, mW
  - $\Delta \lambda_{III} = ITU$  channel spacing, nm
    - $\ddot{B}_m$  = noise equivalent bandwidth NEB, nm
    - $B_r^{m}$  = resolution bandwidth RBW, nm

Special precaution is required if measuring OSNR on the filtered end or demux side (drop side) of a DWDM, OADM, or ROADM,<sup>6</sup> see Fig. 3.5. Due to DWDM, OADM, or ROADM filtering effects, a false noise floor may appear in an OSA view that can be mistaken as the correct noise floor, see Figs. 3.6 and 3.7. This can result in an incorrect automatic OSNR measurement. The correct measurement can be made by manually setting the OSA noise markers to the proper noise floor. The noise hump on both sides of the signal can completely disappear for wide band signals such as in 10 or 40 Gbps signals where demultiplexer filters are the same width as the signal itself. This would make OSNR measurement problematic because the in-band noise still exists but it would be difficult to locate for correct OSNR measurement. One method to located the in-band noise floor would be to polarize the signal at the source. Then the polarized signal can be filtered out by a polarizer at the OSA, which would leave the noise floor level available for measurement. Some OSAs are available to overcome this OSNR measurement issue using this or other methods. OSA user manuals and specifications should be consulted for more information.

## 3.1.3 Resolution Bandwidth

Using proper OSA resolution bandwidth (RBW) for signal measurement is important to ensure the best possible accuracy. If RBW is too



FIGURE 3.5 Simple DWDM link.



FIGURE 3.6 OSA fiber span view of multiplexed DWDM signals.



FIGURE 3.7 Individual signal after filter or DWDM demux.



FIGURE 3.8 RBW too narrow for signal measurement.

narrow, part of the signal power will be missed during the measurement, as shown in Fig. 3.8. If RBW is too wide, then accurate noise measurement near the signal cannot be performed and unwanted noise may be measured with signal power. The ideal RBW should be wide enough to encompass the entire modulated signal down to the noise floor, see Fig. 3.9. Often the manufacturer will specify the proper RBW to be used for their listed transceiver OSNR. It is important to note that laser spectral width varies with the modulation rate; the higher the rate the wider the signal spectral width. Table 3.1 shows the minimum recommended<sup>5</sup> RBW that will cause less than 0.1 dB measurement error for various transmission rates and NRZ modulation.

## 3.1.4 OSNR Link Calculation

When an optical amplifier is added to a fiber link, a small amount of ASE noise is added to the signal channel. Although the amount of noise generated by one amplifier is small and likely not consequential to the system OSNR, additional amplifiers will not only add their own noise power to the signal channel but will also amplify the noise from all upstream amplifiers. A limit is reached where an additional amplifier will result in the degeneration of the link's OSNR past the receiver's minimum specification. This will result in a less desirable BER since it is directly dependent on OSNR.



FIGURE 3.9 Correct RBW for signal measurement.

Modulation Rate	Minimum RBW for Less than 0.1 dB Error	Minimum RBW for Less than 1 dB Error
40 Gbps	1 nm	
10 Gbps	≥ 0.2 nm	≥ 0.1 nm
2.5 Gbps	≥ 0.09 nm	≥ 0.03 nm

 TABLE 3.1
 Minimum RBW for Different Signal Modulation Rates

The OSNR at any point in a fiber link is equal to the signal power divided by the noise power, see Eq. (3.12). For a link with optical amplifiers, ASE noise is the dominant source. If high gain Raman amplifiers are deployed, double Rayleigh scattering (DRS) noise can also be significant. The following OSNR equations<sup>7,8</sup> only consider ASE noise as dominant in a link, see Eqs. (3.21) to (3.24).

$$OSNR = \frac{P_{out}}{P_{ASE}}$$
(3.21)

$$OSNR = \frac{gP_{in}}{2n_{sp}hfB_o(g-1)}$$
(3.22)

$$n_{\rm sp} = 0.5F\left(\frac{g}{g-1}\right) \tag{3.23}$$

$$OSNR = \frac{P_{in}}{FhfB_o}$$
(3.24)

where OSNR = optical signal to noise ratio of the optical amplifier

P<sub>out</sub> = average amplifier output signal power (DWDM systems use single-channel power), W

P<sub>in</sub> = average amplifier input signal power (DWDM systems use single-channel power), W

- $P_{ASE}$  = average amplifier ASE noise power, W
  - F = amplifier noise factor
  - h = Planck's constant 6.626069 × 10<sup>-34</sup>, Js
  - *f* = optical signal center frequency, assuming 193.400 THz (1550.12 nm), Hz
  - $B_{o}$  = optical channel bandwidth, Hz
  - g =amplifier gain

$$n_{\rm sp}$$
 = spontaneous emission (or population inversion) factor

Transceiver OSNR is specified to a standard measurement bandwidth RBW; therefore, we substitute  $B_r$  in the place of  $B_o$ .

Converting Eq. (3.24) to decibel results in Eq. (3.25)

$$OSNR_{dB} = P_{in,dBw} - NF - 10 \log(hf) - 10 \log(B_r)$$
(3.25)

Converting units to dBm results in Eq. (3.21)

$$OSNR_{dB} = 301.787 + P_{in,dBm} - NF - 10\log(f) - 10\log(B_r)$$
(3.26)

If the signal wavelength is 1550.12 nm (f = 193.4 THz) then Eq. (3.26) can be shortened to Eq. (3.27).

$$OSNR_{dB} = 158.9 + P_{in,dBm} - NF - 10 \log(B_r)$$
(3.27)

If the measurement optical bandwidth can be assumed to be 0.1 nm (12.48 GHz), then Eq. (3.27) can be further shortened to Eq. (3.28).

$$OSNR_{dB} = 58 + P_{in.dBm} - NF$$
(3.28)

where  $OSNR_{dB} = optical signal to noise ratio of the optical amplifier, dB$  $<math>P_{in,dBm} = average amplifier input signal power (DWDM systems use single-channel power), dBm$ NF = amplifier noise figure, dB $<math>h = Blongle's constant 6.626060 \times 10^{-34}$  Ja

- $h = \text{Planck's constant } 6.626069 \times 10^{-34}$ , Js
- f = signal center frequency, Hz
- $B_r$  = optical measurement bandwidth RBW, Hz

In a fiber link with numerous noise sources, the total link OSNR can be calculated knowing the OSNR of each individual noise source and using Eq. (3.29).

$$\frac{1}{\text{OSNR}_F} = \frac{1}{\text{OSNR}_1} + \frac{1}{\text{OSNR}_2} + \frac{1}{\text{OSNR}_3} + \dots + \frac{1}{\text{OSNR}_N}$$
(3.29)

In any transmission system, source spontaneous emission (SSE) noise is generated by the laser source and should be included in total link OSNR calculations. For a 1550 nm DWDM DFB laser, typical OSNR/0.1 nm varies between 40 and 65 dB,<sup>9</sup> Eq. (10.12) can be used to calculate laser OSNR given laser relative intensity noise (RIN). Equation (3.29) with the source noise included is shown as Eq. (3.30).

$$\frac{1}{\text{OSNR}_F} = \frac{1}{\text{OSNR}_{\text{source}}} + \frac{1}{\text{OSNR}_1} + \frac{1}{\text{OSNR}_2} + \frac{1}{\text{OSNR}_3} + \dots + \frac{1}{\text{OSNR}_N}$$
(3.30)

where 
$$OSNR_F = final OSNR$$
 seen at the receiver  
 $OSNR_{source} = laser source OSNR$   
 $OSNR_N = OSNR$  of individual optical amplifiers up to N

This equation can be further simplified and final OSNR approximated,<sup>10</sup> as seen in Eq. (3.31) and Fig. 3.10 if we assume all of the following:

- 1. All the link EDFAs have identical gains and noise figures.
- 2. The span loss before each EDFA is the same. (If span losses differ, this equation could still be applied by assuming that all losses are less than or equal to loss, which would result in a worst-case estimate of the OSNR.)
- Each EDFA's gain compensates for the previous span loss and the gain is >> 1.
- 4. Only in-line amplifiers and a pre-amplifier exist in the link, see Fig. 3.10.





- 5. Laser source frequency is centered at 1550.12 nm.
- Laser source OSNR is high (better than 57 dB) and is not considered in calculations.

$$OSNR_{F,dB} = 158.9 + P_{source,dBm} - \Gamma - NF - 10 \log(B_r) - 10 \log N \quad (3.31)$$

where  $OSNR_{EdB}$  = final OSNR seen at the receiver, dB

- $P_{\text{source.dBm}}$  = average source signal power into the first span (DWDM systems use single-channel power), dBm
  - NF = amplifier noise figure, the same for all EDFAs, dB
    - $B_r$  = optical measurement bandwidth, Hz
    - N = number of amplifiers in the fiber link excluding the booster
    - $\Gamma$  = span loss, the same for all spans, dB

For more realistic fiber links where encountering different EDFA gains, different span lengths, and losses, use Eqs. (3.26) and (3.30). This method can be set up in computer spreadsheet table format as shown in Appendix B for easy repeated use. Tables to calculate fiber links with one, two, and three EDFAs are also shown in Appendix B. See Fig. 3.12 for the three-EDFA layout example. For more than three EDFAs in a link, use the established format in Table B.3 and add the next EDFA stage (Table B.1) to the bottom of the table using the output OSNR of the previous EDFA calculation as input to the next EDFA OSNR.

The above equations can be used to calculate OSNR for a single wavelength link or DWDM link. For DWDM OSNR calculations, calculate OSNR for each channel individually and  $P_{\text{in.dBm}}$  and  $P_{\text{source.dBm}}$  are individual channel powers.

Below are a few tips to keep in mind when planning EDFA links.

- 1. Keep input power into each EDFA as high as possible especially for the first few EDFAs in the link (the ones closer to the laser source). They have the most impact on final OSNR.
- 2. If EDFAs are available with different noise figure values, use the EDFA with the lowest noise figure at the beginning of the link (closest to the laser source) and second in the link. This is because the first and second EDFAs have the greatest noise impact. This is shown in Friis' formula, see Eq. (3.32).

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{g_1} + \frac{F_3 - 1}{g_1 g_2} + \frac{F_4 - 1}{g_1 g_2 g_3} + \dots + \frac{F_N - 1}{g_1 g_2 g_3 \dots g_{N-1}}$$
(3.32)

where  $F_{total}$  = total effective noise factor

- $F_i$  = noise factor for EDFA *i*
- $g_i = \text{gain for EDFA} i$
- N = number of EDFAs in the fiber link



FIGURE 3.11 OSNR and power diagram.

The objective of OSNR link calculation is to ensure the link OSNR does not exceed the receiver's minimum specified OSNR for the desired bit error rate and receiver signal level. When optical amplifiers are not used in a link, the link OSNR is much larger than the receiver's minimum OSNR, see Fig. 3.11. When amplifier noise and other noise sources are added, the noise floor increases, which decreases the link OSNR. Link OSNR also decreases with an increase in link optical power loss. Link OSNR should never be less than the receiver's minimum OSNR. If an additional amplifier results in lower OSNR, 3R (reamplifying, retiming and reshaping) regeneration should be used instead of an optical amplifier.

Typically EDFA input power in the above OSNR equations does not include power penalties. For more accurate link assessment with power penalties, a Q-factor budget is completed as shown later in this chapter.

#### 3.1.5 Raman Amplifier

Distributed Raman amplifiers (DRA) exhibit a low equivalent noise figure (-2 to 0 dB) and have good signal gain (5 to 20 dB), but are significantly more expensive than EDFAs. Therefore their use is limited to expanding long EDFA spans where OSNR limits have been reached. Adding a distributed Raman amplifier in the span increases the signal gain by the Raman gain amount but also adds amplified spontaneous emission (ASE) noise along the DRA span length. However, the equivalent noise figure, at the end of the DRA span, can be zero or negative. The overall result is an improvement in link OSNR and longer transmission spans.



FIGURE 3.12 Distributed Raman amplifier equivalent gain and noise figure.

Distributed Raman amplifiers can be placed in a counter pump or a co-pump configuration, refer to Fig. 10.10. Both configurations end up with the same gain. An advantage for the counter pump configuration is that it does not increase nonlinear effects, such as four wave mixing, as much as the co-pump configuration.<sup>11</sup> This is because DRA counter pump amplifies lower power signals near the end of the span.

A convenient configuration<sup>12</sup> used to express Raman distributed noise and gain parameters is as a hypothetical equivalent discrete amplifier that is located at the end of the fiber span. This hypothetical amplifier has the equivalent gain  $(G_{eq})$  and noise figure  $(NF_{eq})$  as the actual DRA, see Fig. 3.12 and Eqs. (3.33) to (3.36). Raman manufacturers typically specify equivalent gain and noise figure parameters.

$$F_{\rm eq} = \frac{F_{\rm R}}{\alpha L} \tag{3.33}$$

$$F = 10^{\rm NF/10} \tag{3.34}$$

$$NF_{eq} = NF_{R} - (\alpha_{dB}L)$$
(3.35)

$$G_{\rm eq} = G_{\rm R} \tag{3.36}$$

 $F_{eq}$  = equivalent noise factor where

 $F_{R}^{'}$  = distributed Raman amplifier noise factor NF<sub>eq</sub> = equivalent noise figure, dB

 $NF_{R}$  = distributed Raman amplifier noise figure, dB  $\alpha$  = attenuation coefficient, km<sup>-1</sup>  $\alpha_{dB}$  = attenuation, dB/km L = transmission fiber length, km  $G_{eq}$  = equivalent gain, dB  $G_{R}$  = distributed Raman amplifier gain, dB  $G_{ret}$  = Raman net gain at the end of the fiber, dB

To estimate link OSNR with hybrid Raman EDFA amplifiers, Eqs. (3.26) and (3.30) are used with the equivalent Raman noise figure and gain values. The typical DRA equivalent noise figure is between -2 to 0 dB. If high optical gains are required (>15 dB) DRS noise may need to be included in OSNR calculations, see Eq. (3.37).

$$OSNR = \frac{P_{out}}{P_{ASE} + P_{DRS}}$$
(3.37)

### 3.1.6 OSNR Examples

Equations (3.26) to (3.31) can be used to estimate OSNR for single- or multiple-channel links. For WDM links, calculate OSNR for each channel individually.  $P_{\text{in.dBm}}$  and  $P_{\text{source.dBm}}$  are individual channel powers for a WDM system.

**Example 3.1** For a single wavelength 2.5 Gbps fiber link that contains three EDFAs, calculate the final OSNR seen by the receiver, see Fig. 3.13. Equipment specifications are as follows:

Tx DFB laser output power:	0.0 dBm
Tx laser wavelength:	1550.12 nm
Rx receiver sensitivity:	-24.0 dBm @ BER 10 <sup>-12</sup>
Rx minimum OSNR:	18.0 dB RBW 0.1 nm ( $1.25 \times 10^{10}$ Hz)
EDFA gains:	$EDFA_1 G_1 = 20.0 dB, EDFA_2 G_2 = 25.0 dB,$
	$EDFA_{a}G_{a} = 20.0 dB$



FIGURE 3.13 Three EDFA OSNR link example.

All EDFAs noise figure (NF):	5.0 dB
Fiber span loss (Γ):	Span 1 loss 22 dB, span 2 loss 23 dB, span 3
	loss 25 dB, span 4 loss 15 dB

First we determine the input signal power to all EDFAs and final receiver power.

$$\begin{split} P_{\text{in1}} &= P_{\text{source}} - \Gamma_1 & (3.38) \\ P_{\text{in1}} &= 0.0 - 22.0 \\ P_{\text{in1}} &= -22.0_{\text{dBm}} & \\ P_{\text{in2}} &= P_{\text{in1}} + G_1 - \Gamma_2 & (3.39) \\ P_{\text{in2}} &= -22.0 + 20.0 - 23.0 \\ P_{\text{in2}} &= -25.0_{\text{dBm}} & \\ P_{\text{in3}} &= P_{\text{in2}} + G_2 - \Gamma_3 & (3.40) \\ P_{\text{in3}} &= -25.0 + 25.0 - 25.0 \\ P_{\text{in3}} &= -25.0_{\text{dBm}} & \\ P_{\text{out3}} &= P_{\text{in3}} + G_3 & (3.41) \\ P_{\text{out3}} &= -5.0_{\text{dBm}} & \\ P_{\text{rec}} &= P_{\text{out3}} - \Gamma_4 & (3.42) \\ P_{\text{rec}} &= -5.0 - 15.0 & \\ \end{split}$$

$$P_{\rm rec} = -20.0_{\rm dBm}$$

where  $P_{\text{source}} = \text{source laser signal output power, dBm}$ 

ъ

 $\Gamma_{1,2,3,4}$  = fiber span 1, 2, 3, and 4 losses, dB  $P_{in1,2,3}^{1,2,3,7}$  = input signal power to EDFAs 1, 2, and 3, dBm  $P_{out3}$  = EDFA 3 output signal power, dBm  $P_{\rm rec}$  = receive signal power

Using Appendix B, Table B.3, we calculate the following OSNR results:

OSNR output of EDFA 1 is 30.9 dB.

OSNR output of EDFA 2 is 26.2 dB.

OSNR output of EDFA 3 and final OSNR is 24.0 dB.

The final OSNR is 24.0 dB, which is well within the receiver minimum OSNR of 18 dB. Also the receive signal power is -20.0 dBm, which is also well within receiver specifications.

**Example 3.2** Estimate the receiver OSNR for a 10 Gbps two-EDFA link shown in Fig. 3.14 using the approximate method Eq. (3.31) and using Eqs. (3.26) and (3.30). Equipment specifications are as follows:

Tx DFB laser output power:	–1.0 dBm
Tx laser wavelength:	1550.12 nm





Rx receiver sensitivity:	-21.0 dBm @ BER 10 <sup>-12</sup>
Rx minimum OSNR:	23.0 dB, RBW 0.5 nm (6.239 × 10 <sup>10</sup> Hz)
EDFA gains:	$EDFA_1 G_1 = 20.0 dB, EDFA_2 G_2 = 20.0 dB$
All EDFA (NF):	5.0 dB
Fiber span loss ( $\Gamma$ ):	Span 1 loss 20.0 dB, span 2 loss 20.0 dB, span 3 loss 15.0 dB

Equation (3.31) method:

$$\begin{aligned} & \text{OSNR}_{F,\text{dB}} \approx 158.921 + P_{\text{source.dBm}} - \Gamma - \text{NF} - 10 \log(B_r) - 10 \log N \\ & \text{OSNR}_{F,\text{dB}} \approx 158.921 - 1 - 20 - 5 - 10 \log(6.239 \times 10^{10}) - 10 \log 2 \\ & \text{OSNR}_{F,\text{dB}} \approx 22.0_{\text{dB}} \end{aligned}$$

Equations (3.27) and (3.30) method:

First we determine the input signal power to all EDFAs and final receiver power.

$$\begin{split} P_{\text{in1}} &= P_{\text{source}} - \Gamma_1 \\ P_{\text{in1}} &= -1.0 - 20.0 \\ P_{\text{in1}} &= -21.0_{\text{dBm}} \\ P_{\text{in2}} &= P_{\text{in1}} + G_1 - \Gamma_2 \\ P_{\text{in2}} &= -21.0 + 20.0 - 20.0 \\ P_{\text{in2}} &= -21.0_{\text{dBm}} \\ P_{\text{out2}} &= P_{\text{in2}} + G_2 \\ P_{\text{out2}} &= -1.0_{\text{dBm}} \\ P_{\text{rec}} &= -1.0 - 15.0 \\ P_{\text{rec}} &= -16.0_{\text{dBm}} \end{split}$$

For the spreadsheet method to calculate OSNR using Eqs. (3.27) and (3.30), see Appendix B.2.

$$\begin{split} & \text{OSNR}_{\text{dB}} = 158.921 + P_{\text{in,dBm}} - \text{NF} - 10 \log(B_r) \\ & \text{OSNR}_{\text{EDFA1.dB}} = 158.921 - 21.0 - 5 - 10 \log(6.239 \times 10^{10}) \\ & \text{OSNR}_{\text{EDFA1.dB}} = 25 \\ & \text{OSNR}_{\text{EDFA2.dB}} = 158.921 - 21.0 - 5 - 10 \log(6.239 \times 10^{10}) \\ & \text{OSNR}_{\text{EDFA2.dB}} = 25 \\ & \frac{1}{\text{OSNR}_F} = \frac{1}{\text{OSNR}_{\text{source}}} + \frac{1}{\text{OSNR}_{\text{EDFA1}}} + \frac{1}{\text{OSNR}_{\text{EDFA2}}} \\ & \frac{1}{\text{OSNR}_F} = \frac{1}{501.19 \times 10^3} + \frac{1}{316.23} + \frac{1}{316.23} \\ & \text{OSNR}_{F,dB} = 22.0 \end{split}$$

OSNR output of EDFA 1 is 25 dB, and OSNR output of EDFA 2 and receiver OSNR is 22 dB. The results from the two methods are the same. OSNR and receiver signal power are within specification.

**Example 3.3** Estimate the OSNR for the hybrid counter pump Raman/EDFA link shown in Fig. 3.15. The transceiver has a 1550 nm 10 Gbps non-DWDM laser with a launch power of -3 dBm and minimum OSNR of 20 dB @ 0.1 RBW for BER 10<sup>-10</sup>. Fiber span is 180 km (112 mi) over G.652 fiber. Total span loss is 45 dB ( $\Gamma_{span}$ ). Also estimate OSNR without the Raman amplifier for comparison. Amplifier gain and noise figure specifications are as follows:

EDFA booster:  $NF_1 = 5.0 \text{ dB}$   $G_1 = 10 \text{ dB}$ EDFA pre-amp:  $NF_3 = 5.0 \text{ dB}$   $G_3 = 10.0 \text{ dB}$ Minimum input power = -30 dBm Raman (G.652 fiber): Equivalent  $NF_2 = -2.0 \text{ dB}$  $G_2 = 10.0 \text{ dB}$ 



FIGURE 3.15 Hybrid Raman/EDFA OSNR example.

First we determine the signal power levels along the span into the EDFAs and Raman amplifiers. Signal power into the EDFA booster is as follows:

$$P_{in1} = P_{source}$$
$$P_{in1} = -3.0_{dBm}$$

Signal power into the equivalent Raman amplifier is as follows:

$$P_{in2} = P_{in1} + G_1 - \Gamma_{span}$$
$$P_{in2} = -3.0 + 10.0 - 45.0$$
$$P_{in2} = -38.0_{dBm}$$

Signal power into the EDFA pre-amplifier is as follows:

$$P_{in3} = P_{in2} + G_2$$
  
 $P_{in3} = -38.0 + 10.0$   
 $P_{in3} = -28.0_{dBm}$ 

Signal power into the receiver is as follows:

$$P_{\rm rec} = P_{\rm in3} + G_3$$
$$P_{\rm rec} = -28.0 + 10.0$$
$$P_{\rm rec} = -18.0_{\rm dBm}$$

Using Table B.3 in Appendix B to calculate OSNR for this link, the results are as follows:

OSNR output of EDFA booster 1 is 49.2 dB.

OSNR output of Raman amplifier is 21.9 dB.

OSNR output of EDFA pre-amp and receiver OSNR is 20.2 dB.

The received signal OSNR of 20.2 dB is greater than the transceiver minimum specified OSNR of 20 dB.

If the Raman amp is not used then OSNR drops to 15 dB, which is significantly below the receiver specified OSNR and the link would not meet BER performance. Also, this EDFA pre-amp could not be used because its specified minimum input power level is –30 dBm, and the signal would be at –38 dBm. EDFAs with minimum input levels below –30 dBm are not common.

**Example 3.4** Determine the maximum number of noise-limited optical amplifier spans that can be achieved for 10, 40, and 100 Gbps NRZ transmission systems. Assume all spans are 100 km in length. Fiber attenuation is 0.22 dB/km and each span's total loss is 22 dB. Fiber maximum launch power limited by nonlinear effects is 20 mW (13 dBm) cumulative for the entire link. Therefore maximum launch power per span is 20/N mW or  $13 - 10 \log(N)$  dBm. Also assume transceiver OSNR for a BER of 1E-12 is 20 dB for a 10 Gbps system, 26 dB for a 40 Gbps system, and 30 dB for a 100 Gbps system. Provide results for a total EDFA solution and total Raman solution. EDFA noise figure is 6 dB and Raman noise figure is 0 dB. The resolution bandwidth *B*<sub>i</sub> is 0.1 nm (12.5 GHz).

Using Eq. (3.31) we can determine the maximum number of spans required as follows:

 $OSNR_{F,dB} = 158.9 + P_{source,dBm} - \Gamma - NF - 10 \log(B_r) - 10 \log N$ 10 log N = 158.9 + P\_{source,dBm} - \Gamma - NF - 10 log(B\_r) - OSNR

We must also include the maximum launch power per span limit due to nonlinear effects; therefore, the maximum number of spans in an amplifier link is as follows.

 $N = 10^{(158.9 + P_{source dBm} - \Gamma - NF - 10 \log(B_r) - OSNR)/20)$ 

For the EDFA system the results are as follows:

10 Gbps transmission is limited to a maximum of 14 spans.

40 Gbps transmission is limited to a maximum of 7 spans.

100 Gbps transmission is limited to a maximum of 4 spans.

For the Raman system the results are as follows:

10 Gbps transmission is limited to a maximum of 28 spans.

40 Gbps transmission is limited to a maximum of 14 spans.

100 Gbps transmission is limited to a maximum of 8 spans.

# 3.2 Bit Error Ratio

Bit error ratio (BER) (also known as bit error rate) can be defined as the ratio of the number of erroneous bits received to the total number of bits transmitted, see Eq. (3.43).

$$BER = \frac{E}{n}$$
(3.43)

$$n = TR \tag{3.44}$$

where BER = bit error ratio

E = number of erroneous bits received

n = number of bits transmitted

- T = time to transmit n bits, seconds
- R =transmission rate, bits/second

A BER test is often requested as the final quality acceptance test for a newly installed digital circuit. It is also useful in testing and debugging existing system transmission bit errors. Typical BER values for circuits range from  $10^{-9}$  to  $10^{-13}$  with  $10^{-12}$  being the most common for telecom circuits and is the ITU-T<sup>13</sup> standard for SONET/SDH transmission systems. A  $10^{-12}$  BER means that one bit is received in error for every terabit of transmitted data bits. Depending on the transmission rate, it may take quite a while to transmit a terabit of data bits. For a 10 Gbps circuit where the bit time slot period is 100 ps, it will take 1.67 minutes for 1 terabit of data to be transmitted (assuming synchronous circuit such as SONET/SDH). However for a 155 Mbps circuit such as OC-3, the bit time slot period is 6.43 ns and therefore it will take 1.786 hours to transmit 1 terabit of data bits.

A question often asked is how long does one need to continue with a BER test to ensure the circuit meets or exceeds BER specification? The test needs to be run such that enough bits are transmitted so that the results are statistically meaningful. Ideally the test is run for an infinite amount of time, transmitting an infinite amount of bits, which results in the channel's true bit error ratio. However this is obviously not practical and therefore a statistical method is used to determine the channel's BER within a certain confidence level. This confidence level is a percentage that represents the probability the true BER is equal to or better than the test BER. Typical confidence levels are 95% or 99%. Calculation of the required number of transmitted bits for a certain confidence level is based on the binomial distribution model, see Eq. (3.45). Note that the probability of error p is the same as the bit error rate (p = BER). The necessary assumptions to use this model are that the bit errors are statistically independent, the bit errors are due to random noise, and the bit errors are not due to any equipment problems or noise bursts.

$$P_n = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}$$
(3.45)

- where  $P_n$  = probability of *k* events (bit errors) occurring in *n* trials (*n* bits transmitted)
  - *p* = probability an event (one bit error) will occur in one trial
  - *n* = total number of trials (total number of bits transmitted)
  - *k* = number of events occurring in *n* trials (number of bit errors)
  - $\mu$  = mean of the distribution,  $\mu$  = *np*
  - $\sigma^2$  = variance of the distribution,  $\sigma^2 = np(1-p)$

The confidence level is defined as the cumulative binomial distribution, see Eq. (3.46). For a confidence level of C and probability of error p, Eq. (3.46) provides the number of n bits that need to be transmitted for E or fewer errors, see Fig. 3.16.

$$C = 1 - \sum_{k=0}^{E} \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}$$
(3.46)

where *C* = confidence level

*E* = maximum number of bit errors



FIGURE 3.16 Binomial distribution.

Equation (3.45) is difficult to solve for *n*, therefore the Poisson theorem<sup>14</sup> is used as an approximation for large values of *n*, see Eq. (3.47). Equation (3.46) is obtained from Eq. (3.47) as an approximation for the cumulative solution.

$$\frac{n!}{k!(n-k)!}p^k(1-p)^{n-k} \approx \frac{(np)^k}{k!}e^{-np} \quad \text{as } n \longrightarrow \infty$$
(3.47)

$$C = 1 - \sum_{k=0}^{E} \frac{(np)^k}{k!} e^{-np}$$
(3.48)

Solving Eq. (3.48) for the amount of bits to be transmitted *n* we get Eq. (3.49). Notice that for the case of no bit errors, where E = 0, the second term is 0. Now by using Eq. (3.44) the length of time *T* needed for a BER test can be calculated.

$$n = \frac{1}{p} \left[ -\ln(1-C) + \ln\left(\sum_{k=0}^{E} \frac{(np)^k}{k!}\right) \right]$$
(3.49)  
$$T = \frac{n}{R}$$

where n = number of transmitted bits

- *p* = probability of a bit error, the maximum (worst) bit error rate (BER) of the channel to be verified
- C = confidence level %/100. The higher the confidence level the more probable the true channel BER is equal to or greater than the test BER. However, a higher confidence level increases the test time.
- *E* = maximum number of bit errors
- *R* = transmission rate, bits/second

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This equation is simple to solve if the number of bit errors is zero. For one or more errors, a computer algorithm can be written to solve for *n*. The way to interpret this equation is that the length of time to test a channel to a target bit error ratio is dependent on the required confidence level and the number of bit errors. For example, the time required to test a 10 Gbps channel to a target BER of 10<sup>-12</sup>, a confidence level of 99%, and for zero received bit errors is 7 minutes and 41 seconds. To test for five errors, the test time increases to 21 minutes and 51 seconds. However a BER test with only five detected errors does not have sufficient sample size for a good degree of accuracy. To achieve a two-digit accuracy, a BER test needs to run until at least 100 bit errors are observed. To calculate the length of time a BER test needs to run to achieve this accuracy, a target BER value is entered into Eq. (3.49) as well as 100 bit errors that are expected for this target and a confidence interval. The BER test is run for the calculated time. If 100 or less errors are observed, one can conclude that the channel BER is better than the target BER. For the above 10 Gbps example, the BER test time for 100 expected errors is 3 hours and 23 minutes. Therefore after running a BER test for 3 hours and 30 minutes and 100 or less errors are detected, one can conclude the link has a BER of 10<sup>-12</sup> or better with a confidence level of 99% and two-digit accuracy. Table 3.2 lists a few common test times for 100 expected errors and a confidence level of 99%.

Alternately, to determine the BER of a circuit, a BER test is run and the length of time is recorded when 100 bit errors are detected. Knowing variables E and T, variable n is calculated using Eq. (3.44). Then use Eq. (3.49) to solve for p the circuit BER for a target confidence level.

	BER 10-9	BER 10 <sup>-11</sup>	BER 10 <sup>-12</sup>	BER 10 <sup>-13</sup>
100 Gbps	1 sec	2 min	21 min	3 hr 29 min
40 Gbps	3 sec	6 min	53 min	8 hr 47 min
10 Gbps	13 sec	21 min	3 hr 30 min	1 day 10 hr 58 min
2.5 Gbps	51 sec	1 hr 25 min	14 hr 3 min	5 day 20 hr 29 min
1 Gbps	2 min	3 hr 30 min	1 day 10 hr 58 min	14 day 13 hr 33 min
622 Mbps	4 min	5 hr 37 min	2 day 8 hr 12 min	23 day 9 hr 55 min
155 Mbps	14 min	22 hr 29 min	9 day 8 hr 46 min	93 day 15 hr 38 min

TABLE 3.2         BER Test Times for 99% Confidence Level for 100 Bit Errors San	ple
--	-----

# 3.3 Q-Factor

The Q-factor is another performance parameter that can be used as an alternative to BER testing and can be used for performance planning during system design stage. To test a 10 Gbps circuit to a BER of  $10^{-13}$  value will take 1 day and 9 hours as shown in Table 3.2. However, considerable time can be saved by measuring the circuit's Q-factor, which can be done in minutes. Also, designing a system for a specific Q-factor that considers link impairments and gains such as FEC is straightforward and has good accuracy.

Q-factor is defined as the ratio of the difference of average photodiode currents between one bit state and zero bit state divided by the sum of the standard deviation (RMS) of the noise currents for both states, see Eqs. (3.50), (3.51), and Fig. 3.17. It is similar to and can be thought of as the electrical signal to noise ratio at the receiver's decision circuitry, see Eq. (3.53).

$$Q = \frac{|I_1 - I_0|}{\sigma_1 + \sigma_0} = \frac{|V_1 - V_0|}{\sigma_1 + \sigma_0}$$
(3.50)

also written as

$$\sigma_T^2 = \sigma_1^2 + \sigma_0^2 \tag{3.51}$$

$$I_p = R_p P_{\rm in} \tag{3.52}$$

$$SNR = \frac{I_p^2}{\sigma_T^2}$$
(3.53)

where

- Q = linear quality factor
  - $I_{n}$  = average photodiode signal current, A
  - $I_1 =$  average photodiode current for 1 (high) bit state, A
  - $I_0$  = average photodiode current for 0 (low) bit state, A
- $V_1$  = average photodiode voltage across  $R_L$  for 1 (high) bit state, A
- $V_0$  = average photodiode voltage across  $R_L$  for 0 (low) bit state, A
- $\sigma_1$  = standard deviation (RMS) for photodiode noise current for 1 (high) bit state, A
- $\sigma_0$  = standard deviation (RMS) for photodiode noise current for 0 (low) bit state, A

 $\sigma_{T}$  = total RMS noise photodiode current, A

 $R_{n}$  = photodiode responsivity, A/W

- $P_{in}^{r}$  = average signal photodiode optical power, W
- SNR = electrical optical signal to noise ratio measure after the photodiode
  - $R_{L}$  = photodiode's load resistance,  $\Omega$



FIGURE 3.17 Receiver circuit signal probability distribution.

The photodiode current levels fluctuate from bit to bit around an average current level of  $I_1$  for the logical one bit and  $I_0$  for the logical zero bit. This fluctuation can be modeled by a probability distribution curve for both one and zero bit levels where each has its own average (mean) level and standard deviation, see Fig. 3.17. Signal current from the photodiode passes through a low pass filter and amplifier before entering the receiver decision circuitry. The filter amplifier combination reduces signal noise and boosts the signal for

the next stage. The decision circuitry then compares signal bit levels with a threshold level  $I_{\rm th}$ . If the received bit level is greater than the threshold level,  $I_p > I_{\rm th}$ , then the circuit identifies the received level as a one bit. If the received bit level is less than the threshold level,  $I_p < I_{\rm th'}$  then the circuit identifies the received level as a zero bit. A problem occurs when an intended one bit level is below the threshold,  $I_1 < I_{\rm th'}$  and is interpreted as a zero bit, or when an intended zero bit level is above the threshold,  $I_0 > I_{\rm th'}$  and is interpreted as a one bit. For both cases the result is a bit error. The receiver bit error ratio can then be defined<sup>15</sup> by the probability of receiving correct bits and bit errors as shown in Eq. (3.54).

BER = 
$$p_r(1)p_r(0,1) + p_r(0)p_r(1,0)$$
 (3.54)

For long transmission streams the probability of a one bit or a zero bit being received can be assumed to be equal at 50%. Therefore Eq. (3.54) can be rewritten as Eq. (3.55).

$$BER = 0.5[p_{x}(0,1) + p_{x}(1,0)]$$
(3.55)

where BER = probability of error or bit error ratio

- $p_r(1)$  = probability of a one bit being interpreted
- $p_r(0)$  = probability of a zero bit being interpreted
- $p_r(0,1)$  = probability of a zero bit being interpreted when a one bit is received
- $p_r(1,0)$  = probability of a one bit being interpreted when a zero bit is received

Fluctuations in logical one and zero bit current levels due to random noise in the circuitry or link can be modeled by a Gaussian distribution curve. Each logical level will have its own individual probability curve characteristics. As can be seen from Eq. (3.55), BER is dependent only on the probability of receiving bit errors  $p_r(0,1)$  and  $p_r(1,0)$ . The probability for bit errors can now be calculated by determining the area under the probability curve at  $p_r(0,1)$  and  $p_r(1,0)$  by using Eqs. (3.57) and (3.58).

$$p_r(I_x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left(-\frac{(I - I_x)^2}{2\sigma_x^2}\right)$$
(3.56)

$$p_{r}(0,1) = \frac{1}{\sigma_{1}\sqrt{2\pi}} \int_{-\infty}^{I_{\text{th}}} \exp\left(-\frac{(I-I_{1})^{2}}{2\sigma_{1}^{2}}\right) dI = \frac{1}{2} \operatorname{erfc}\left(\frac{I_{1}-I_{\text{th}}}{\sigma_{1}\sqrt{2}}\right)$$
(3.57)

$$p_r(1,0) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{I_{\text{th}}}^{\infty} \exp\left(-\frac{(I-I_0)^2}{2\sigma_0^2}\right) dI = \frac{1}{2} \operatorname{erfc}\left(\frac{I_{\text{th}}-I_0}{\sigma_0 \sqrt{2}}\right)$$
(3.58)

where *erfc* is the complementary error function,  $erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \exp(-y^2) dy$ .

By substituting Eqs. (3.57) and (3.58) into Eq. (3.55) we get Eq. (3.59).

$$BER = \frac{1}{4} \left[ erfc \left( \frac{I_1 - I_{th}}{\sigma_1 \sqrt{2}} \right) + erfc \left( \frac{I_{th} - I_0}{\sigma_0 \sqrt{2}} \right) \right]$$
(3.59)

Therefore the BER of the received signal depends on the receiver circuitry decision threshold for both one and zero received bit levels. The receiver decision circuitry design is optimized to a minimum BER by choosing the threshold current to be as shown in Eqs. (3.60) and (3.61).

$$\frac{(I_1 - I_{\rm th})}{\sigma_1} = \frac{(I_{\rm th} - I_0)}{\sigma_0} \equiv Q$$
(3.60)

$$I_{\rm th} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \tag{3.61}$$

The BER as shown in Eq. (3.59) for an optimize receiver circuit setting can now be shown as Eq. (3.62).

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$
(3.62)

The Q-factor is given by Eq. (3.50).

$$Q = \frac{\left|I_1 - I_0\right|}{\sigma_1 + \sigma_0}$$

An approximation to Eq. (3.62) for Q > 3 (Gaussian assumption) to calculate BER given a Q-factor is shown as Eq. (3.63).

BER 
$$\approx \frac{1}{Q\sqrt{2\pi}} \exp\left(-\frac{Q^2}{2}\right)$$
 (3.63)

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A more accurate expression<sup>16</sup> for the entire range of Q values is given by Eq. (3.64).

$$BER \approx \frac{1}{\sqrt{2\pi}} \left[ \frac{1}{\left(1 - \frac{1}{\pi}\right)Q + \frac{\sqrt{Q^2 + 2\pi}}{\pi}} \right] \exp\left(-\frac{Q^2}{2}\right)$$
(3.64)

As can be seen from Eq. (3.63) or (3.64), if the receiver Q-factor is known, the circuit BER can be determined. This relationship is plotted in Fig. 3.18. Some notable values are shown in Table 3.3.



FIGURE 3.18 BER and Q-factor relationship.

Q-Factor	Q-Factor (dB)	BER
6.00	15.57	10-9
6.37	16.08	10-10
6.71	16.53	10-11
7.04	16.95	10-12
7.35	17.32	10-13
7.65	17.68	10-14
7.94	18.0	10-15

 TABLE 3.3
 BER and Q-Factor Cross Reference

To convert back to Q-factor knowing BER, use a brute force software algorithm with Eq. (3.63) or estimate<sup>17</sup> using Eq. (3.65).

$$Q = \sqrt{-2\ln(\text{BER})} - \left[\frac{2.307 + 0.2706\sqrt{-2\ln(\text{BER})}}{1 + \sqrt{-2\ln(\text{BER})}(0.9923 + 0.0448\sqrt{-2\ln(\text{BER})})}\right]$$
(3.65)

Q-factor is also commonly represented in decibel form. Equations (3.66) and (3.67) are used to convert between these two units.

$$Q_{\rm dB} = 20 \log(Q)$$
 (3.66)

$$Q = 10^{Q_{\rm dB}/20} \tag{3.67}$$

where Q = Q-factor, linear  $Q_{dB} = Q$ -factor, dB

The reason the 20 multiplier (and not 10) is used in Eq. (3.66) is because *Q* is calculated using current or voltage ratios and not power.



FIGURE 3.19 Rectangular NRZ modulated carrier.

### 3.3.1 Extinction Ratio and Optical Modulation Amplitude

The extinction ratio is a measure of the extent of digital modulation on an optical carrier. It is defined as the average optical power of a one bit divided by the average optical power of a zero bit, see Eq. (3.68) and Fig. 3.19. This results in an extinction ratio that is always greater than 1. In the ideal case the zero bit optical power is zero, which results in an extinction ratio of infinity. However in practice this is not achievable for many high-speed modulators. Consequently the zero bit has some amount of optical power associated with it. As the extinction ratio decreases the difference between zero bit and one bit average optical powers decreases. This results in sensitivity degradation and a higher probability the receiver decision circuitry will mistake zero bits for one bits (or vice versa) resulting in bit errors. Extinction ratio is treated as Q-factor impairment and has an associated optical penalty<sup>18</sup> defined by Eq. (3.70) and in dB units see Eq. (3.71), see Table 3.4. It is included in Q-factor budgeting. The extinction ratio is often expressed as a positive dB value as shown by Eq. (3.69). The larger the value the better, typically the value is 9 dB or larger.

$$R_{\rm ex} = \frac{P_1}{P_0}$$
(3.68)

$$R_{\rm ex,dB} = 10 \log(R_{\rm ex})$$
 (3.69)

$$\delta_{\rm ex} = \frac{R_{\rm ex} + 1}{R_{\rm ex} - 1} \tag{3.70}$$

$$\delta_{\text{ex.dB}} = 10 \log \left( \frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1} \right)$$
(3.71)

Note, some documents define the extinction ratio as the inverse of Eq. (3.68). This is identified by the extinction ratio being less than 1 or a negative dB value. In this case Eqs. (3.72) to (3.74) are used.

$$r_{\rm ex} = \frac{1}{R_{\rm ex}} = \frac{P_0}{P_1}$$
(3.72)

$$\delta_{\rm ex} = \frac{1 + r_{\rm ex}}{1 - r_{\rm ex}} \tag{3.73}$$

$$\delta_{\text{ex.dB}} = 10 \log \left( \frac{1 + r_{\text{ex}}}{1 - r_{\text{ex}}} \right)$$
(3.74)

where 
$$R_{ex}$$
 = optical extinction ratio (>1)  
 $R_{ex,dB}$  = optical extinction ratio, dB  
 $r_{ex}$  = optical extinction ratio inverse (<1)  
 $P_1$  = high power level for the one bit, mW  
 $P_0$  = low power level for the zero bit, mW  
 $\delta_{ex}$  = extinction ratio power penalty, linear  
 $\delta_{ex,dB}$  = extinction ratio power penalty relative to an ideal  
system r =  $\infty$ , dB

Optical modulation amplitude (OMA) power is another parameter that represents the depth of optical signal modulation. It is introduced by IEEE 802.3ae standard and is defined as the difference between the optical powers for the binary one and the binary zero bits, see Eq. (3.75) and Fig. 3.19.

$$OMA = P_1 - P_0 \tag{3.75}$$

The average optical power (for an NRZ signal) is then defined as Eq. (3.76).

	Extincti	Power	Penalty		
r <sub>ex</sub>	r <sub>ex</sub> (dB)	R <sub>ex</sub>	R <sub>ex</sub> (dB)	δ <sub>ex</sub>	$\delta_{_{\!\!\!ex}}\left( dB  ight)$
0.5	-3.0	2.0	3.0	3.0	4.8
0.33	-4.8	3.0	4.8	2.0	3.0
0.17	-7.8	6.0	7.8	1.4	1.5
0.11	-9.5	9.0	9.5	1.3	0.97
0.10	-10.0	10.0	10.0	1.2	0.87
0.091	-10.4	11.0	10.4	1.2	0.79
0.083	-10.8	12.0	10.8	1.2	0.73
0.079	-11.0	12.6	11.0	1.2	0.69
0.063	-12.0	15.9	12.0	1.1	0.55
0.050	-13.0	20.0	13.0	1.1	0.43
		~	~	1.0	0.0

$$P_{\rm ave} \approx \frac{P_1 + P_0}{2} \tag{3.76}$$

 TABLE 3.4
 Extinction Ratio and Power Penalty

Additional OMA power relationships are shown with Eqs. (3.77) to (3.81).

$$OMA \approx 2P_{ave} \left( \frac{R_{ex} - 1}{R_{ex} + 1} \right)$$
(3.77)

$$P_{\text{ave}} \approx \frac{1}{2} \text{OMA}\left(\frac{R_{\text{ex}} + 1}{R_{\text{ex}} - 1}\right)$$
 (3.78)

$$R_{\rm ex} \approx \frac{\rm OMA}{P_0} + 1 \tag{3.79}$$

$$P_0 \approx P_{\text{ave}} - \frac{1}{2} \text{OMA} = 2P_{\text{ave}} \left(\frac{1}{R_{\text{ex}} + 1}\right)$$
 (3.80)

$$P_1 \approx P_{\text{ave}} + \frac{1}{2} \text{OMA} = 2P_{\text{ave}} \left(\frac{R_{\text{ex}}}{R_{\text{ex}} + 1}\right)$$
 (3.81)

For the ideal case for an infinite extinction ratio,  $R_{ex} = \infty$ , then Eq. (3.82) can apply.

$$P_{\rm ave} \approx \frac{1}{2} \, \text{OMA} \qquad \text{for } R_{\rm ex} = \infty$$
 (3.82)

OMA power can also be shown in dBm units using Eq. (3.83) for the conversion.

$$OMA_{dBm} = 10 \log(OMA)$$
(3.83)

where OMA = optical modulation amplitude power, mW

OMA<sub>dBm</sub> = optical modulation amplitude power, dBm

*P*<sub>ave</sub> = average optical power (optical power measured with a power meter or OSA), assuming NRZ signal, mW

Note that extinction ratio does not change as a signal is linearly attenuated during its propagation in a fiber. However, OMA does decrease in power during signal propagation by the same amount as the attenuation. Refer to Chap. 2 for more details on how to use OMA in optical power budget planning.

### 3.3.2 Q-Factor Budget

Q-factor budget planning is a way to account for expected optical link impairments over the link's lifetime. Table 3.5 is a typical budget layout also available from ITU-T G.977.<sup>19</sup>

Explanations of the Q-factor budget line items are as follows:

 This first line represents a theoretical linear Q-factor due only to the fiber link optical signal to noise ratio (OSNR) and excludes any receiver noise. The link OSNR is first

Line	Parameter	Value (dB)
1.0	Mean Q-factor (from link OSNR calculation)	
2.0	Propagation impairment penalties	
2.1	Chromatic dispersion (CD)	
2.2	Polarization mode dispersion (PMD)	
2.3	Polarization dependent loss (PDL)	
2.4	Polarization dependent gain (PDG)	
2.5	Self phase modulation (SPM)	
2.6	Cross phase modulation (XPM)	
2.7	Four wave mixing (FWM)	
2.8	Stimulated Raman scattering (SRS)	
2.9	Stimulated Brillouin scattering (SBS)	
3.0	Mode partition noise (MPN)	
4.0	Misadjustment of channel wavelength penalty	
5.0	Manufacturing and environmental impairments	
6.0	Supervisory impairments (submarine systems)	
7.0	Fiber link Q-factor value (L1.0 – sum(L2.0 to L6.0))	
8.0	Transceiver back to back Q-factor	
9.0	Total Link Q-factor	
10.0	BER corresponding to total link Q-factor without FEC	
11.0	BER corresponding to total link Q-factor with FEC	
12.0	Effective Q-factor with FEC	
13.0	Q-factor for network planned BER	
14.0	Q-factor margin BoL (L12 – L13)	
15.0	System aging	
16.0	Cable repair margin	
17.0	Q-factor margin EoL (L14 – L15 – L16)	

 TABLE 3.5
 Q-Factor Budget

calculated using Eq. (3.26) as described earlier in this chapter. When calculating EDFA input power levels only link loss is considered (fiber loss and component loss). Power penalties are not included since they are added in this Q budget. Then Eq.  $(3.84)^{20,21}$  can be used to convert the receiver OSNR value to a mean linear Q-factor knowing the extinction ratio, receiver electrical bandwidth, and optical channel bandwidth. This equation assumes the data format is NRZ. Equation (3.66) is used to convert the linear Q-factor to a dB value.

$$Q = \frac{2\delta_{\text{ex}}^{-1}\text{OSNR}\sqrt{\frac{B_o}{B_e}}}{\sqrt{1 + 4\delta_{\text{ex}}^{-1}\text{OSNR}\left(1 + \frac{r_{\text{ex}}}{1 - r_{\text{ex}}}\right)} + \sqrt{1 + 4\delta_{\text{ex}}^{-1}\text{OSNR}\left(\frac{r_{\text{ex}}}{1 - r_{\text{ex}}}\right)}}$$
(3.84)

$$\delta_{\rm ex}^{-1} = \frac{1 - r_{\rm ex}}{1 + r_{\rm ex}} \tag{3.85}$$

- where *Q* = mean Q-factor assuming NRZ signal format, linear OSNR = link OSNR, linear
  - $B_o$  = optical channel bandwidth typically set by DWDM bandwidth, GHz
  - $B_e$  = receiver electrical bandwidth available from transceiver specifications, GHz
  - $\delta_{ex}^{-1}$  = extinction ratio power penalty inverse, linear
  - $r_{ex}$  = extinction ratio (inverse) available from transceiver specifications
  - 2. The next nine lines (L2.1 through L2.9) represent linear and nonlinear propagation impairment penalties. Their explanations are found in various chapters in this book.
  - 3. Mode partition noise typically is a concern only for MLM lasers, but can also be significant for SLM lasers where SMSR is less than 20 dB. See Chap. 10 for details.
  - 4. WDM channel passband ripple, channel passband misalignment between WDMs can result in additional signal loss during laser wavelength drift, which can lead to Q-factor degradation. WDM ripple value is available from manufacturer specifications and is typically less than 0.5 dB.
  - 5. Manufacturing and environmental impairment penalty covers variations in population distribution of components due to imperfect manufacturing processes. It also covers system degradation due to environmental condition variations such as temperature and pressure. This value is difficult to determine exactly but is estimated at 2 dB<sup>20</sup> for some systems.
  - 6. For submarine systems, the supervisory commands are sent to subsea EDFAs and other equipment by low frequency amplitude modulation of the optical signal. This modulation amplitude is small compared to the data signal but does result in a small Q-factor penalty.

- 7. The fiber link Q-factor value is calculated by subtracting the sum of lines L2 to L6 from line L1 the mean Q-factor.
- 8. Optical transceivers are not perfect and introduce their own impairments, including noise and jitter. The back to back Q-factor is measured with the transceivers connected locally with each other by two short fiber jumpers and a proper attenuator in between to ensure source power does not overload the receiver.
- The total link Q-factor is calculated<sup>22</sup> using the fiber link Q-factor and the transceiver back-to-back Q-factor as shown in Eq. (3.86).

$$Q_{\text{total}} = \sqrt{\left(\frac{1}{Q_{\text{fiber}}^2} + \frac{1}{Q_{\text{bb}}^2}\right)^{-1}}$$
 (3.86)

where  $Q_{\text{fiber}} = Q$ -factor due to the fiber link as shown in line L7  $Q_{\text{bb}} = Q$ -factor of the transceivers connected back to back using a short length of fiber jumper cable, from line L8

10. This line represents the link BER calculated using the total link Q-factor from line L9, see Eqs. (3.62), (3.63), or (3.64).

$$BER = \frac{1}{2} erfc \left(\frac{Q}{\sqrt{2}}\right)$$

- 11. If forward error correct is used then with FEC BER input/output curves the new BER is determined and shown on this line.
- 12. This line is the new effective Q-factor with FEC that is converted from FEC BER line L11. Rearranged Eq. (3.96) as shown below can be used to determine this value.

$$Q_{\text{FEC}} = 20 \log(Q(\text{BER}_{\text{FEC}})) + 10 \log(R_d)$$
 (3.87)

where  $R_d$  is the FEC redundancy ratio, and  $R_d < 1$ .

- 13. This line shows the required link Q-factor for the planned link BER.
- 14. This line is the beginning of life (BoL) Q-factor margin calculated by subtracting line L13 from L12.
- 15. This line accounts for fiber link system aging. We generally assume all fiber link components will be replaced as they fail. Therefore, the main aging component that remains for the entire life span is the fiber optic cable. Typical values used for fiber aging<sup>22</sup> over a 25-year life span are 0.003 dB/km for hydrogen degradation plus 0.002 dB/km for gamma radiation degradation (if applicable).

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- 16. The cable repair margin is the estimated loss of all repair cable lengths spliced into the link over the life span of the link.
- 17. The end of life (EoL) Q-factor margin is the amount of Q-factor remaining after the link's life span. It is calculated by subtracting lines L15 and L16 from L14.

### **Q-Factor Budget Example**

A 16 channel, 10 Gbps, 100 GHz spaced DWDM system is planned to be built over an existing long terrestrial fiber link. Equipment specifications are as follows:

Transceiver

Extinction ratio: 9 dB Electrical 3 dB bandwidth: 8 GHz Back to back Q-factor: 20 dB Chromatic dispersion penalty: 2 dB PMD penalty: 1 dB FEC available: GFEC

DWDM

DWDM optical 3 dB bandwidth: 25 GHz

Channel ripple: 0.5 dB

Numerous EDFAs are planned in the link and after detailed OSNR planning the final receiver OSNR is calculated to be 16.5 dB. To determine the mean Q-factor, Eq. (3.84) is used with this OSNR value, transceiver extinction ratio of  $R_{ex}$  = 9 dB, electrical bandwidth of 8 GHz, and DWDM optical bandwidth of 25 GHz. The mean fiber link Q-factor is calculated to be 17.1 dB.

Propagation linear impairments are 2 dB for chromatic dispersion penalty and 1 dB for PMD penalty. The maximum channel power is kept below 5 dBm in an NZ-DSF fiber and therefore calculations show that nonlinear effects are negligible. Maximum channel ripple is estimated to be 0.5 dB. Manufacturing variations and environmental impairments due to temperature are estimated to be 1 dB. Total Q-factor due to the fiber link itself is determined by subtracting the sum of all impairments (lines L2.0 to L5.0) from the mean Q-factor (line L1) which results in 12.6 dB.

The transceiver manufacturer has measured the back to back Q-factor for the transceiver and it is 20 dB. Therefore using Eq. (3.86), total link Q-factor is calculated to be 11.9 dB. Converting the value to BER results is  $4.5 \times 10^{-5}$ . By using the transceiver's GFEC coding, this BER is decreased to  $2.19 \times 10^{-19}$ . Using Eqs. (3.87) and (3.96) the GFEC BER corresponds to a Q-factor of 18.7 dB. The required BER

for the link is 10<sup>-12</sup> which corresponds to a Q-factor of 17 dB. The resulting Q-factor margin at beginning of life is then calculated to be 1.7 dB. Fiber aging over a 25-year life span estimated using 0.003 dB/km attenuation for the 330 km link results in 1.0 dB penalty. The cable repair margin estimated for the link assumes a maximum of two repairs over the 25-year life span with maximum loss for each repair not to exceed 0.3 dB. The resulting end of life Q-factor margin is 0.1 dB. The Q-factor budget is shown in Table 3.6.

Line	Parameter	Value (dB)
1.0	Mean Q-factor (from link OSNR calculation)	17.1
2.0	Propagation impairment penalties	
2.1	Chromatic dispersion (CD)	2
2.2	Polarization mode dispersion (PMD)	1
2.3	Polarization dependent loss (PDL)	0
2.4	Polarization dependent gain (PDG)	0
2.5	Self phase modulation (SPM)	0
2.6	Cross phase modulation (XPM)	0
2.7	Four wave mixing (FWM)	0
2.8	Stimulated Raman scattering (SRS)	0
2.9	Stimulated Brillouin scattering (SBS)	0
3.0	Mode partition noise (MPN)	0
4.0	Misadjustment of channel wavelength penalty	0.5
5.0	Manufacturing and environmental impairments	1
6.0	Supervisory impairments (submarine systems)	0
7.0	Fiber link Q-factor value (L1.0 – sum (L2.0 to L6.0))	12.6
8.0	Transceiver back to back Q-factor	20
9.0	Total link Q-factor	11.9
10.0	BER corresponding to total link Q-factor without FEC	$4.15  imes 10^{-5}$
11.0	BER corresponding to total link Q-factor with FEC	$2.19\times10^{\scriptscriptstyle-19}$
12.0	Effective Q-factor with FEC	18.7
13.0	Q-factor for network planned BER of 10 <sup>-12</sup>	17.0
14.0	Q-factor margin BoL (L12 – L13)	1.7
15.0	System aging over 25-year life span	1.0
16.0	Cable repair margin	0.6
17.0	Q-factor margin EoL (L14 – L15 – L16)	0.1

 TABLE 3.6
 Q-Factor Budget Example

# 3.4 Forward Error Correction

Forward error correction (FEC) is a mathematical signal encoding and decoding algorithm that is available in some high-speed transceivers, typically 10 Gbps and above, that helps to detect and correct a certain percentage of received bit errors. This results in a lower BER for a set OSNR or a lower OSNR and Q-factor for a target BER. Lowering the OSNR allows for longer span lengths and reduced number of EDFAs in a fiber link.

The FEC process requires the coder algorithm to create a short check code for a block of information bytes that is used by the decoder to correct any bytes that may have been received in error. This check code is sent along with the block of information bytes during transmission within the data stream (in-band) or external to the data stream (out-of-band). In-band check codes are transported within spare spaces in the data stream protocol. For SONET they are carried in the SONET overhead. This spare space is usually limited and therefore the power of the FEC (the amount of errors that the algorithm can correct) is restricted. The advantage of using in-band FEC is that the aggregate transmission rate is not increased and interoperability with non-FEC systems is possible. For out-of-band FEC, the extra check coding is appended to the transmission signal and therefore increases the signal's transmission rate. An OC-192 SONET signal has a transmission rate of 9.958 Gbps, but with generic FEC (GFEC) added the signal rate increases by 6.6% to 10.6 Gbps. This method is protocol independent and does not restrict the FEC's ability to correct errors. Therefore it is stronger than the in-band method. If using signal regenerators at intermediate locations, the regeneration equipment needs to be compatible with the FEC protocol.

A popular FEC method is defined in ITU-T G.975 and G.709 and is referred to as generic FEC (GFEC). It employs the Reed-Solomon (255, 239) code algorithm. Reed-Solomon codes are block codes that are identified by the (n, k) notation. The *k* represents the block of input information bytes (also referred to as symbols), of *m* bits in length, that the algorithm encodes for error correction, see Fig. 3.20. An error check field of r = n - k bytes in length is appended to the block's end (out-of-band). The total output is *n* bytes in length, which is the sum of the input *k* bytes and the error check *r* bytes, see Eq. (3.88). Byte sizes



FIGURE 3.20 Reed-Solomon FEC code block.
range from 3 to 12 bits. Total block length depends on the byte size as shown in Eq. (3.90). For an 8 bit length byte, the output block size is 255 bytes. The maximum number of bytes that can be corrected in a block is (n - k)/2. The popular (255, 239) code has a total block length of 255 bytes, of which 16 are check bytes. The maximum amount of errors that can be corrected is eight errored bytes in a 239 block of data. The increased size of the output coded block is 6.6%, which is determined by Eq. (3.91).

$$n = k + r \tag{3.88}$$

$$t = \frac{(n-k)}{2} \tag{3.89}$$

$$n = 2^m - 1 \tag{3.90}$$

$$s = \frac{n-k}{k} \times 100 \tag{3.91}$$

- where n = total length of the output block, bytes
  - *k* = number of the input information, bytes
  - r = number of appended check, bytes
  - *t* = maximum number of errored bytes that can be corrected
  - m = number of bits in a byte
  - *s* = percentage increase of the output coded block size compared to the input block size

GFEC has a correction ability that provides for a net Q-factor gain of 5.6 dB. This means that a system that experiences a BER of  $10^{-4}$  before FEC, which is a Q-factor of 11.4 dB, would achieve a Q-factor of 17 dB or BER of  $7.2 \times 10^{-13}$ , see Table 3.7. FEC coding also requires a maximum BER input level in order for it to work. For GFEC the maximum input BER is  $10^{-3}$ . A BER value higher than  $10^{-3}$  is beyond the capability of the FEC algorithm to correct the errors. ITU-T G.975.1 defines other super or enhanced FEC (EFEC) codes that further improve BER results and have better Q-factor gain.

Input BER	Output BER	Coding Gain (dB)	Net Coding Gain (dB)
10-4	$5.4 imes10^{-15}$	6.3	6.0
10-5	$6.3 imes10^{-24}$	7.4	7.1
10-6	$6.4  imes 10^{-33}$	7.9	7.7
10-7	$6.4  imes 10^{-42}$	8.3	8.0
10 <sup>-8</sup>	$6.4 imes10^{-51}$	8.5	8.2

TABLE 3.7	GFEC Q-Factor	<sup>r</sup> Coding Gain
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FIGURE 3.21 GFEC BER gain curve.

Refer to equipment manufacturer specifications to determine the type of FEC code used and its FEC gain curves. BER input and output curve for GFEC is shown in Fig. 3.21. The FEC curves can be estimated<sup>23</sup> using Eq. (3.92). Assumptions are that the input errors are independent of each other and that the decoder always operates properly.

$$P_{U} \approx \frac{1}{n} \sum_{i=t+1}^{n} i \binom{n}{i} P_{S}^{i} (1 - P_{S})^{n-i}$$
(3.92)

$$\binom{n}{i} = \frac{n!}{i!(n-i)!} \tag{3.93}$$

$$BER_{input} = 1 - (1 - P_S)^{1/m}$$
(3.94)

$$BER_{output} = 1 - (1 - P_{\rm U})^{1/m} \tag{3.95}$$

where

 $P_u$  = probability of an uncorrectable byte error  $P_s$  = probability of a byte (symbol) error BER<sub>input</sub> = input bit error ratio BER<sub>output</sub> = output bit error ratio

Many manufacturers that provide FEC capability in their transceivers also provide BER gain curves similar to Fig. 3.21 for these products. If the BER gain curve is known, the net coding gain (NCG) in dB units can be calculated<sup>24</sup> using the inverse of the complementary function shown in Eq. (3.62) or the approximation in Eqs. (3.65) and (3.96). Table 3.7 list a few NCG values for GFEC coding.

 $NCG = 20 \log(Q(BER_{output})) - 20 \log(Q(BER_{input})) + 10 \log(R_d)$ (3.96)

$$R_d = \frac{k}{n} \tag{3.97}$$

where NCG = net coding gain, dB

 $R_d$  = FEC redundancy ratio, and  $R_d$  <1

The NCG is applied to the Q-factor budget (or OSNR budget) and allows for systems to operate at a given BER with a higher noise threshold than without FEC. This allows for longer EDFA span spacing and/or improvement in system BER performance.

Note that all FEC coding introduces latency to the transmission signal to some degree due to the coding algorithm. Exact values can be obtained from manufacturer specifications but typically range from 1 to 200  $\mu$ s and are included in signal latency calculations.

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# CHAPTER 4 Chromatic Dispersion

# 4.1 Description

Chromatic dispersion (CD) is a property of optical fiber (or optical component) that causes different wavelengths of light to propagate at different velocities. Since all light sources consist of a narrow spectrum of light (comprising of many wavelengths), all fiber transmissions are affected by chromatic dispersion to some degree. In addition, any signal modulating a light source results in its spectral broadening and hence exacerbating the chromatic dispersion effect. Since each wavelength of a signal pulse propagates in a fiber at a slightly different velocity, each wavelength arrives at the fiber end at a different time. This results in signal pulse spreading, which leads two intersymbol interference between pulses and increases bit errors, see Fig. 4.1a. For example, assume an optical pulse of width  $T_{h}$  and spectral width  $\Delta\lambda$ can be broken into a group of seven monochromatic spectral components with wavelengths  $\lambda_1$  to  $\lambda_7$  and launched into a fiber of length *L*. Then in the presence of chromatic dispersion, each spectral component will propagate in the fiber at different velocities  $v_1$  to  $v_7$  and will arrive at the fiber end at different group delay times of  $\tau_1$  to  $\tau_2$ . This results in pulse spreading by the amount of  $\Delta \tau$  called relative group delay, see Fig. 4.1b and Eq. (4.1) and Eq. (4.2). Total pulse width at the end of the fiber is  $T_b + \Delta \tau$ .

$$\tau_x = \frac{L}{v_x} \tag{4.1}$$

$$\Delta \tau = \tau_7 - \tau_1 \tag{4.2}$$

where L =fiber length, m

- $\tau_x$  = propagation time of the *x*'th spectral component, s
- $\Delta \tau$  = relative group delay of the pulse, s
- $v_x$  = phase velocity of the *x*'th spectral component, m/s



b. Pulse propagation in fiber with CD

FIGURE 4.1 Fiber transmission pulse spreading caused by chromatic dispersion.

This example is not realistic because an optical pulse cannot be broken into its monochromatic components. But it is useful in helping to explain the effect. All optical sources will always emit a range of wavelengths referred to as its spectral width.

Plotting the delays of various spectral components in a fiber will result in a relative group delay curve similar to Fig. 4.2. Chromatic dispersion can be defined as the relative group delay of a range of spectral components divided by the range of the component wavelengths,



FIGURE 4.2 Relative group delay and chromatic dispersion curves.

see Eq. (4.3). This also means that chromatic dispersion is the slope of any point on the relative group delay curve as shown by Eq. (4.4). As can be seen in Fig. 4.2 chromatic dispersion varies with wavelength. It can be zero, positive, or negative depending on the signal wavelength. For standard single-mode fiber, G.652, chromatic dispersion is positive in the C and L bands.

$$CD = \frac{\Delta \tau}{\Delta \lambda}$$
(4.3)

$$CD = \frac{d\tau}{d\lambda}$$
(4.4)

where CD = fiber's chromatic dispersion at wavelength  $\lambda$ , ps/nm

 $\Delta \tau$  = relative group delay of a pulse, ps

 $\Delta \lambda$  = spectral width of a pulse with center wavelength  $\lambda$ , nm L = fiber length, km

The phase velocity (see Fig. 1.6) of a propagating wave is defined in Chap. 1 and is related to the propagation parameter  $\beta$  as defined in Eqs. (1.20) and (4.5). However, phase velocity is an ideal characteristic of a monochromatic optical signal, which is not realistic. Therefore, group velocity  $v_g$  is defined in Eq. (4.6) as the derivative of Eq. (4.5), which represents the velocity of the envelope of an optical signal. It can also be thought of as the speed of the signal pulse or information in the fiber.

$$v = \frac{\omega}{\beta} = \frac{c}{n_{\text{eff}}}$$
(4.5)

$$v_g = \frac{L}{\tau_g} = \frac{c}{n_g} = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1} = -\frac{2\pi c}{\lambda^2} \left(\frac{\partial\beta}{\partial\lambda}\right)^{-1}$$
(4.6)

where v = phase velocity of an optical wavelength, m/s

c = speed of light in a vacuum, m/s

 $\beta$  = phase propagation parameter, rad/m

 $\omega$  = angular frequency,  $\omega$  =  $2\pi c/\lambda$ , rad/s

 $v_g$  = group velocity of the signal, m/s

 $n_{\rm eff}$  = fiber's effective refractive index at  $\omega$  or  $\lambda$ 

 $n_{o}$  = fiber's effective group refractive index at  $\omega$  or  $\lambda$ 

Note, depending on the equation the angular frequency  $\omega$ , frequency *f*, and wavelength  $\lambda$  are used interchangeably using Eqs. (4.7) and (4.8) identities.

$$\omega = 2\pi f = \frac{2\pi c}{\lambda} \tag{4.7}$$

$$\Delta \omega = -\frac{2\pi c}{\lambda^2} \Delta \lambda \tag{4.8}$$

From Eqs. (4.1), (4.2), and (1.35) broadening a pulse can now be defined as Eq. (4.9).<sup>1</sup>

$$\Delta \tau_{g} = \frac{d\tau_{g}}{d\omega} \Delta \omega = \frac{d(L/v_{g})}{d\omega} \Delta \omega = L \frac{d^{2}\beta}{d\omega^{2}} \Delta \omega = L\beta_{2} \Delta \omega$$
(4.9)

where  $\Delta \omega$  is the spectral width of the pulse.

Taking the derivative of Eq. (4.9) as shown in Eq. (4.4) provides the chromatic dispersion, see Eq. (4.10).

$$CD = \frac{d(L/v_g)}{d\lambda} = -L\frac{2\pi c}{\lambda^2}\beta_2$$
(4.10)

where  $\beta_2$  is group-velocity dispersion (GVD) parameter,  $s^2/m$ .

The group-velocity dispersion (GVD) parameter is a convenient parameter often used in calculations instead of CD to determine propagating pulse broadening in a fiber such as in Eqs. (1.54) and (1.61).

The chromatic dispersion (CD) parameter is a measure of signal pulse spread in a fiber due to this effect. It is expressed with ps/nm units, where the picoseconds refer to the signal pulse spread in time and the nanometers refer to the signal's spectral width. Chromatic dispersion can also be expressed as fiber length multiplied by a proportionality coefficient, see Eq. (4.11). This coefficient is referred to as the chromatic dispersion coefficient and is measured in units of picoseconds per nanometer times kilometer, ps/(nm km). It is typically specified by the fiber the cable manufacturer and represents the chromatic dispersion characteristic for a 1 km length of fiber. It can also be estimated for standard G.652 fiber given the fiber's dispersion slope and zero dispersion coefficient is referred to as chromatic dispersion, which causes confusion between these two terms.

$$CD = CD_c \times L \tag{4.11}$$

where CD = fiber chromatic dispersion, ps/nm  $CD_c$  = fiber chromatic dispersion coefficient, ps/(nm · km) L = fiber length, km

Equation (4.10) can be rewritten using chromatic dispersion coefficient, see Eq. (4.12).

$$CD_{c} = \frac{d(1/v_{g})}{d\lambda} = -\frac{2\pi c}{\lambda^{2}}\beta_{2}$$
(4.12)

Chromatic dispersion can be broken into two components, material dispersion and waveguide dispersion. Material dispersion  $D_m$  is the predominant reason for chromatic dispersion and is due to the core's refractive index changing with wavelength, see Eqs. (4.13) and (4.14).<sup>2</sup>

$$n_g = n_{\text{eff}} + \omega \frac{dn_{\text{eff}}}{d\omega}$$
 or  $n_g = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}$  (4.13)

$$D_m = \frac{1}{c} \frac{dn_g}{d\lambda} \tag{4.14}$$

where  $n_{a}$  = effective group refractive index at  $\omega$  or  $\lambda$ 

 $\lambda$  = signal component center wavelength, m

 $n_{\rm eff}$  = fiber's phase effective refractive index at  $\omega$  or  $\lambda$ ,  $n_{\rm eff} = c/v_n$ 

c = speed of light in a vacuum, m/s

 $D_m$  = material dispersion coefficient, s/(m · m)

Waveguide dispersion  $D_w$  effect is due to the physical structure of the fiber core cladding waveguide that causes different wavelengths to propagate at different velocities. Changes in this physical structure in the manufacturing process allow fiber to be created with various dispersion characteristics such as dispersion flattened or dispersion shifted fiber.

The sum of material dispersion and waveguide dispersion, see Eq. (4.15), results in the total chromatic dispersion as shown in Fig. 4.3.

$$CD_c = D_m + D_m \tag{4.15}$$

where CD<sub>c</sub> = fiber chromatic dispersion at wavelength  $\lambda$ , ps/(nm · km)

 $D_m$  = fiber material dispersion at wavelength  $\lambda$ , ps/(nm · km)

 $D_w^{m}$  = fiber waveguide dispersion at wavelength  $\lambda$ , ps/(nm · km)

As a signal pulse propagates in a fiber, chromatic dispersion causes the pulse to widen, which results in the leading and trailing edges of the pulse to spread into the adjacent bit time slots, see Fig. 4.1*a*. This can result in intersymbol interference and higher bit errors if the pulse spread exceeds a certain dispersion limit. It also results in a



FIGURE **4.3** NDSF fiber chromatic dispersion resulting from material and waveguide dispersion.

decrease in optical power in the pulse's time slot, since its power is now spread into adjacent time slots, see Fig. 4.1*a*. This is referred to as the *power penalty* and needs to be considered when planning link optical budgets. After propagating some distance in the fiber, a point is reached where the accumulating pulse spread is too great for the receiver to recover the signal pulses within the equipment BER specifications. This point is referred to as the *dispersion limit* and is often specified by the optical transceiver manufacturer in units ps/nm or as a maximum chromatic dispersion limited length in km. It can also be estimated by the pulse broadening factor equation Eq. (1.61) developed in Chapter 1 for a propagating Gaussian pulse, see Eq. (4.16).

$$\frac{\sigma(z)}{\sigma_0} = \sqrt{\left(1 + \frac{C_0 \beta_2 z}{2\sigma_0^2}\right)^2 + \left(1 + (2\sigma_{\omega c}\sigma_0)^2\right) \left(\frac{\beta_2 z}{2\sigma_0^2}\right)^2 + \left(1 + C_0^2 + (2\sigma_{\omega c}\sigma_0)^2\right) \frac{1}{2} \left(\frac{\beta_3 z}{4\sigma_0^3}\right)^2}$$
(4.16)

Equation (4.19) shows the relationship between angular frequency and frequency spectral widths.

Substituting known relations for  $\beta_2$  and  $\beta_3$  from Chap. 1, Eqs. (4.17) and (4.18) we get Eq. (4.20).

$$\beta_2 = -\frac{\lambda_c^2}{2\pi c} CD_c \tag{4.17}$$

$$\beta_3 = \frac{\lambda_c^3}{(2\pi c)^2} (\lambda_c S_c + 2CD_c)$$
(4.18)

$$\sigma_{\omega c} = 2\pi \sigma_{fc} \tag{4.19}$$

$$\sigma^{2} = \left(\sigma_{0} - \frac{CD_{c}C_{0}\lambda_{c}^{2}z}{4\pi\sigma_{0}c}\right)^{2} + \left((4\pi\sigma_{0})^{-2} + \sigma_{fc}^{2}\right)\left(\frac{CD_{c}\lambda_{c}^{2}z}{c}\right)^{2}$$
(4.20)

$$+\frac{z^{2}}{2}\left(1+C_{0}^{2}+(4\pi\sigma_{0}\sigma_{fc})^{2}\right)\left((\lambda_{c}S_{c}+2CD_{c})\frac{\lambda_{c}^{3}}{(4\pi\sigma_{0}c)^{2}}\right)^{2}$$

where 
$$\sigma = \text{signal RMS pulse width at distance } z, s$$
  
 $\sigma_0 = \text{signal Gaussian pulse initial launch RMS width, s}$   
 $\sigma_{oc} = \text{optical carrier RMS spectral width, rad/s}$   
 $\sigma_{fc} = \text{optical carrier RMS spectral width (unmodulated), Hz}$   
 $\lambda_c = \text{optical carrier center wavelength, m}$   
 $\text{CD}_c = \text{chromatic dispersion coefficient at carrier center wavelength, s/(m \cdot m)}$ 

 $C_0$  = initial pulse chirp parameter  $\beta_2$  = group-velocity dispersion (GVD) parameter, s<sup>2</sup>/m  $\beta_3$  = slope of GVD, or second order GVD, s<sup>3</sup>/m z = distance along the fiber length, m  $S_c$  = chromatic dispersion slope at carrier center wavelength, s/m<sup>2</sup>

Pulse broadening Eq. (4.20) can be simplified if we assume the laser has no chirp, such as with an externally modulated laser, and therefore  $C_0 = 0$ . Also assume that the carrier center wavelength is away from the zero dispersion wavelength and therefore  $\beta_3$  can be assumed to be zero. Equation (4.20) simplifies to Eq. (4.21).

$$\sigma^2 = \sigma_0^2 + \left(\frac{1}{(4\pi\sigma_0)^2} + \sigma_{fc}^2\right) \left(\frac{CD_c \lambda_c^2 z}{c}\right)^2$$
(4.21)

The pulse width can be written as the initial pulse width plus the pulse broadening amount  $\sigma_D$  due to chromatic dispersion, see Eqs. (4.22) and (4.23).

$$\sigma^2 = \sigma_0^2 + \sigma_D^2 \tag{4.22}$$

$$\sigma_{D} = \frac{CD_{c}\lambda_{c}^{2}z}{c} \left(\frac{1}{(4\pi\sigma_{0})^{2}} + \sigma_{fc}^{2}\right)^{1/2}$$
(4.23)

To help simplify this equation further we can convert the carrier spectral width from frequency units to wavelength units using the relationship in Eq. (4.24).

$$\sigma_{\rm fc} = \frac{c}{\lambda^2} \sigma_{\lambda c} \tag{4.24}$$

$$\boldsymbol{\sigma}_{D} = CD_{c} z \left( \left( \frac{\lambda_{c}^{2}}{4\pi c \boldsymbol{\sigma}_{0}} \right)^{2} + \boldsymbol{\sigma}_{\lambda c}^{2} \right)^{1/2}$$
(4.25)

where  $\sigma_D = \text{RMS}$  amount of pulse spread due to chromatic dispersion (it is not the pulse width), s

 $\sigma_{\lambda}$  = optical carrier RMS width at distance *z*, m

It is easy to see in Eq. (4.25) the pulse spread has components due to the carrier  $\sigma_{\lambda c}$  and due to the modulating Gaussian signal  $\lambda^2/4\pi_0 c$  term. We can simplify further for two types of optical carrier sources:

distributed feedback (DFB) type lasers where the carrier spectral width is much less than the modulating signal spectral width  $\sigma_{\lambda c} \ll \lambda^2/4\pi \sigma_0 c$  and all other laser and LED sources where the carrier spectral width is greater than the signal spectral width  $\sigma_{\lambda c} \gg \lambda^2/4\pi \sigma_0 c$ . For very narrow laser sources, such as DFB lasers, Eq. (4.25) is simplified to Eq. (4.26).

$$\sigma_D \approx CD_c z \frac{\lambda_c^2}{4\pi c \sigma_0}$$
(4.26)

For other optical sources where the carrier width is much wider than the signal width see Eq. (4.27).

$$\sigma_D \approx CD_c z \sigma_{\lambda c} \tag{4.27}$$

From Chap. 1 we know that the transmission rate *R* is the reciprocal of the bit slot width *T*, see Fig. 1.2 and Eq. (4.28).

$$R = \frac{1}{T} \tag{4.28}$$

where R = transmission rate, bps T = bit time slot width, s

ITU-T G.Sup39<sup>3</sup> presents an equation that relates the initial RMS pulse width to a shape factor *N* times the bit slot width *T* and a duty cycle  $d_c$ , see Eq. (4.29). The value of *N* depends on the type of input pulse. The value of  $d_c$  is a fraction for RZ modulation and one for NRZ modulation. This equation states that the RMS pulse width should be equal to 1/N times the bit time slot width that is reduced in width by some duty cycle fraction  $d_c$ . For NRZ modulation, 4 is commonly used for *N*, which allows for 95% of a Gaussian pulse's energy to be contained in the bit time slot.

$$\sigma_0 = \frac{Td_c}{N} = \frac{d_c}{NR} \tag{4.29}$$

Using  $\sigma_D$  Eq. (4.23) where carrier spectral width is in frequency units and substituting Eq. (4.29) for  $\sigma_0$  we get Eq. (4.30).

$$\sigma_D = \frac{CD_c \lambda_c^2 z}{c} \left( \left( \frac{NR}{4\pi d_c} \right)^2 + \sigma_{\rm fc}^2 \right)^{1/2}$$
(4.30)

$$\sigma = \sqrt{\sigma_0^2 + \sigma_D^2} \tag{4.31}$$

where N = pulse shape factor

- R =transmission rate, bps
- $d_c$  = duty cycle, 1 for NRZ modulation
- $\sigma$  = signal RMS pulse width at distance *z*, s
- $\sigma_0$  = signal Gaussian pulse initial launch RMS width, s
- $\sigma_{fc}$  = optical carrier RMS spectral width (unmodulated), Hz

Equation (4.30) states the amount of pulse width increase knowing the transmission rate, carrier spectral width, and chromatic dispersion as the pulse propagates in the fiber at distance z. Equation (4.31) provides the total RMS pulse width at location z.

ITU-T G.Sup39 defines an epsilon value  $\varepsilon$  for NRZ modulation where for a specific optical power penalty  $\delta_{cd}$  (typically 1 or 2 dB) and bit error rate (typically  $10^{-10}$  or  $10^{-12}$ ) there is a maximum allowable pulse spread due to chromatic dispersion. If this pulse spread is exceeded the BER would worsen above specifications due to intersymbol interference. This maximum pulse spread is defined as the fraction epsilon times the time slot width, see Eq. (4.32).

$$\sigma_{DMax} \le \varepsilon T = \frac{\varepsilon}{R} \tag{4.32}$$

Assuming NRZ modulation the *N* shape factor is 4 and  $d_c$  is 1, we insert Eq. (4.32) into Eq. (4.30) for  $\sigma_D$  to determine the maximum allowable transmission distance due to chromatic dispersion, see Eq. (4.33).

$$\left(\frac{\varepsilon c}{\operatorname{CD}_{c} R \lambda_{c}^{2} z}\right)^{2} \leq \left(\frac{4R}{4\pi}\right)^{2} + \sigma_{\mathrm{fc}}^{2}$$
(4.33)

Solving for the chromatic dispersion and transmission distance, the result is Eq. (4.34).

$$CD_{cMax} z \le \frac{\varepsilon c}{\lambda_c^2 R \sqrt{\left(\frac{R}{\pi}\right)^2 + \sigma_{fc}^2}}$$
(4.34)

$$CD_{Max} = CD_{cMax} z \tag{4.35}$$

- where  $CD_{cMax}$  = maximum tolerable chromatic dispersion coefficient, s/(m · m)
  - $CD_{Max}$  = maximum tolerable chromatic dispersion limit, s/m
    - $\varepsilon$  = epsilon value = 0.3 for 1 dB power penalty and 0.48 for 2 dB power penalty at BER 10<sup>-12</sup> for NRZ modulated signals
    - z = transmission distance, m

R = transmission rate, bps  $\sigma_{fc}$  = optical carrier RMS spectral width, Hz c = speed of light in a vacuum, m/s  $\lambda_{c}$  = carrier center wavelength, m

This result estimates<sup>4</sup> the maximum tolerable chromatic dispersion for an input Gaussian NRZ modulated optical signal at transmission distance *z*. If the fiber link chromatic dispersion coefficient is known the result estimates the maximum transmission distance.

Often the laser spectral width is given as the -20 dB full width, and therefore Eq. (4.36) can be used to convert to the RMS spectral width assuming a Gaussian spectral shape.

$$\Delta f_{-20\rm dB} = 6.0697\sigma_{\rm fc} \tag{4.36}$$

For very narrow optical sources, such as a DFB laser with a spectral width of 100 MHz, and a high transmission rate where the carrier unmodulated spectral width is  $\Delta f_{-20dB} < R/10$ , Eq. (4.34) is simplified to Eq. (4.37).

$$CD_{cMax} z \le \frac{\varepsilon c\pi}{\lambda_c^2 R^2}$$
(4.37)

For other optical sources where the carrier width is much wider than the modulating signal width, where  $\Delta f_{-20dB} > 14R$ , Eq. (4.34) is simplified to Eq. (4.38).

$$CD_{cMax} z \le \frac{\varepsilon c}{\lambda_c^2 R \sigma_{fc}}$$
(4.38)

ITU-T G.Sup39 epsilon values for specific optical power penalties for BER of 10<sup>-12</sup> due to chromatic dispersion pulse spreading using NRZ modulation and DFB lasers are shown in Table 4.1.

Using epsilon values shown in Table 4.1, Eq. (4.37) can be written as Eq. (4.39) for 1 dB power penalty. Assume high bit rate transmission systems, narrow spectrum lasers (DFB), no chirp in the signal, and initial launch Gaussian NRZ pulse.

Epsilon Value	Optical Power Penalty (dB)
0.2	0.5
0.3	1
0.48	2
0.3	1 2

 TABLE 4.1
 Epsilon and Power

 Penalty Values for NRZ Modulation
 for BER 10<sup>-12</sup>

Bit Rate (Gbps)	Protocol (NRZ)	Chromatic Dispersion Limit 1 dB Penalty (ps/nm)	Distance Limit G.652 Fiber (km)
2.5	0C-48 & STM-16	18800	1100
10	0C-192 & STM-64	1176	69
40	0C-768 & STM-256	73.5	4.3
100	100G Ethernet	11.8	0.69

 TABLE 4.2
 Estimated Chromatic Dispersion Limits for Externally Modulated

 Chirp-Free DFB Laser over G.652 Fiber with a 1 dB Power Penalty

$$CD_{cMax} z \le \frac{2.8255 \times 10^8}{\lambda_c^2 R^2}$$
 (4.39)

For a 2 dB optical budget power penalty, see Eq. (4.40).

$$CD_{cMax} z \le \frac{4.5208 \times 10^8}{\lambda_c^2 R^2}$$
 (4.40)

Table 4.2 shows estimated chromatic dispersion pulse propagation limits for a 1 dB optical power penalty calculated using Eq. (4.39), assuming G.652 fiber with CD<sub>c</sub> at 17 ps/(nm · km) at 1550 nm, externally modulated DFB laser with chirp free ideal NRZ Gaussian pulse transmissions. The actual pulse shape may be more rectangular (super Gaussian), which may reduce these limits. Note, dispersion limits vary greatly between different manufacturer equipment and this table should be used only for general reference for possible maximum reach under ideal conditions. Directly modulated DFB lasers experience frequency chirp, which greatly reduces these limits. For accurate dispersion limit values, equipment manufacturer specifications should be consulted.

For a 2 dB optical power penalty see Table 4.3.

For broad spectrum lasers such as Fabry-Perot or light emitting diodes (LED), lower transmission rates and a 1 dB optical budget, Eq. (4.38) can be shown as Eq. (4.41).

$$CD_{cMax}z \le \frac{8.9938 \times 10^7}{\lambda_c^2 R\sigma_{fc}}$$
(4.41)

For example, if an LED source has an RMS spectral width of 1870 GHz (15 nm) at 1550 nm and is modulated at 1 Gbps it would have an estimated dispersion limit of 20 ps/nm or 1.2 km using G.652 fiber.

To see the effect of laser chirp we can keep the chirp parameter  $C_0$  in Eq. (4.20) and keep the assumption that the carrier wavelength is

Bit Rate (Gbps)	Protocol (NRZ)	Chromatic Dispersion Limit 2 dB Penalty (ps/nm)	Distance Limit G.652 Fiber (km)
2.5	0C-48 & STM-16	30100	1770
10	0C-192 & STM-64	1880	111
40	0C-768 & STM-256	117	6.9
100	100G Ethernet	18.8	1.1

 TABLE 4.3
 Estimated Chromatic Dispersion Limits for Externally Modulated

 Chirp-Free DFB Laser over G.652 Fiber with a 2 dB Power Penalty

far away from the zero dispersion wavelength; therefore,  $\beta_3$  can be assumed to be zero, and we get Eq. (4.42).

$$\sigma^{2} = \left(\sigma_{0} - \frac{\mathrm{CD}_{c}C_{0}\lambda_{c}^{2}z}{4\pi\sigma_{0}c}\right)^{2} + \left((4\pi\sigma_{0})^{-2} + \sigma_{\mathrm{fc}}^{2}\right)\left(\frac{\mathrm{CD}_{c}\lambda_{c}^{2}z}{c}\right)^{2}$$
(4.42)

which can be rewritten as Eq. (4.43).

$$\sigma^{2} = \sigma_{0}^{2} - \frac{2CD_{c}C_{0}\lambda_{c}^{2}z}{4\pi c} + \left(\frac{CD_{c}C_{0}\lambda_{c}^{2}z}{4\pi\sigma_{0}c}\right)^{2} + \left((4\pi\sigma_{0})^{-2} + \sigma_{fc}^{2}\right)\left(\frac{CD_{c}\lambda_{c}^{2}z}{c}\right)^{2}$$
(4.43)

The pulse broadening amount  $\sigma_{D}$  can then be shown as Eq. (4.44).

$$\sigma_{D} = \sqrt{-\frac{2CD_{c}C_{0}\lambda_{c}^{2}z}{4\pi c} + \left(\frac{CD_{c}C_{0}\lambda_{c}^{2}z}{4\pi\sigma_{0}c}\right)^{2} + ((4\pi\sigma_{0})^{-2} + \sigma_{fc}^{2})\left(\frac{CD_{c}\lambda_{c}^{2}z}{c}\right)^{2}}$$
(4.44)

For the condition where the laser is DFB type and its spectral width is much smaller than the modulation spectral width, we get Eq. (4.45).

$$\sigma_D = \sqrt{-\frac{2CD_c C_0 \lambda_c^2 z}{4\pi c} + \left(\frac{CD_c \lambda_c^2 z}{4\pi \sigma_0 c}\right)^2 (C_0^2 + 1)}$$
(4.45)

To include the data rate and *N* factor we substitute Eq. (4.29) for  $\sigma_0$  and get Eq. (4.46).

$$\sigma_D = \sqrt{-\frac{2CD_cC_0\lambda_c^2 z}{4\pi c} + \left(\frac{CD_cNR\lambda_c^2 z}{d_c 4\pi c}\right)^2 (C_0^2 + 1)}$$
(4.46)

Assuming NRZ modulation then N = 4 and  $d_c = 1$ , we insert Eq. (4.32) into Eq. (4.46) for  $\sigma_D$  and solve for CD to determine the maximum allowable pulse spread due to chromatic dispersion, see Eq. (4.47).

$$\left(\frac{\varepsilon}{R}\right)^2 = -\frac{2CD_cC_0\lambda_c^2 z}{4\pi c} + \left(\frac{CD_cR\lambda_c^2 z}{\pi c}\right)^2 (C_0^2 + 1)$$
(4.47)

$$0 = R^{2} (C_{0}^{2} + 1) \left( \frac{CD_{c} \lambda_{c}^{2} z}{\pi c} \right)^{2} - \frac{C_{0}}{2} \frac{CD_{c} \lambda_{c}^{2} z}{\pi c} - \left( \frac{\varepsilon}{R} \right)^{2}$$
(4.48)

$$CD_{cMax} z = \frac{\pi c (C_0 \pm \sqrt{C_0^2 + 16\epsilon^2 (C_0^2 + 1)})}{4R^2 \lambda_c^2 (C_0^2 + 1)}$$
(4.49)

Let's choose a chirp factor that is common for directly modulated DFB lasers of  $C_0 = -5$  and chromatic dispersion optical power penalty of 1 dB then  $\varepsilon = 0.3$ . The results can be seen in Table 4.4. Comparing results of Table 4.2 for an unchirped laser and Table 4.4, it is obvious that this amount of chirp significantly decreases the chromatic dispersion transmission distance in standard G.652 fiber.

The chromatic dispersion power penalty  $\delta_{cd}$  is defined as the increase in optical signal power (in dB units) required to compensate for power reduction due to chromatic dispersion. It can be estimated by taking the log of the RMS pulse width after transmission distance *z* divided by the launch pulse width. See Eqs. (4.50) to (4.53) for the assumptions of no chirp and NRZ modulation.

$$\delta_{\rm cd} = 10\log\left(\frac{\sigma(z)}{\sigma_0}\right) \tag{4.50}$$

Bit Rate (Gbps)	Protocol (NRZ)	Chirped DFB Laser Chromatic Dispersion Limit 1 dB Penalty (ps/nm)	Distance Limit G.652 Fiber (km)
2.5	0C-48 & STM-16	1750	103
10	0C-192 & STM-64	109	6
40	0C-768 & STM-256	7	0.4
100	100G Ethernet	1	0.06

**TABLE 4.4**Estimated Chromatic Dispersion Limits for Directly ModulatedChirped DFB Laser over G.652 Fiber with a 1 dB Power Penalty

Chromatic Dispersion 115

$$\sigma(z) = \sqrt{\sigma_0^2 + \sigma_D^2} \tag{4.51}$$

The total pulse spread at distance z can be determined by Eq. (4.30) modified by factor 1.559 to account for ITU epsilon requirement.

$$\boldsymbol{\sigma}_{D} = \frac{\text{CD}_{c}\lambda_{c}^{2}z}{1.559c} \left[ \left( \frac{NR}{4\pi d_{c}} \right)^{2} + \boldsymbol{\sigma}_{\text{fc}}^{2} \right]^{1/2}$$
(4.52)

$$\sigma_0 = \frac{1}{4R} \tag{4.53}$$

Figure 4.4 shows estimated power penalties for various lengths of G.652 fiber and transmission rates.

It must be stressed that all these dispersion limit values are estimates only and actual values are typically less. Refer to manufacturer specifications for accurate values.

Chromatic dispersion accumulates along the fiber length, positively or negatively depending on fiber type. The total amount of chromatic dispersion in a fiber link should be considered for all systems with optical transmission rates of 1 Gbps and greater. Below this rate, optical loss and link OSNR are more limiting to transmission distance than chromatic dispersion. Therefore, equipment specifications typically do not include chromatic dispersion limits for their transceivers below this rate.

For analog systems, such as analog fiber cable TV systems, chromatic dispersion can cause signal distortion and increase the signal noise floor. Therefore, it is also important to plan acceptable chromatic dispersion budgets for analog systems.



FIGURE 4.4 Chromatic dispersion power penalties.

# 4.2 Fiber Types

There are four basic fiber types with different chromatic dispersion characteristics as shown in Fig. 4.5 and Table 4.5.



FIGURE 4.5 Chromatic dispersion plots for different fiber types.

Type of Fiber	Chromatic Dispersion Coeff. at 1550 nm (ps/(nm · km))	Typical Slope at 1550 nm (ps/(nm² km))	RDS at 1550 nm (nm <sup>-1</sup> )	Affective Area Aeff μm²
NDSF, SSMF (G.652)	17	0.056	0.003	80
DSF (G.653)	<3.5	0.07	0.024 @1590 nm	70
NZ-DSF (G.655)	0.1 to 10	0.045 to 0.085	0.006 to 0.01	50 to 70
(-D) NZ-DSF	-10 to -1	0.04 to 0.1	-0.006 to -0.01	50 to 70
DCF	-100	-0.2	varies	

 TABLE 4.5
 Typical Chromatic Dispersion Coefficient Values for Different Fiber Types

- 1. Non-dispersion shifted fiber (NDSF, ITU-T G.652) also known as standard single-mode fiber (SSMF) has its zero dispersion wavelength ( $\lambda_0$ ) at approximately 1310 nm. This is the most commonly deployed type of fiber. Its chromatic dispersion increases positively with increasing wavelength above  $\lambda_0$  and increases negatively for wavelengths less than  $\lambda_0$ . SMF-28\* fiber made by Corning\* is a popular NDSF type fiber. This fiber type works well for both time domain multiplexing (TDM) systems in 1310 and 1550 nm windows, DWDM systems, and 8-channel CWDM systems. For long distance and high data rate deployments, dispersion management is required. Suppressed attenuation at water peak fibers type G.652.c/d can be used for 16-channel CWDM systems.
- 2. Dispersion shifted fiber (DSF, ITU-T G.653) has its zero dispersion wavelength ( $\lambda_0$ ) in the 1550 nm window. This greatly reduces dispersion in this window but results in a significant increase in nonlinear distortions such as four wave mixing (FWM) when WDM and DWDM systems are deployed. This fiber type is intended for only single-channel TDM systems in the 1550 nm window. Chromatic dispersion may be too high for communications in the 1310 nm window. This fiber type is not commonly deployed.
- 3. Non-zero dispersion shifted fiber (NZ-DSF, ITU-T G.655) has its zero dispersion wavelength ( $\lambda_0$ ) just outside of the 1550 nm window. This fiber type chromatic dispersion level is low but not zero in the 1550 nm window. NZ-DSF was developed to help mitigate the effects of nonlinear distortions but still allow for much longer transmission links due to lower chromatic dispersion values than standard NDSF. An example of this fiber type is Corning\* LEAF\*. Positive (+D) and negative (-D) dispersion options with this fiber are available. Negative dispersion NZ-DSF has its chromatic dispersion zero wavelength ( $\lambda_0$ ) shifted to the 1640 nm region and therefore provides low negative dispersion in the 1550 window. It has been shown<sup>5,6</sup> that negative dispersion NZ-DSF can increase the chromatic dispersion transmission limit when used with directly modulated distributed feedback (DM-DFB) lasers that have a high positive chirp. An example of this fiber type is Corning\* MetroCor\*. This fiber type works well with TDM systems in the 1310 and 1550 nm windows, DWDM systems, and 8-channel CWDM systems. Suppressed attenuation at water peak fibers can be used for 16-channel CWDM systems.

<sup>\*</sup>Registered trademark of Corning, Inc.



FIGURE 4.6 Chromatic dispersion map of alternating lengths of NZ-DSF and DCF fiber cable.

4. Dispersion compensating fiber (DCF) has negative dispersion and negative dispersion slope to compensate for the positive dispersion and slope of installed fibers. Long lengths of this type of fiber are wound onto small reels and placed into dispersion compensation modules (DCM). DCF typically has higher attenuation than SSMF, which would result in high insertion loss. Overcoming this loss by increasing signal power may be problematic because the smaller fiber core effective area of DCF makes it more susceptible to nonlinear effects, see Table 4.5.

Another method to control chromatic dispersion<sup>7</sup> over long links, such as in submarine networks,<sup>8</sup> is to splice together alternating lengths of NZ-DSF and DCF cable, see Fig. 4.6. This can result in low dispersion levels across the entire band without the need for any further external compensation. An example of this fiber type is Corning<sup>\*</sup> Vascade.<sup>\*</sup>

# 4.3 Coping with Chromatic Dispersion

Chromatic dispersion affects all optical transmissions to some degree. These effects become more pronounced as the transmission rate increases and fiber length increases. As optical transmission systems are designed

<sup>\*</sup>Registered trademark of Corning, Inc.

to work closer to equipment limits, dispersion budget planning may be required. Section 4.3.1 lists some of the conditions where chromatic dispersion planning is required for any optical transmission system.

#### **Conditions for Chromatic Dispersion Planning** 4.3.1

Not all fiber transmission links require chromatic dispersion planning by the deployment engineer. Most transceiver manufacturers account for chromatic dispersion in their transmission limit specification for standard fiber (G.652). As long as the transceivers are deployed within the manufacturer's recommendations, dispersion planning is typically not required. Below are conditions when the deployment engineer should consider performing chromatic dispersion budget planning.

- 1. Dispersion planning is recommended by the equipment manufacturer or manufacturer specifications are not available.
- 2. Optical amplifiers are used in the fiber link to extend the fiber transmission distance.
- 3. DWDMs or CWDMs are used in the fiber link.
- 4. Standard single-mode fiber (SSMF, G.652) is not used in the link or the link fiber type is unknown.
- 5. Equipment inserted into the fiber link alters the link total dispersion budget.
- 6. Transceiver chromatic dispersion limit is exceeded.
- 7. Transceiver optical power budget is exceeded.
- 8. For any other conditions where equipment chromatic dispersion limits may be approached or exceeded.

#### 4.3.2 **Chromatic Dispersion Limit**

Transceiver specifications list a maximum tolerable chromatic dispersion, in units ps/nm, to achieve a specific transmission BER (typically 10<sup>-12</sup>). It can also be expressed as a fiber cable length in kilometers assuming standard single-mode fiber is used (G.652) with a chromatic dispersion coefficient of 17 ps/(nm · km) for transmission. The transceiver specification will also list an optical power penalty associated with the chromatic dispersion limit and BER, typically 1 or 2 dB. This power penalty reduces the receiver's specified maximum sensitivity and should be included in all optical budget calculations. Note, the chromatic dispersion power penalty cannot be measured using an optical power meter and laser source. The fiber link total chromatic dispersion must be maintained below or equal to the manufacturer specified transceiver dispersion limit in order to maintain the specified BER. If this limit is exceeded, dispersion compensation or transceiver replacement with a higher limit is required.

The chromatic dispersion limit is inversely proportional to the transmission bit rate squared. This bit rate squared effect is due to higher bit rates having smaller pulse widths that increase receiver sensitivity to pulse spreading and broader signal spectral width that results in more pulse spreading. Chromatic dispersion limit is also sensitive to the equipment optical signal formats and laser types. Limits are different for non-return to zero (NRZ) and return to zero (RZ) formats, lasers with and without chirp, directly and externally modulated lasers, as well as different laser spectral widths. Refer to Tables 4.2, 4.3, and 4.4 for typical examples.

Long reach transceivers commonly use directly modulated DFB (DML-DFB) lasers. This amplitude modulation technique is simple, low cost, and is currently available for transmission rates up to 10 Gbps. Unfortunately, DML-DFB lasers suffer from laser chirp, which decreases the chromatic dispersion limit for standard G.652 fiber significantly, see Tables 4.2 and 4.4. There may be an advantage<sup>9</sup> in using negative dispersion fiber (–D) NZ-DSF with these chirped lasers. It has been shown<sup>10</sup> that DML-DFB chirped laser transmission over negative dispersion fiber can result in longer dispersion limits.<sup>11</sup> Using Eq. (1.54), we can estimate chirped DFB laser pulse broadening effects for (–D) NZ-DSF where chromatic dispersion coefficient at 1550 nm is –7 ps/(nm  $\cdot$ km) and for standard NZ-DSF where chromatic dispersion coefficient at 1550 nm is 7 ps/(nm  $\cdot$ km). Figure 4.7 shows a significant advantage in using (–D) NZ-DSF with negative chirp DFB



**FIGURE 4.7** Chirped pulse broadening as a function of normalized fiber distance for (–D) NZ-DSF fiber.

Bit Rate (Gbps)	Distance Limit (+D) NZ-DSF G.655 Fiber 7 ps/(nm·km) DML-DFB Chirp (km)	Distance Limit (-D) NZ-DSF G.655 Fiber -7 ps/(nm·km) DML-DFB Chirp (km)	Distance Limit (+D) NZ-DSF G.655 Fiber +7 ps/(nm · km) Zero Chirp (km)	Distance Limit G.652 fiber 17 ps/(nm·km) DML-DFB Chirp (km)
2.5	250	1111	2688	103
10	15	69	168	6
40	1	4	10.5	0.4
100	0.16	0.7	1.7	0.06

 TABLE 4.6
 Estimated Chromatic Dispersion Limits for Chirped and Unchirped

 DFB Lasers
 DFB Lasers

lasers where  $C_0 = -5$ . It also shows that a laser with no chirp (externally modulated) produces the furthest dispersion limit distance. Note, the laser chirp alpha parameter is  $a_c \approx 5$ , refer to Eq. (1.51).

Using Eq. (4.49) we estimate DFB chirped laser limits for (+/–D) NZ-DSF fiber, see Table 4.6. The DFB laser chirp parameter used is  $C_0 = -5$  and power penalty is 1 dB.

Table 4.6 shows that the longest dispersion limit distance is achieved when zero chirped lasers are deployed. However in the absence of this laser type, standard DML-DFB lasers produce better results over negative NZ-DSF. A possible application for (–D) NZ-DSF is in metro fiber networks. Extended dispersion limits for high data rate transmissions may be achieved by using standard lower cost DML-DFB lasers.

Frequency chirp is controlled and reduced by using more costly externally modulated DFB (EML-DFB) lasers. Current EML technologies use lithium niobate based (LiNbO<sub>3</sub>) Mach-Zehnder modulators (MZM) or indium phosphide based (InP) electro absorption modulators (EAM). With EML technology the DFB lasers acts as a continuous wave light source whose output is directed into the external modulator unit to be amplitude modulated. Chirp is produced but is low and can be controlled to positive, negative, or zero values. The positive value may be advantageous in extending the dispersion limit with G.652 fiber. As can be seen in Tables 4.2, 4.4, and 4.6, chirp-free transmission results in much longer dispersion limits than chirped transmissions.

#### 4.3.3 Factors That Contribute to Chromatic Dispersion

Factors contributing to increasing chromatic dispersion signal distortion include the following:

1. Laser spectral width, modulation method, and frequency chirp. Lasers with wider spectral widths and chirp have shorter

dispersion limits. It is important to refer to manufacturer specifications to determine the total amount of dispersion that can be tolerated by the lightwave equipment.

- 2. The wavelength of the optical signal. Chromatic dispersion varies with wavelength in a fiber. In a standard non-dispersion shifted fiber (NDSF G.652), chromatic dispersion is near or at zero at 1310 nm. It increases positively with increasing wavelength and increases negatively for wavelengths less than 1310 nm, see Fig. 4.5.
- 3. The optical bit rate of the transmission laser. The higher the fiber bit rate, the greater the signal distortion effect.
- 4. The chromatic dispersion characteristics of fiber used in the link. Different types of fiber have different dispersion characteristics, see Fig. 4.5.
- 5. The total fiber link length, since the effect is cumulative along the length of the fiber.
- 6. Any other devices in the link that can change the link's total chromatic dispersion including chromatic dispersion compensation modules.
- 7. Temperature changes of the fiber or fiber cable can cause small changes to chromatic dispersion. Refer to the manufacturer's fiber cable specifications for values.

### 4.3.4 Methods to Reduce Link Chromatic Dispersion

Methods to reduce link chromatic dispersion are as follows:

- 1. Change the equipment laser with a laser that has a specified longer dispersion limit. This is typically a laser with a more narrow spectral width or a laser that has some form of precompensation. As laser spectral width decreases, chromatic dispersion limit increases.
- 2. For new construction, deploy NZ-DSF instead of SSMF fiber. NZ-DSF has a lower chromatic dispersion specification.
- Insert chromatic dispersion compensation modules (DCM) into the fiber link to compensate for the excessive dispersion. The optical loss of the DCM must be added to the link optical loss budget and optical amplifiers may be required to compensate.
- 4. Deploy a 3R optical repeater (re-amplify, reshape, and retime the signal) once a link reaches chromatic dispersion equipment limit.
- 5. For long haul undersea fiber deployment, splicing in alternating lengths of dispersion compensating fiber can be considered.
- 6. To reduce chromatic dispersion variance due to temperature, buried cable is preferred over exposed aerial cable.

# 4.4 Planning a Chromatic Dispersion Budget

#### 4.4.1 Total Link Chromatic Dispersion

To plan a chromatic dispersion budget, total fiber link dispersion must first be determined. Fiber link components (such as certain WDMs) added to a fiber link may contribute to the total link dispersion. Therefore, all link component specifications should be reviewed to ensure they have negligible or zero chromatic dispersion effect. DCMs add negative or positive chromatic dispersion for fiber compensation requirements and need to be included in the total chromatic dispersion budget. Second-order PMD, can increase or decrease chromatic dispersion in a fiber link, should also be included. Since chromatic dispersion increases linearly along a fiber link, the total chromatic dispersion of a fiber link is the sum of all fiber and other chromatic dispersion contributions, as shown in Eqs. (4.50) and (4.51).

Because chromatic dispersion is wavelength dependent, the total link dispersion should be calculated at the operating wavelength or wavelength range (for DWDM/CWDM systems) of the transmission equipment.

Equation (4.54) estimates total chromatic dispersion using fiber specified chromatic dispersion coefficient and Eq. (4.55) determines total chromatic dispersion using measured fiber values. Fiber specification sheets will list the fiber chromatic dispersion coefficient with units  $ps/(nm \cdot km)$ . The fiber link chromatic dispersion can be estimated by multiplying the chromatic dispersion coefficient by the fiber link length as shown in Eq. (4.54).

$$CD_{tot} = \sum_{i} (L_{i} \times CD_{ci}) + CD_{DCM} + CD_{other}$$
(4.54)

$$CD_{tot} = \sum_{i} CD_{fi} + CD_{DCM} + CD_{other}$$
(4.55)

where CD<sub>tot</sub> = fiber link total chromatic dispersion, ps/nm

- $CD_{ci}$  = chromatic dispersion coefficient of the *i*'th cable section from cable specifications, ps/(nm·km)
- CD<sub>fi</sub> = chromatic dispersion of the *i*'th fiber cable section from cable specifications or measurement, ps/nm
- $CD_{DCM}$  = dispersion compensation module CD, ps/nm
- CD<sub>other</sub> = chromatic dispersion due to other components or effects, ps/nm
  - $L_i$  = length of the *i*'th cable section, km

#### 4.4.2 Chromatic Dispersion Compensation Modules

Chromatic dispersion compensation modules (DCM), also known as dispersion compensation units (DCU), can be added to an existing fiber link to compensate for high link dispersion totals, see Eq. (4.54). These DCM are made of various spool lengths of dispersion compensating fiber (DCF). Their negative chromatic dispersion characteristics compensate for the transmission fiber's positive dispersion. The modules are typically specified by what length, in km, of standard G.652 fiber will be compensated or by the total dispersion compensation over a specific wavelength range, in ps/nm. The following considerations should be reviewed when deploying DCF compensation modules.

- 1. DCF typically has high fiber attenuation and therefore the insertion loss will be high. Optical amplification may be required to compensate for the DCM optical loss.
- 2. The effective core area of a DCF is much smaller than standard transmission fiber such as G.652; consequently DCF experience much higher nonlinear signal distortions. Lowering DCF optical power can help to reduce this nonlinear effect.
- 3. DCF adds polarization mode dispersion (PMD) to the link, which needs to be considered in PMD budgets.

A DCM that contains chirped fiber Bragg gratings instead of long spools of DCF fiber are also available. William Lawrence Bragg was a physicist who in 1913 discovered that a change of a material's refractive index resulted in a small amount of X-ray wavelengths to be reflected. Then in 1978 at the Canadian Research Council (CRC), K.O. Hill demonstrated the first in fiber Bragg grating. A short length of fiber with a periodic change in its refractive index (known as a grating) works as a highly reflective mirror to a narrow band of wavelengths and passes all other wavelengths. The distance between two adjacent maximum values of the refractive index is referred to as the grating period. The fiber grating reflects a narrow spectrum of wavelengths centered at  $\lambda_{B}$  and passes all the others,<sup>12</sup> see Eq. (4.56).

$$\lambda_{B} = 2\Lambda n_{g} \tag{4.56}$$

where 
$$\lambda_{B}$$
 = reflected wavelength, nm

 $\Lambda$  = grating period, nm

 $n_{o}$  = fiber's effective group refractive index

Chirped means that the fiber grating period changes linearly over the length of the grating with the shorter grating period located at the



FIGURE 4.8 Chirped fiber Bragg grating wavelength delay.

beginning of the grating. This allows for shorter signal wavelengths to be reflected sooner and have less propagation delay through the unit. Longer signal wavelengths travel further into the fiber grating before they are reflected and therefore have more propagation delay through the unit. This is the exact opposite of fiber chromatic dispersion and therefore helps reverse pulse spreading due to fiber dispersion, see Fig. 4.8. The length of the chirped fiber grating is typically between 10 and 100 cm.

The advantage in deploying the fiber Bragg grating DCMs is in their lower insertion loss and higher power handling capabilities without signal nonlinear effects concerns. However, fiber Bragg grating channel bandwidth is narrow, and proper DWDM lasers must be used for their deployment. Fiber Bragg gratings also add PMD to the link, which needs to be considered in PMD budgets. These modules are typically specified by what length of standard G.652 fiber will be compensated or by the total dispersion compensation over a wavelength range, in ps/nm.

DCMs are available with many different compensation values and specifications. It is important to refer to the manufacturer DCM specifications in order to select the proper DCM for your network.

#### 4.4.3 Chromatic Dispersion Compensation

To determine if chromatic dispersion compensation is required for a fiber cable link, lightwave equipment manufacturer specifications need to be reviewed and chromatic dispersion limits noted. Chromatic dispersion is wavelength, transmission rate, and laser dependent; therefore, chromatic dispersion specification for the specific laser module that will be deployed should be used for the equipment chromatic dispersion limit value. Next, the total fiber link chromatic dispersion should be calculated from the fiber cable specification sheets or should be obtained from field measurements, as shown in the previous section.

The total link chromatic dispersion should be compared to the equipment dispersion limit. If total dispersion is exceeded, compensation is required or dispersion needs to be reduced, see Sec. 4.3.

$$\begin{split} |CD_{tot}| &\leq |CD_{equip}| \\ CD_{+tot} &\leq CD_{+equip} \\ CD_{+tot} &\geq CD_{-equip} \\ CD_{-tot} &\leq CD_{+equip} \\ CD_{-tot} &\geq CD_{-equip} \end{split}$$
(4.57)

where  $CD_{tot} = total fiber link chromatic dispersion, ps/nm$   $CD_{+tot} = positive total fiber link chromatic dispersion, ps/nm$   $CD_{-tot} = negative total fiber link chromatic dispersion, ps/nm$   $CD_{equip} = equipment chromatic dispersion limit, ps/nm$   $CD_{+equip} = positive equipment chromatic dispersion limit, ps/nm$  $CD_{-equip} = negative equipment chromatic dispersion limit, ps/nm$ 

Typically, for most fiber links, the cumulative chromatic dispersion is positive and therefore negative dispersion modules are added to compensate. Total chromatic dispersion in a fiber link is equal to the sum of all fiber section and component dispersion values, see Eq. (4.55).

$$CD_{tot} = \sum_{i} CD_{fi} + CD_{DCM} + CD_{other}$$

Equipment dispersion limit can be rewritten as below.

$$|CD_{equip}| \ge \sum_{i} CD_{fi} + CD_{DCM} + CD_{other}$$
 (4.58)

It is important not to reduce the chromatic dispersion to zero in the fiber link due to the increase in fiber nonlinear distortions at zero. Fiber nonlinear distortions are reduced by fiber chromatic dispersion.

**Example 4.1** A 10 Gbps, single wavelength, 1550 nm transmission system is planned to be installed on a fiber cable link of 100 km. The fiber cable link uses standard NDSF. How much chromatic dispersion compensation is required? The 10 Gbps lightwave equipment specifications are as follows:

 Tx power:
 4.0 dBm 

 Rx sensitivity (@ BER  $10^{-12}$ ):
 -29.0 dBm 

 Equipment CD limit:
 +/-1000 ps/nm 

 Rx CD power penalty:
 2.0 dB 

First, one must determine the fiber cable link values. For the standard NDSF cable, the fiber specifications are known to be as follows:

Fiber specified attenuation at 1550 nm:	0.21 dB/km
CD <sub>c</sub> at 1550 nm:	+18.0 ps/(nm km)
Other losses (connectors, splices, etc.):	1.5 <sub>dB</sub>

Fiber link optical loss is calculated as:

$$\Gamma_{\rm tot} = \alpha_{\rm dB} \times L + \Gamma_{\rm other} \tag{4.59}$$

where  $\Gamma_{tot} = \text{total fiber link optical loss, dB}$ 

 $\alpha_{dB}$  = specified fiber cable attenuation, dB/km

L = fiber link length, km

 $\Gamma_{other}$  = total of all other fiber losses such as connector and splice, dB

$$\Gamma_{\rm tot} = 0.21_{\rm dB/km} \times 100_{\rm km} + 1.5_{\rm dB}$$

$$\Gamma_{\rm tot} = 22.5_{\rm dB}$$

Fiber link chromatic dispersion is calculated from Eq. (4.11) as:

$$CD_{f} = CD_{c} \times L$$

$$CD_{f} = +18.0_{\text{ps/(nm km)}} \times 100_{\text{km}}$$

$$CD_{f} = +1800_{\text{ps/nm}}$$

Since the fiber link total dispersion of 1800 ps/nm is greater than the chromatic dispersion limit for the equipment of 1000 ps/nm, chromatic dispersion compensation is required.

The amount of dispersion compensation required to compensate for the positive equipment limit is as follows, see Eq. (4.58):

$$CD_{equip} \ge CD_{f} + CD_{DCM}$$

$$CD_{DCM} \le CD_{+equip} - CD_{f}$$

$$CD_{DCM} \le 1000_{ps/nm} - 1800_{ps/nm}$$

$$CD_{DCM} \le -800_{ps/nm}$$

For the negative equipment limit, the amount of dispersion compensation is as follows:

$$CD_{DCM} \ge CD_{-equip} - CD_{f}$$
$$CD_{DCM} \ge -1000_{ps/nm} - 1800_{ps/nm}$$
$$CD_{DCM} \ge -2800_{ps/nm}$$

Total DCM compensation needs to be in the range as follows:

 $-2800_{ps/nm} \le CD_{DCM} \le -800_{ps/nm}$ 

If -500 ps/nm DCM with 3 dB insertion loss per module are available, two of these modules can be inserted into the fiber link to reduce total link dispersion to an acceptable level of +800 ps/nm.

$$CD_{tot} = CD_{DCM} + CD_{f}$$
$$CD_{tot} = 2(-500_{ps/nm}) + 1800_{ps/nm}$$
$$CD_{tot} = +800_{ps/nm}$$

New fiber link total optical loss including DCMs is as follows:

$$\Gamma_{tot} = \Gamma_{DCM} + \Gamma_{tot.old}$$

$$\Gamma_{tot} = 6_{dB} + 22.5_{dB} \qquad (4.60)$$

$$\Gamma_{tot} = 28.5_{dB}$$

This is the total fiber span loss that can be measured by an optical power meter.

To calculate receiver signal power the chromatic dispersion penalty needs to be included as follows: (Note, the dispersion penalty loss cannot be measured by an optical power meter.)

$$P_{\rm in} = P_{\rm out} - \Gamma_{\rm tot} - \Gamma_{\rm CD} \tag{4.61}$$

where  $\Gamma_{tot}$  = total fiber optical loss including DCMs, dB

 $\Gamma_{\text{totold}}$  = previous total fiber optical loss not including DCMs, dB

 $\Gamma_{CD}$  = receiver chromatic dispersion power penalty, dB

 $\Gamma_{\text{DCM}}^{\text{C}} = \text{DCM optical loss, dB}$   $P_{\text{in}}^{\text{in}} = \text{minimum receiver optical power, dBm}$   $P_{\text{out}}^{\text{in}} = \text{minimum laser output optical power, dBm}$   $P_{\text{rx}}^{\text{rx}} = 4_{\text{dBm}} - 28.5_{\text{dB}} - 2_{\text{dB}}$   $P_{\text{rx}}^{\text{rx}} = -26.5_{\text{dBm}}$ 

The calculated optical receive power of -26.5 dBm is stronger than the minimum receiver sensitivity specification of -29 dBm and therefore this plan can produce a 1550 nm 10 Gbps transmission system with a BER 10<sup>-12</sup> or better.

#### 4.4.4 Compensation for DWDM Networks

For dispersion compensation in links that carry DWDM wavelengths, the chromatic dispersion across the entire operating DWDM band needs to be compensated equally. This is accomplished by matching chromatic dispersion and dispersion slope of the link fiber with the dispersion compensating fiber (DCF).<sup>13</sup> A parameter called relative dispersion slope (RDS) is used in these calculations. RDS is defined as the ratio of the chromatic dispersion slope to the chromatic dispersion at the 1550 nm wavelength. For good compensation, the RDS of the transmission fiber should equal the RDS of the compensating fiber. See Table 4.5 for typical fiber RDS values.

$$RDS_f = \frac{S_f}{CD_f}$$
(4.62)

$$RDS_{DCF} = \frac{S_{DCF}}{CD_{DCF}}$$
(4.63)

where  $RDS_f = fiber relative dispersion slope at 1550 nm, nm<sup>-1</sup>$   $S_f = fiber chromatic dispersion slope at 1550 nm, ps/nm<sup>2</sup>$   $CD_f = fiber chromatic dispersion at 1550 nm, ps/nm$   $RDS_{DCF} = DCF$  relative dispersion slope at 1550 nm, nm<sup>-1</sup>  $S_{DCF} = DCF$  chromatic dispersion slope at 1550 nm, ps/nm<sup>2</sup>  $CD_{DCF} = DCF$  chromatic dispersion at 1550 nm, ps/nm<sup>2</sup>

The dispersion slope compensation ratio (DSCR) provides an indication of how well the dispersion is compensated. If the RDS of the transmission fiber is the same as the DCF (or DCF module) then the DSCR is 100%, which provides for the best compensation.

$$DSCR = \frac{RDS_{DCF}}{RDS_{f}} \times 100$$
(4.64)

where DSCR is the dispersion slope compensation, %.

If DSCR is not 100%, there will be an uneven increase in accumulated dispersion across the compensated band and some DWDM wavelengths may exceed the chromatic dispersion acceptable level.

**Example 4.2** For a newly planned 10 Gbps, C-band, DWDM system to be added to an existing 70 km length of SSMF/cable, how much chromatic dispersion compensation will be required?

The 10 Gbps lightwave equipment specifications are as follows:

Tx power:	4.0 dBm
Rx sensitivity (@ BER 10 <sup>-12</sup> ):	–27.0 dBm
Equipment CD limit:	+/-1000 ps/nm
Rx CD power penalty:	2.0 dB

Fiber specifications are as follows:

Fiber loss at 1550 nm:	0.21 dB/km
Other losses (connectors, splices, etc.):	1.5 dB
CD <sub>c</sub> at 1550 nm:	+18.0 ps/(nm · km)
CD slope at 1550 nm:	$0.058 \text{ ps}/(\text{nm}^2 \text{ km})$
RDS at 1550 nm:	0.0032 nm <sup>-1</sup>

To determine if dispersion compensation will be required we calculated fiber dispersion at 1550 nm using Eq. (4.11).

$$CD = CD_{c} \times L$$
$$CD = +18.0_{ps/(nm \cdot km)} \times 70_{km}$$
$$CD = +1260_{ps/nm}$$

Therefore +1260 ps/nm is higher than the optics dispersion limit of 1000 ps/nm and chromatic dispersion compensation will be required.

To match the fiber dispersion slope across the 1550 nm DWDM band, we will need to compensate with a DCM that has an RDS of  $0.0032 \text{ nm}^{-1}$ . A C-band DCM was found to have the same DCF RDS, with chromatic dispersion of -400 ps/nm and insertion loss of 3 dB.

$$DSCR = \frac{RDS_{DCF}}{RDS_{f}} \times 100$$
$$DSCR = \frac{0.0032}{0.0032} \times 100$$
$$DSCR = 100\%$$

The total link chromatic dispersion after the DCM module is added is calculated from Eq. (4.55) as follows:

$$CD_{tot} = CD_{DCM} + CD$$
$$CD_{tot} = -400_{ps/nm} + 1260_{ps/nm}$$
$$CD_{tot} = +860_{ps/nm}$$

With this module added to the link, the link total dispersion is +860 ps/nm, which is within acceptable limits for this optical equipment across the DWDM band.

We calculate the link optical budget, Eq. (4.59) as follows:

$$\begin{split} &\Gamma_{\rm tot} = A \times L + \Gamma_{\rm other} \\ &\Gamma_{\rm tot} = 0.21_{\rm dB/km} \times 70_{\rm km} + 1.5_{\rm dB} + 3_{\rm dB} \\ &\Gamma_{\rm tot} = 19.2_{\rm dB} \end{split}$$

Calculate receive level, Eq. (4.61), as follows.

$$P_{in} = P_{out} - \Gamma_{tot} - \Gamma_{CD}$$
$$P_{in} = 4_{dBm} - 19.2_{dB} - 2_{dB}$$
$$P_{in} = -17.2_{dBm}$$

Receive level of -17.2 dBm is within acceptable limits for this equipment.

## 4.4.5 Deploying DCMs

A DCM is typically deployed at the beginning or end of a fiber span to manage the chromatic dispersion. The following pointers should be considered when planning DCM deployment:

- 1. Do not exceed DCM maximum allowable input optical power.
- 2. Include the chromatic dispersion optical power penalty in optical budget plans.
- 3. Include DCM insertion loss in optical budget plans.
- 4. Optical amplifiers do not increase or decrease chromatic dispersion.
- 5. To minimize nonlinear distortion effects, maintain a small amount of residual dispersion in every span.
- 6. For 40 Gbps and higher systems, consider span pre-compensation to minimize intrachannel nonlinear effects.

Two plans for DCM placements in a fiber and EDFA link are called post-compensation and pre-compensation deployments, see Figs. 4.9 and 4.10. Since DCMs are considered part of the transmission line, the prefixes "post-" (after) and "pre-" (before) refer to the section of the transmission line that requires the compensation. For the post-compensation DCM deployment, DCMs are placed after the fiber span that needs the compensation as shown in Fig. 4.9. For G.652 fiber compensation, dispersion remains positive throughout the link. For the pre-compensation DCM deployment, DCMs are placed before the fiber span that needs the compensation as shown in Fig. 4.10. For G.652 fiber compensation dispersion remains negative throughout the link.

Figures 4.9 and 4.10 show DCM modules placed immediately before or after optical amplifiers. Both methods are acceptable since optical amplifiers do not add dispersion into the link provided that the DCM maximum power specifications are not exceeded. Placing DCMs after the optical amplifier can reduce link OSNR, but may increase nonlinear distortions due to high power levels if DCMs use DCF fiber. DCF fiber is more susceptible to nonlinear effects due to its smaller core area. Optical amplifiers are available with intermediate stage access designed to accept DCM connections. This allows for dispersion compensation with less impact on the link loss, OSNR, and nonlinear distortions.

A DCM is placed in a fiber span in order to reduce chromatic dispersion to an acceptable level at the end of the span that is below the transceiver's dispersion limit. The remaining dispersion is referred to as the net residue dispersion. For multiple span links, DCMs are placed at EDFA locations with values that result in two dispersion compensation schemes called full optimized compensation scheme


FIGURE 4.9 Post-compensation DCM deployment dispersion map.

(FOCS) and distributed under compensation scheme (DUCS), see Fig. 4.9*a* and *b*. The difference between the two schemes is the amount of span residual dispersion that remains at the end of each span. FOCS results in zero span residue and DUCS results in some amount of remaining span residue. Although both schemes result with the same net residual dispersion at the end of the link, the DUCS method is known to be better for also reducing nonlinear effects. Refer to Chap. 7 for more details and optimum compensation levels.

There is also evidence<sup>14</sup> that supports the deployment of precompensation DCM to reduce intrachannel cross-phase modulation (IXPM) and intrachannel four wave mixing (IFWM) interference for systems with transmission rates of 40 Gbps and above. Pre-compensation would result in a symmetrical dispersion map, which helps in the cancellation of in-phase components and thereby improves transmission



FIGURE 4.10 Pre-compensation DCM deployment dispersion map.

BER. Figure 4.9 shows a typical asymmetric dispersion map, where the DCMs are deployed at the middle and end of a link. This configuration is often used with SSMF fiber to effectively compensate dispersion and nonlinear effects. Figure 4.11 shows a symmetric dispersion map created when DCMs are placed at the beginning and the end of a fiber span. Pre-compensation DCM dispersion value to reduce intrachannel interference for SSMF can be estimated<sup>15,16</sup> as follows:

$$CD_{pre-DCM} = -\frac{N \times CD_{res}}{2} - \frac{CD_c}{\alpha_0} \ln\left(\frac{2}{1 + \exp(-\alpha_0 L_{span})}\right)$$
(4.65)

where  $CD_{pre-DCM} = pre-compensation DCM value, ps/nm$   $CD_{res} = span residual dispersion, see Fig. 4.9, ps/nm$   $CD_c = fiber dispersion coefficient, ps/(nm km)$  N = number of spans, assuming all spans are the same length  $L_{span} = fiber span length, km$  $\alpha_0 = fiber attenuation constant, km^{-1}$ 

#### 4.5 Chromatic Dispersion Measurement Methods

Chromatic dispersion is a property of a fiber and is stable over time. Therefore consistent repeatable measurements with good accuracy are possible over a fiber link. Three common methods are currently



FIGURE 4.11 Symmetric dispersion map.

used in measuring chromatic dispersion in a fiber link: time of flight, modulated phase shift, and differential phase shift.

#### 4.5.1 The Time of Flight Method

The time of flight method (FOTP-168)<sup>17</sup> directly measures the relative group delay between the pulses of different wavelengths of light. It requires a tunable wavelength laser source, pulse generator, and an accurate receiver that can measure group delay of short spectral pulses, as shown in Fig. 4.12.

To determine the chromatic dispersion, measurements of pulse group delays are recorded over numerous wavelengths and then a five-term Sellmeier equation is fitted to the result, see Eq. (4.66).

$$\tau = a\lambda^4 + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e \tag{4.66}$$

where

 $\tau$  = measured pulse delay at a center wavelength  $\lambda$ , ps  $\lambda$  = pulse center wavelength, nm a,b,c,d,e = fitting coefficients

The first derivative (slope) of this relative group delay equation with respect to wavelength provides the chromatic dispersion across the measured wavelength band, see Eqs. (4.4) and (4.67), and Fig. 4.2.



FIGURE 4.12 Time of flight method (FOTP-168) block diagram.

$$CD = \frac{d\tau}{d\lambda}$$
(4.67)

where CD = chromatic dispersion, ps/nm

 $d\tau$  = measured relative group delay at a wavelength  $\lambda$ , ps

 $d\lambda$  = measured incremental wavelength, nm

Accuracy using this method depends on the number of wavelengths tested, fitting equation type, pulse width, fiber length, and accuracy of the receiver. This method is not commonly used for field measurements. The following table summarizes the advantages and disadvantages of this method.

Time of Flight Method		
Advantage	Disadvantages	
Does not require communications link between test equipment at both ends of fiber	Lower accuracy, especially in fiber lengths less than a few km	
	Chromatic dispersion not directly measured	
	Test equipment required at both ends of fiber	
	Difficult to measure through optical amplifiers	

#### 4.5.2 The Time of Flight–OTDR Method

The time of flight—OTDR method is similar to the time of flight method (FOTP-168) in determining chromatic dispersion except it uses an OTDR at one end of the fiber for the test. At the other end of the fiber a good reflective fiber end is required, such as an open connector, to produce strong reflections for good readings, as shown in Fig. 4.13. The OTDR launches short pulses into the fiber over three or four wavelengths (typically 1310, 1410, 1550, and 1625 nm) and measures the elapsed time between the reflected pulses, as shown in Fig. 4.14.

The total elapsed time measured for the reflected pulses must be divided by two in order to account for the light pulse traveling twice the fiber length. The fiber length is determined by the OTDR from the pulse delay using the formula below:

$$L = \frac{\tau_{2L}c}{2n_g} \tag{4.68}$$

where L =length of the fiber under test, km

- $\tau_{2L}$  = elapsed time of reflected pulse for both directions at wavelength, s
  - c = velocity of light in a vacuum, 299,792,458 m/s
- n<sub>o</sub> = fiber's effective group index of refraction at wavelength

The pulse delay of different wavelengths is measured. The results are fitted with an appropriate curve, as shown in Fig. 4.2. A three-term



FIGURE 4.13 Time of flight—OTDR method block diagram.



FIGURE 4.14 OTDR trace to determine chromatic dispersion pulse delay.

Sellmeier equation or parabolic equation is typically used for fitting the curve. Equation (4.69) shows a three-term Sellmeier equation and Eq. (4.70) is a parabolic equation.

$$\tau = a\lambda^2 + b\lambda^{-2} + c \tag{4.69}$$

$$\tau = a\lambda^2 + b\lambda + c \tag{4.70}$$

#### where $\tau$ = measured pulse delay at a center wavelength $\lambda$ , ps $\lambda$ = pulse center wavelength, nm a,b,c = fitting coefficients

The derivative of this curve with respect to wavelength provides the chromatic dispersion across the measured wavelength band, see Eq. (4.67).

If the end of the fiber provides a poor reflection such as with an angle connector or broken fiber, the fiber length is too long, or the loss is too high, then measurements using this method may not be possible. The following table summarizes the advantages and disadvantages of this method.

#### 4.5.3 Modulated Phase Shift Method

Modulated phase shift method (standard FOTP-169) and differential phase shift method (standard FOTP-175) are techniques, where wavelengths of laser light are intensity modulated at a frequency of typically 10 MHz to 2 GHz. The phase shift of the modulated light at the far end of the fiber is compared to a reference source and the delay due to CD is computed.

The modulated phase shift method is accurate but takes longer to complete. The test system consists of a tunable laser that is intensity modulated at one end of the fiber and an optical receiver with a phase comparator at the other end, as shown in Fig. 4.15. As the laser wavelength is stepped in small increments across the test band, the

Time of Flight—OTDR Method		
Advantages	Disadvantages	
Requires measurement from only one end of fiber	Lower accuracy, especially in fiber lengths less than a few km	
Requires only one test instrument at one end of the fiber, typically a dual purpose OTDR/CD tester	Not a direct dispersion measurement	
Less training needed for test technician	Limited accuracy because only three or four wavelengths are measured (typically 1310, 1410, 1550, and 1625 nm)	
Easier procedure to administer	Will not work through DWDMs	
Fiber length is also provided	Cannot measure through optical amplifiers and other non-bidirectional components	
	If a low reflection fiber end is encountered (e.g., a broken fiber or fiber terminated with an angled connection), a highly reflective end must be added to perform the measurement	
	Fiber lengths limited by OTDR dynamic range at 1310 nm	
	Measurements are typically for fiber lengths between 2 and 100 km	
	Accurate value of the fiber's group index of refraction $(n_g)$ at the measured wavelength must be entered into the OTDR	
	Due to insufficient test wavelengths, a five-term Sellmeier equation cannot fit, which further reduces accuracy	

receiver directly measures the change in phase of the modulate light as compared to the reference signal. The optical signal relative group delay for each wavelength increment can be calculated by the test system computer as follows:

$$\Delta \tau = \frac{\Delta \phi_{\text{shiftref}}}{360 f_{\text{mod}}} \times 10^{12}$$
(4.71)

where

 $\Delta \tau$  = incremental relative group delay, ps

 $\Delta \Phi_{\text{shiftref}}$  = measured phase change in degrees of modulated test signal compared to reference signal at the receiver, degrees

 $f_{\rm mod}$  = modulation frequency, Hz



FIGURE 4.15 Modulated phase shift method block diagram.

A curve such as the five-term Sellmeier equation is fitted to the relative group delay result, see Eq. (4.66). The chromatic dispersion can be determined by differentiating the group delay curve as shown in Eq. (4.67).

$$CD = \frac{d\tau}{d\lambda}$$

The advantages and disadvantages of this method are summarized in the following table.

Modulated Phase Shift Method		
Advantages	Disadvantages	
High accuracy due to fixed reference signal	Takes longer than differential phase shift method	
Delay can be resolved to 0.001 ps	Test equipment required at both ends of fiber	
Wavelength steps can be reduced to less than 0.1 nm with excellent accuracy	Communications reference fiber is required	
Can measure through optical amplifiers and other non-bidirectional components	Expensive	
High-accuracy measurements for narrow band components such as Bragg gratings and DWDM		

#### 4.5.4 Differential Phase Shift Method

Differential phase shift method measurement is similar to modulated phase shift method except that it allows chromatic dispersion to be determined directly from the detected signal. As in the modulated phase shift method, the signal amplitude is modulated; however, the wavelength is also modulated around a central wavelength, where the relative group delay is to be measured. The detected signal not only has a phase difference from the modulated signal (compared to the reference signal) but also has a small wavelength difference that allows the dispersion to be calculated directly by Eq. (4.72)

$$CD = \frac{\Delta \phi_{\text{shift }\lambda}}{360 f_{\text{mod}} \times \Delta \lambda} \times 10^{12}$$
(4.72)

where CD = chromatic dispersion at wavelength, ps/nm  $\Delta \Phi_{shift\lambda} = measured phase change in degrees of modulated test signal over a small wavelength interval <math>\Delta \lambda$ , degrees  $\Delta \lambda =$  wavelength interval, nm  $f_{mod} =$  modulation frequency, Hz

The advantages and disadvantages of this method are summarized in the table below.

Differential Phase Shift Method		
Advantages	Disadvantages	
Faster results	Larger wavelength steps are required to increase accuracy	
Good accuracy	Test equipment required at both ends of fiber	
Can measure through optical amplifiers and other non- bidirectional components	Communications reference fiber is required	
	Expensive	

#### 4.6 Chromatic Dispersion Planning Summary

During the planning stages of any optical transmission system, determine if chromatic dispersion budget planning is required, refer to Sec. 4.3.1. If not, proceed with equipment installation as recommended by the equipment manufacturer. If planning is required then follow these simple steps to determine chromatic dispersion requirements for system implementation.

1. Determine the fiber cable total chromatic dispersion from direct link measurements (preferable) or from calculations using cable and equipment specifications as described in Sec. 4.4.1. Include all components that may contribute to chromatic dispersion.

- 2. Compare total link chromatic dispersion to equipment tolerable chromatic dispersion and if greater, determine appropriate course of action as indicated in Sec. 4.4.3.
- 3. Include chromatic dispersion power penalty in optical power budget calculations.

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## CHAPTER 5 Polarization Mode Dispersion

#### 5.1 Description

Polarization mode dispersion (PMD) is a property of a single-mode fiber or an optical component where pulse spreading is caused by different propagation velocities of the signal's two orthogonal polarizations. Optical fibers or optical components can be modeled with two orthogonal polarization axes called principal states of polarization (PSP). An optical signal propagating in a fiber is resolved into these two PSP axes. Each polarization axis (fast and slow axis) has a different propagation velocity. This is due to different refractive indexes in each axis caused by the birefringence of the material. The different velocities lead to pulse spreading at the receiver end because optical receivers are insensitive to polarization of incident light, as shown in Fig. 5.1. The amount of pulse spreading in time between the two polarization pulses is referred to as differential group delay (DGD) and is measured in units of picoseconds. Note, the time it takes for a pulse to propagate in a fiber is referred to as the group delay. DGD is an instantaneous value that varies randomly along the length of a fiber. PMD is defined as the linear average of many instantaneous differential group delay values over a wavelength region  $\langle DGD \rangle_{\lambda}$  or as the root-means-square (RMS) average of instantaneous differential group delay values over a wavelength region  $\sqrt{\text{DGD}^2}$ , see Fig. 5.3. PMD is measured in units of picoseconds (ps). For long fibers (>2 km) the linear average and RMS average values are similar. The following equation relates these two averages.<sup>1</sup>

$$PMD_{rms} = \sqrt{\frac{3\pi}{8}} PMD_{ave}$$
(5.1)

 $PMD_{rms} = 1.085 PMD_{ave}$ 

where PMD<sub>rms</sub> = PMD root-means-square value, ps PMD<sub>ave</sub> = PMD linear average value, ps



FIGURE 5.1 DGD of a fiber optical pulse.

As the optical pulse travels along the fiber, random changes in fiber local birefringence cause some optical pulse power to be coupled from one mode to the other. This is referred to as *mode coupling*. Experiments have shown that long fibers (>2 km) have strong mode coupling that results in the fiber PMD being proportional to the square root of the fiber length.<sup>2</sup> Therefore, PMD can be expressed as the square root of the fiber length multiplied by a proportionality coefficient, see Eq. (5.2). This coefficient is referred to as the PMD coefficient and is measured in units of picoseconds per square root kilometer (ps/ $\sqrt{km}$ ). The PMD coefficient is typically specified by fiber cable manufacturers and represents the PMD characteristic for a particular length of that fiber. Often the PMD coefficient is referred to as PMD, which can cause confusion regarding these two terms.

$$PMD = PMD_c \times \sqrt{L}$$
(5.2)

where PMD = polarization mode dispersion ps, for the fiber length *L* PMD<sub>c</sub> = polarization mode dispersion coefficient, ps/ $\sqrt{km}$ *L* = fiber length, km

Due to this pulse spreading, PMD can cause intersymbol interference that results in signal bit errors. This effect is small and therefore need only to be considered for fiber systems with short bit periods where transmission rates are greater than or equal to 10 Gbps. It also should be considered for analog fiber systems due to its contribution in increasing signal distortion and decreasing OSNR. PMD seems to be the worst in older fiber cable plants possibly due to poorer fiber manufacturing tolerances.

#### 5.2 Causes of DGD

DGD occurs because of the fiber's birefringence that is due to internal and external stress on the fiber as well as imperfect manufacturing processes. In an ideal fiber, the fiber core geometry is perfectly circular



FIGURE 5.2 Fiber core cross section with PSP axis.

and symmetrical. The fiber indexes of refraction along the x and y PSP axes are equal and light travels with identical velocities (DGD = 0) in the fiber as shown in Fig. 5.2*a*. In real fibers, asymmetry in the fiber geometry and other stresses result in the fiber becoming locally bire-fringent with different refractive indices for the two PSPs. This leads to different velocities for both polarizations of the optical signal as shown in Fig. 5.2*b*. Velocity of light in a material is dependent on the material's index of refraction as defined by the following equation.

$$v = \frac{c}{n} \tag{5.3}$$

where *v* = phase velocity of light in a material (not the same as group velocity), m/s

- c = speed of light, m/s in a vacuum
- n = material index of refraction

PSP axes are not uniform along the fiber length. Over a certain length of fiber the PSP axis can rotate with respect to the adjacent fiber PSP axis. Consequently, each time the PSP orientation changes polarization, mode coupling occurs between the fast and slow PSP signals, which affects DGD. A method of manufacturing fiber called *fiber spinning technology* introduces controlled polarization mode coupling during the fiber draw process that has been proven to reduce fiber PMD.<sup>3</sup>

Causes of high DGD include poor-quality fiber (older fiber manufactured before 1995 PMD can be >0.5 ps/ $\sqrt{km}$ ), noncircular fiber, air bubbles in fiber, fiber core misalignment, fiber impurities, external and internal stresses on fiber, bends and twists of the fiber (example, excessive twisting of fiber cable or excessive movement of buried cable), fiber connections, fiber splices, temperature changes, and mode coupling.<sup>4</sup> Fibers in aerial cable are more prone to PMD fluctuations than buried cable due to aerial cable exposure to weather elements.

PMD is not static and may change after the cable has been installed and may change over time. DGD events vary with wavelength and can be spectrally localized, see Fig. 5.3. All wavelengths are equally susceptible to PMD and, over time, DGD at each wavelength will



FIGURE 5.3 DGD varies with wavelength.

exhibit the same Maxwellian distribution. The variance of DGD over wavelength is referred to as second-order PMD.

#### 5.3 Probability Distribution

DGD is a function of the fiber's birefringence that varies randomly along a fiber. As a result, DGD for any given wavelength at any moment in time is a random variable that has been shown by numerous experiments<sup>5,6</sup> to have a Maxwellian probability distribution, see Eq. (5.4). Figure 5.4 shows a typical Maxwellian probability distribution<sup>7</sup> that is normalized by the average DGD for a buried fiber cable.

$$p_r(\Delta \tau_{\rm DG}) = \frac{32}{\pi^2} \frac{\Delta \tau_{\rm DG}^2}{<\Delta \tau_{\rm DG}^3} \exp\left(-\frac{4\Delta \tau_{\rm DG}^2}{\pi < \Delta \tau_{\rm DG}^2 >^2}\right)$$
(5.4)

where  $p_r(\Delta \tau_{DG})$  = Maxwellian probability distribution for any given wavelength, ps<sup>-1</sup>

 $\Delta \tau_{DG} = DGD, ps$ <  $\Delta \tau_{DG} > = average DGD (PMD), ps$ 

Since DGD is a random event, the probability of a DGD event exceeding some value x can be found<sup>8</sup> by integrating the Maxwellian distribution, see Eq. (5.5). Results are shown in Table 5.1 and graphed in Fig. 5.4.

$$p_r(\Delta \tau_{\rm DG} \ge x) = 1 - \int_0^x p_r(\Delta \tau_{\rm DG}) d\Delta \tau_{\rm DG}$$
(5.5)

where  $p_r(\Delta \tau_{DG} \ge x)$  is the probability a DGD event is greater than value *x* in a fiber.



FIGURE 5.4 Normalized Maxwellian probability density function.

SF Ratio	Probability of a DGD Event Exceeding DGD <sub>max</sub> in 1 Fiber	Circuit Availability for 2 Fibers (%)	Circuit Unavailability per Year for 2 Fibers
2.000	$1.705  imes 10^{-2}$	96.59	12.45 days
2.245	$5.00  imes 10^{-3}$	99.00	3.65 days
2.500	$1.180  imes 10^{-3}$	99.76	20.7 hours
2.639	$4.997  imes 10^{-4}$	99.900	8.8 hours
2.976	$4.999  imes 10^{-5}$	99.9900	52.6 minutes
3.000	$4.198  imes 10^{-5}$	99.9916	44.2 minutes
3.277	$4.9998  imes 10^{-6}$	99.99900	5.3 minutes
3.550	$4.998  imes 10^{-7}$	99.999900	31.5 seconds
3.700	$1.322 \times 10^{-7}$	99.9999736	8.3 seconds
3.803	$4.998  imes 10^{-8}$	99.999990	3.2 seconds
4.039	$5.001 \times 10^{-9}$	99.99999900	0.3 seconds
4.500	$3.703 \times 10^{-11}$	99.999999993	0.002 seconds

TABLE 5.1 SF Ratios and DGD Event Probabilities

It is possible for values of DGD to occur that exceed an equipment maximum tolerable value (DGD<sub>max</sub>). DGD<sub>max</sub> is defined as the value of DGD that the transceiver must tolerate with a maximum sensitivity degradation of 1 dB. A DGD event larger than an equipment maximum tolerable value would likely cause bit errors or a

communications outage for the length of the event. The probability of this DGD event occurring in a fiber can be determined by Eq. (5.5) where  $DGD_{max}$  is represented by *x*. The ratio of  $DGD_{max}$  to fiber PMD<sub>tot</sub> (link average DGD) can be referred to as the safety factor (SF).<sup>9</sup> The safety factor is a simple method to represent the probability of fiber DGD events disrupting communications as shown in Table 5.1. This is referred to as Method 2 by TIA TR-1029.<sup>10</sup>

$$SF = \frac{DGD_{max}}{PMD_{tot}}$$
(5.6)

where SF = safety factor

DGD<sub>max</sub> = maximum fiber link DGD across a specific wavelength range, ps

PMD<sub>tot</sub> = total fiber link PMD (average link DGD) across a specific wavelength range, ps

Table 5.1 relates different values of SF with the probability, derived from Eq. (5.5), of a DGD event occurring that exceeds  $DGD_{max}$  in a buried fiber cable. Table 5.1 circuit availability percentage and unavailability per year are calculated for two fiber circuits. Circuit unavailability is determined<sup>11</sup> by Eq. (5.7).

$$U = 2 \times 365.2422 \times 24 \times 60 \times p_r \tag{5.7}$$

where *U* = circuit unavailability (two-fiber link), min

 $p_r$  = probability of a DGD event exceeding DGD<sub>max</sub>

The factor "2" is used in Eq. (5.7) due to the fact that two fibers or wavelengths are required for a full duplex circuit.

Transceiver specifications list a maximum tolerable DGD  $(DGD_{max})$  as well as a power penalty. Typically the transceiver maximum tolerable DGD with a 1 dB penalty is 30% of the bit period.<sup>12</sup> This value is approximate and varies for different modulation formats. Refer to transceiver specifications for accurate values. The 1 dB PMD power penalty should be included in optical link loss budget planning, where PMD is a concern.

Fiber maximum total PMD<sub>tot</sub> value and cable length can be calculated knowing the SF ratio and transceiver maximum DGD<sub>max</sub>. For example, a 10 Gbps lightwave system that uses a transceiver with a tolerable DGD<sub>max</sub> of 30 ps and requires design SF ratio of 3.6 can be deployed only in a fiber link that has a maximum PMD<sub>tot</sub> of 8.3 ps, from Eq. (5.6). If the fiber cable maximum PMD coefficient is 0.2 ps/ $\sqrt{km}$ and there are no other PMD contributors in the link, the PMD limited maximum fiber cable link length is calculated using Eq. (5.2) to be 1700 km. Table 5.2 shows other typical transmission rates and PMD limited maximum cable lengths assuming 0.2 ps/ $\sqrt{km}$  fiber is used and there are no other PMD contributors in the link.

Bit Rate (Gbps)	Bit Period (ps)	Transceiver DGD <sub>max</sub> at 30% Bit Period (ps)	Maximum PMD <sub>tot</sub> for SF = 3 Av. = 99.99% (ps)	Maximum PMD <sub>tot</sub> for SF = 3.6 Av. = 99.9999% (ps)	Maximum Length for 0.2 ps/√km Fiber and SF = 3.6 (km)
2.5	400	120	40	33	27,000
10	100	30	10	8.5	1,800
40	25	7.5	2.5	2.1	110
100	10	3	1	0.85	18

Other circuit PMD outage information such as mean time between outages (MTBO), mean outage duration (MOD), and mean outage rate ( $R_{out}$ ) can be estimated if the fiber link DGD temporal characteristics and length are known. A PMD outage can be defined as any time a fiber link DGD event exceeds the receiver's maximum tolerable DGD. Kondamuri<sup>13</sup> has shown the mean outage rate can be determined by Eq. (5.8) for buried fiber optic cable if the fiber link Laplacian parameter a  $\alpha_{t}$  and total link PMD are known.

$$R_{\rm out} = 8765.813 \frac{1}{2\alpha_{\rm L}} p_r(\Delta \tau_{\rm DG})$$
(5.8)

where  $R_{out} = \text{single-fiber mean outage rate, outages per year}$   $\alpha_L = \text{fiber's Laplacian parameter, hr/ps}$   $p_r(\Delta \tau_{DG}) = \text{Maxwellian probability, ps}^{-1}$   $\Delta \tau_{DG} = \text{maximum tolerable DGD, receiver DGD}_{max}$ , note  $DGD_{max} > PMD_{tot}$ 8765.813 = hour-to-year adjustment factor, 365.2422 days × 24 hours

The Laplacian parameter can only be estimated using a series of DGD field measurements over time for the fiber link. Kondamuri indicates that to estimate the Laplacian parameter within 10% of its actual value, the measurements need to be made over 10 to 14 days. The Laplacian parameter is inversely proportional to the link length and can be shown as Eq. (5.9), where  $A_L$  is a constant for the fiber link. Therefore, the longer the fiber link length the higher the outage rate. Equation (5.8) can be shown as Eq. (5.10).<sup>13</sup>

$$\alpha_{\rm L} = \frac{A_{\rm L}}{L} \tag{5.9}$$

$$R_{\rm out} = 8765.813 \frac{L}{2A_{\rm L}} p_r (\Delta \tau_{\rm DG})$$
(5.10)

where  $A_L$  = constant, km-hr/ps L = fiber link length, km

The mean time between outages is the inverse of the outage rate, see Eq. (5.11). The mean outage duration due to a DGD event can be determined by Eqs. (5.12) and (5.13).<sup>13</sup>

$$MTBO = \frac{1}{R_{out}}$$
(5.11)

$$T_{\rm out} = \frac{p_r}{R_{\rm out}}$$
(5.12)

$$MOD = T_{out} \times 525948.8$$
 (5.13)

where MTBO = single-fiber mean time between outages, years MOD = single-fiber mean outage duration, min

 $R_{out}$  = single-fiber mean outage rate, outages per year

 $p_r$  = single-fiber probability of an outage, Eq. (5.5)

 $T_{out}$  = single-fiber mean outage duration (MOD), years

Table 5.3 shows single-fiber estimated mean outage rate, MTBO, and MOD example values for various buried fiber lengths and fiber Laplacian parameters reported by Kondamuri.<sup>13</sup> Outages are estimated for a 40 Gbps transceiver with a DGD<sub>max</sub> of 6.25 ps.

Link Length (km)	Link PMD (ps)	Fiber α <sub>∟</sub> (hr∕ps)	SF Ratio	R <sub>out</sub> (outages per year)	MTBO (time between outages)	MOD (min)
200	1.41	0.4	4.42	$6.8 imes10^{-6}$	148,000 years	7.0
400	2	0.2	3.13	1.38	8.9 months	6.0
600	2.45	0.13	2.55	73.2	5 days	6.3
800	2.83	0.1	2.21	492.1	17.8 hours	6.4
1,000	3.16	0.08	1.98	1,510	5.8 hours	6.5
1,200	3.46	0.07	1.8	3,005	2.9 hours	7.2
1,400	3.74	0.06	1.67	5,051	1.7 hours	7.2
1,600	4	0.05	1.56	7,749	1.1 hours	7.0

 TABLE 5.3
 40 Gbps Transceiver Example Showing MTBO and MOD for Various

 Link Lengths
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#### 5.4 Spectral Behavior of DGD

It is important to estimate how much bandwidth may be affected by a DGD event and for a DWDM system how many adjacent DWDM channels may be affected. Theory and experiments have demonstrated<sup>8,14</sup> that affected bandwidth is inversely proportional to fiber mean DGD (or PMD). The longer the fiber cable, the more narrow the DGD event spectrum.

$$BW = \frac{900}{<\Delta\tau_{DG}>}$$
(5.14)

where BW = spectral bandwidth, GHz  $<\Delta \tau_{DG} >$  = fiber average DGD or fiber PMD, ps

If a fiber's PMD coefficient is  $0.1 \text{ ps}/\sqrt{\text{km}}$  and link length is 100 km, then the PMD for the link is 1 ps. The estimated DGD event bandwidth given by Eq. (5.14) is therefore 900 GHz. In a 100 GHz spaced DWDM system, nine adjacent channels (900 GHz, 7.5 nm) may be affected by a single DGD event.

#### 5.5 Link Design Value (PMD<sub>o</sub>) and Maximum PMD

Fiber cable manufacturers provide two common fiber PMD specifications, maximum fiber PMD coefficient and link design value ( $PMD_Q$ ). Maximum fiber PMD coefficient is the maximum PMD coefficient value that each fiber is manufactured to fall below. Link design value (LDV), also referred to as  $PMD_Q$  or Method 1 by TIA TR-1029, is a statistical design parameter used to calculate link PMD coefficient value when numerous cable sections are concatenated.

Traditional methods to calculate link total PMD coefficient for many concatenated fiber cable sections would use worst-case PMD value (maximum fiber PMD) for each cable section, see Eq. (5.15).

$$PMD_{\max c} = \left(\frac{1}{L}\sum_{i=1}^{N} L_{i}PMD_{\max i}^{2}\right)^{1/2}$$
(5.15)

$$PMD_{tot} = \left(\sum_{i=1}^{N} L_i PMD_{maxi}^2\right)^{1/2}$$
(5.16)

- where  $PMD_{maxc}$  = maximum PMD coefficient for the concatenated fiber link, ps/ $\sqrt{km}$ 
  - PMD<sub>tot</sub> = maximum PMD for the concatenated fiber link, ps
    - $\hat{L}$  = total length of the concatenated fiber cable link, km
    - N = number of fiber cable sections comprising the link
    - $L_i$  = length of the *i*'th fiber section, km
  - $PMD_{\max i} = maximum PMD \text{ coefficient of the } i'\text{th fiber section,} \\ ps/\sqrt{km}$

However, this does not take into account the randomness of a fiber's PMD coefficient in any given cable section and can result in an overly conservative total PMD value. Note, the PMD coefficient for a given fiber is not a random number. When a fiber cable is assembled, fibers are drawn arbitrarily from the cable manufacturer's inventory to be placed into the cable. Each fiber in the manufacturer's inventory has its own characteristic PMD coefficient, below the maximum, that is not tracked through the cable manufacturing process due to manufacturing logistical reasons. Consequently, fiber sections that are spliced together to form the cable have random PMD coefficients. After the cable is made, it is cut to cable reel lengths (typically 5 to 8 km) for field deployment. During the field installation process, fiber cables from arbitrary cable reels are joined together to form the final fiber link, which further contributes to this randomness. Thus the overall installed fiber link is made from numerous fiber pieces whose PMD coefficients are randomly joined together to form the final fiber link. This randomness requires a statistical approach to achieve a more realistic link PMD coefficient.

 $PMD_Q$  was created as a statistical solution to PMD coefficient specifications where concatenation of numerous cable sections is taken into account. Calculations using fiber cable specified  $PMD_Q$ provide for more of an actual total PMD coefficient value when many fiber sections are spliced together. Figure 5.5 shows the benefit of using the  $PMD_Q$  instead of the maximum fiber PMD. By definition,  $PMD_Q$  is a statistical upper bound value specified for an imaginary reference link consisting of at least *M* equal length sections (typically M = 20) of concatenated, randomly selected, fiber cables with a probability of less than *Q* (typically Q = 0.01% for 99.99 percentile) that the actual link PMD coefficient will exceed the PMD<sub>Q</sub> value.<sup>15</sup> Methods to calculate PMD<sub>Q</sub> appear in EIA/TIA Standard TR-1029.



FIGURE 5.5 Example of fiber cable section PMD distribution and PMD<sub>o</sub> benefit.

 $PMD_Q$  values can be used in the calculation of total fiber span PMD together with other components that contribute to span PMD, see Eqs. (5.21) to (5.23).  $PMD_Q$  is a useful parameter for concatenated links of 20 or more cable sections but can be inaccurate for shorter links.

#### 5.6 Total Link PMD

Fiber link components can contribute to fiber link total PMD. PMD for most components such as WDM, DWDM, CWDM, DCM (except DCM using DCF), and many optical amplifiers are deterministic (DGD does not vary in time but may vary with wavelength). These component specifications should be reviewed and PMD values included in PMD link budget calculations. Since PMD adds quadratically along a fiber span, the total PMD of a fiber link is the square root sum of the squares of the fiber PMD. However, if deterministic components are included, the formula changes slightly as shown below.

For a cable link of the same fiber type and no other PMD components in the link, total cable link PMD can be calculated using cable  $PMD_Q$  or  $PMD_{max}$  specifications with Eq. (5.17) or Eq. (5.18). If the link is made up of numerous cables with different fiber types, then Eq. (5.19) can be used.

$$PMD_f = PMD_Q \times \sqrt{L}$$
(5.17)

$$PMD_f = PMD_{maxc} \times \sqrt{L}$$
(5.18)

$$PMD_{f} = \left(\sum_{i} L_{i} PMD_{Qi}^{2}\right)^{1/2}$$
(5.19)

where  $PMD_{g} = fiber link PMD, ps$   $PMD_{Q} = fiber cable PMD_{Q}, ps/\sqrt{km}$   $PMD_{Qi} = fiber PMD_{Q} of i'th cable section, ps/\sqrt{km}$   $PMD_{maxc} = fiber cable maximum PMD coefficient, ps/\sqrt{km}$  L = fiber cable link length, km $L_{i} = length of the i'th cable section, km$ 

To calculate the total PMD of numerous concatenated cable sections using measured PMD values for each section and no other PMD components in the link, use Eq. (5.20).

$$PMD_{tot} = \left(\sum_{i} PMD_{mi}^{2}\right)^{1/2}$$
(5.20)

where PMD<sub>tot</sub> = link total PMD, ps PMD<sub>mi</sub> = measured fiber PMD for *i*'th cable section, ps For fiber cable with nondeterministic components in the link, such as dispersion compensation modules using dispersion compensating fiber, total cable link PMD can be calculated as follows:

$$PMD_{tot} = \left(L \times PMD_Q^2 + \sum_i PMD_{Ri}^2\right)^{1/2}$$
(5.21)

1 /0

For fiber cable link with deterministic components added such as optical amplifiers and DWDM, total cable link PMD can be calculated using Eq. (5.22) or Eq. (5.23).<sup>12</sup> Equation (5.15) is used if all deterministic components are at the end of a fiber link and Eq. (5.16) is used if most deterministic components are embedded in the fiber link (deterministic components are followed by fiber cable).

$$PMD_{tot} = \left(L \times PMD_Q^2 + \sum_i PMD_{Ri}^2\right)^{1/2} + \sum_j PMD_D$$
(5.22)

$$PMD_{tot} = \left(L \times PMD_Q^2 + \sum_i PMD_{Ri}^2 + \sum_j PMD_{Dj}^2\right)^{1/2} + PMD_{Dlast} \quad (5.23)$$

where  $PMD_{tot} = link total PMD, ps$   $PMD_Q = fiber cable PMD_Q, ps/\sqrt{km}$   $PMD_{Ri} = PMD of nondeterministic (randomly varying in time) components, ps$   $PMD_{Dj} = PMD of deterministic components, ps$   $PMD_{Dlast} = PMD of the last non-embedded deterministic component, ps$ L = fiber link length, km

#### 5.7 Second-Order PMD

Second-order PMD (PMD2) is the DGD dependency on wavelength that causes the PSP pulses to broaden or shrink as shown in Fig. 5.1. Like PMD, second-order PMD is stochastic due to the random mode coupling that occurs in optical fiber. PMD2 is measured in units ps/nm and PMD2 coefficient in units ps/(nm  $\cdot$  km), just like CD. Components of PMD2 are polarization-dependent chromatic dispersion that is the DGD magnitude change with wavelength and depolarization rate that is the rotation of the PSP with wavelength. PMD2 increases linearly with fiber length and is a concern only for systems with bit rates of 10 Gbps and higher.

PMD2 can be estimated <sup>16,17,18</sup> and related to the PMD for long fiber lengths (>2 km) with strong mode coupling with Eq. (5.24).

$$PMD2_{c} = \frac{2\pi c}{\lambda^{2}\sqrt{3}} \times PMD_{c}^{2}$$
(5.24)

where PMD2<sub>c</sub> = second-order polarization mode dispersion coefficient,  $ps/(nm \cdot km)$ 

- PMD<sub>a</sub> = first-order polarization mode dispersion coefficient, ps/√km
  - $\lambda$  = signal wavelength, nm
  - c = speed of light in a vacuum, km/s

For accurate values, it is always best to measure the fiber cable second-order PMD instead of estimating it. Second-order PMD value (PMD2) is added directly to the fiber's chromatic dispersion to determine the fiber's total dispersion, see Eq. (5.25).

$$CD_{tot} = CD_f + PMD2 \tag{5.25}$$

where  $CD_{tot}$  = total link chromatic dispersion, ps/nm  $CD_f$  = fiber link chromatic dispersion, ps/nm PMD2 = second-order PMD, ps/nm

#### 5.8 **Polarization-Dependent Loss**

Polarization-dependent loss is the optical signal power loss in a component or fiber due to the change in the signal's polarization. Since laser light is polarized to some degree and changes randomly along the fiber length this effect can cause fluctuations in received signal power. The maximum optical power fluctuation is represented by the symbol PDL and is defined as the ratio of the output maximum to the output minimum transmittances for all possible input polarization states assuming constant input power, see Eq. (5.26).

$$PDL = 10 \log \left( \frac{T_{rmax}}{T_{rmin}} \right)$$
(5.26)

Transmittance is defined as the output optical power divided by input optical power, see Eq. (5.27).

$$T_r = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{5.27}$$

PDL can also be defined in terms of measured optical output power assuming constant input power for all polarization states, see Eq. (5.28) and Fig. 5.6. Therefore, PDL is the measure of maximum peak to minimum peak difference in output power of a fiber or component when the input power changes through all possible polarizations.

$$PDL = 10 \log\left(\frac{P_{max}}{P_{min}}\right)$$
(5.28)

Polarization-dependent loss effect is also wavelength dependent. However, unlike PMD it is not transmission rate dependent. Therefore, it is considered for all transmission rates in optical power budgets.





Unpolarized light is an equal mixture of the two orthogonal polarized states and its power can be determined by Eq. (5.29).

$$P_{\rm dep} = \frac{P_{\rm max} + P_{\rm min}}{2} \tag{5.29}$$

where PDL = system or component polarization-dependent loss at a specific wavelength, dB

- $T_{rmax}$  = maximum transmittance of optical power over all polarization states
- $T_{r\min}$  = minimum transmittance of optical power over all polarization states
  - $T_r$  = optical power transmittance of a system or component
  - $P_{\rm out}$  = optical output power at a specific wavelength, mw
  - $P_{in}$  = optical input power at a specific wavelength, mw
- $P_{\text{max}}$  = maximum optical output power over all polarization states at a specific wavelength, mw
- $P_{\min}$  = minimum optical output power over all polarization states at a specific wavelength, mw
- $P_{dep}$  = unpolarized optical power at a specific wavelength, mw

PDL can be thought of as an uncertainty in the received optical signal power. For example, a component PDL of 0.5 dB can result in signal power output uncertainty<sup>19</sup> of  $\pm$  0.5 dB. Therefore, PDL is treated as a power penalty and included in optical power budgets.

Signal polarization is variable and random along a fiber length or in a component; PDL is a statistical impairment. When two or more components or fiber lengths are concatenated the total link PDL is not simply the sum of all individual component PDLs. This is because total link PDL depends on the relative orientation of the PDL axes at each component connection. Since each component has a random PDL axis orientation and polarization axis orientation changes along a fiber, a statistical description is needed to predict the mean link PDL. It has been shown<sup>20</sup> for small values of component PDL (<3 dB), mean link PDL can be approximated by a Maxwellian distribution. This distribution mean can be calculated with some difficulty. A simpler worst-case total link PDL maximum can be approximated<sup>21</sup> by the sum of the individual PDL components, see Eq. (5.30).

Component	Typical PDL (dB)
10 km G.652 fiber	<0.05
1 meter G.652 fiber	<0.02
PC fiber connector	<0.05
Angled fiber connector	<0.1
Isolator	<0.3
EDFA (PDG)	<0.5

TABLE 5.4Typical PDL Values for CommonComponents

$$PDL_{T_{max}} = PDL_1 + PDL_2 + PDL_3 + \dots + PDL_r$$
(5.30)

where  $PDL_{Tmax}$  = maximum total link PDL, dB PDL<sub>x</sub> = component or fiber PDL or PDG, dB

For EDFA amplifiers PDL is referred to as polarization-dependent gain and is represented by the symbol PDG. It occurs because EDFA gain varies slightly with signal polarizations. For calculations using Eq. (5.30), PDG is treated as PDL.

Typical PDL values of components and fiber range from 0.05 to 0.5 dB. Some of the worst offenders are EDFAs, isolators, and APC connectors, see Table 5.4.

For example, if a 10 km SSMF fiber link has one APC connection and two EDFAs, the total PDL maximum is calculated using Eq. (5.30) to be 1.15 dB assuming the component and fiber PDL specifications are as shown in Table 5.4.

$$PDL_{Tmax} = 0.05 + 0.1 + 2 \times 0.5$$

$$PDL_{Tmax} = 1.15_{dE}$$

PDL is a liability in fiber links. It builds up along the fiber link inducing signal power fluctuations and increasing link power loss. In the presence of PMD, the combined effect of PMD and PDL increases pulse distortions and link bit error rate<sup>22</sup> above expected levels. Total link PDL should be kept to a minimum and included in optical power budgets for any transmission rate.

#### 5.9 Polarization Maintaining Fiber

Polarization maintaining fiber (PMF) is an optical fiber that maintains polarization state constant along the length of the fiber. There is very little cross coupling of power between PSP axes. PMF is used in specialty applications where the polarization of an optical signal has to have a known orientation. Optical modulators (fiber between laser and modulator), EDFAs, interferometers, sensors, and fiber optic gyroscopes (FOG) are some applications for PMF. Because of the higher expense, increased fiber coupling difficulty, splicing difficulty, and larger attenuation of PMF fiber than SSMF, PMF is not used in fiber optic transmission cables.

### 5.10 PMD Measurement Methods

Three standardized methods have been established to measure PMD and DGD in the field or lab environments. The methods are the interferometric, fixed analyzer, and Jones matrix eigenanalysis.

#### 5.10.1 Interferometric Method (TIA FOTP-124)<sup>23</sup>

This is a time domain measurement method based on measuring pulse delay. It uses a Michelson or Mach-Zehnder interferometer and measures the electric field autocorrelation of wide spectrum light source split into two polarized parts. The two parts are delayed (relative to each other) by DGD as they travel in the fiber under test. The delayed parts are recombined for an interference pattern interferogram at the detector. The mean DGD (PMD) is determined by fitting a Gaussian curve to the results and determining the standard deviation of this curve.

The following table outlines advantages and disadvantages of the interferometric method.

Interferometric Method		
Advantages	Disadvantages	
Lower instrument cost	Indirect measurement	
Measurements can be completed quickly	Lower accuracy	
Well-suited for field measurements	Sensitive to input polarization	
	Sensitive to degree of mode coupling in fiber and therefore should be used only for long fibers	
	Equipment required at both ends of fiber under test	
	No second-order PMD	
	No DGD versus wavelength	
	No DWDM measurements	
	Only PMD available	

#### 5.10.2 Fixed Analyzer Method (TIA FOTP-113)<sup>24</sup>

The fixed analyzer method (also known as the wavelength scanning method) is a frequency domain measurement method that measures PMD by calculating the Fourier transform of the receive spectrum of a tunable laser source (or broadband laser source but results in lower accuracy) that is launched into a fiber at different source wavelengths and polarizations. The PMD can be determined from the Fourier transformation results.

The following table outlines advantages and disadvantages of the fixed analyzer method.

Fixed Analyzer Method		
Advantages	Disadvantages	
Lower instrument cost	Indirect measurement	
Measurements can be completed quickly	Lower accuracy	
Easy to perform	Sensitive to degree of mode coupling in fiber and therefore should be used only for long fibers	
	Equipment required at both ends of fiber under test	
	Sensitive to input polarization	
	No second-order PMD	
	No DGD versus wavelength	
	No DWDM measurements	
	Only PMD available	

#### 5.10.3 Jones Matrix Eigenanalysis Method (TIA FOTP-122)<sup>25</sup>

This frequency domain measurement method uses a tunable narrow band laser with three states of linear polarizations (typically 0, 45, and 90 degrees) to determine the Jones matrix and complex algorithms to calculate DGD values at a particular wavelength. PMD is calculated by averaging the DGD values over a wavelength range.

The table below outlines the advantages and disadvantages of the Jones matrix eigenanalysis method.

Jones Matrix Eigenanalysis Method		
Advantages	Disadvantages	
Direct measurement of DGD	Higher cost of equipment	
Measurement of second-order PMD	More complex operation may require training	

Advantages	Disadvantages
High accuracy	Equipment required at both ends of fiber under test
Measures DGD versus wavelength	
Not sensitive to input polarization	
Not sensitive to degree of mode coupling in fiber and can be used for short or long fibers	

#### 5.10.4 Measurement Accuracy

PMD is determined by averaging DGD measurements over time or wavelength. Time averaging is normally impractical because the instantaneous DGD values may take many days (or longer) to change. Therefore, obtaining a large enough sample would be impractical. Consequently, most PMD measurements are based on averaging over wavelength. For an adequate sample of DGD measurements over wavelength and to ensure the best possible measurement accuracy, the measurements must be made in a wide enough wavelength range. It has been found that the measurement wavelength range is dependent on the PMD value itself, see Table 5.5. The measurement uncertainty can be approximated by Eq. (5.31).<sup>26</sup>

$$\frac{\Delta PMD}{PMD} \approx \pm \frac{0.9}{\sqrt{PMD \times 2\pi \times \Delta f}}$$
(5.31)

where  $\Delta PMD = PMD$  uncertainty, ps PMD = polarization mode dispersion, ps $\Delta f = measurement range expressed as frequency, THz$ 

This uncertainty limitation is intrinsic to all measurement methods that average DGD over a wavelength range and needs to be considered with equipment accuracy values.

PMD	$\Delta \mathbf{f} = 1.25 \text{ THz}$ $\Delta \lambda = 10 \text{ nm}$	$\Delta \mathbf{f} = 6.24 \text{ THz}$ $\Delta \lambda = 50 \text{ nm}$	$\Delta \mathbf{f} = 12.5 \text{ THz}$ $\Delta \lambda = 100 \text{ nm}$	$\Delta \mathbf{f} = 25 \text{ THz}$ $\Delta \lambda = 200 \text{ nm}$	$\Delta \mathbf{f} = 50.8 \text{ THz}$ $\Delta \lambda = 400 \text{ nm}$
0.1 ps	±102%	±45%	±32%	±23%	±16%
1.0 ps	±32%	±14%	±10%	±7.2%	±5.1%
10 ps	±10%	±4.5%	±3.2%	±2.3%	±1.6%

 TABLE 5.5
 PMD Measurement Uncertainty for DGD Wavelength Averaging

 Centered at 1550 nm

#### 5.11 Coping with PMD

PMD cannot be easily reduced due to its random nature. The following measures can be considered to help reduce link PMD to acceptable levels:

- 1. Replace sections of cable that have been tested to have high PMD values with cable that has lower PMD. Older cables tend to have higher PMD values.
- 2. Measure PMD for all fibers in a cable and select the fibers with low PMD values to be considered for high bit rate (≥10 Gbps) systems. Different fibers in the same cable span can have greatly different PMD values.
- 3. Shorten fiber cable spans by deploying midspan optical 3R regenerators.
- 4. PMD compensation devices<sup>27</sup> are available and are typically located at the receiver. Compensation devices introduce signal loss, have a narrow optical bandwidth, and are expensive. For DWDM systems, a separate compensation may be required for each channel and is located just after the DWDM demultiplexer and before the receiver.
- 5. Use different laser modulation methods because PMD depends on pulse width and spacing. RZ modulation may be more tolerant than NRZ modulation.
- 6. Select optical components with low PMD and PDL values.
- 7. For new fiber cable installs, check the fiber manufacturer's specifications to ensure PMD values will exceed your link requirements for present and future lightwave equipment deployments.
- 8. Buried fiber should be isolated from main sources of vibration such as roads and railroads. Buried fiber can be insulated from temperature change if exposed or if attached to a bridge.<sup>28</sup>
- 9. Fiber cable bends should be kept large and smooth with bending radius greater than 0.25 m or as recommended by cable manufacturers for low PMD.

#### 5.12 PMD Planning Summary

PMD need only be considered for lightwave systems with fiber transmission rates of at least 10 Gbps and greater. Rates lower than this will not likely cause any significant signal distortion and/or bit errors. The following steps can be followed to help plan your next system.

- 1. Determine fiber cable PMD from direct span measurements as described in Sec. 5.10 (preferable) or from calculations using cable specifications as shown in Sec. 5.5.
- 2. Determine total link PMD<sub>tot</sub>, including all components that may contribute to PMD, by direct measurement and/or calculations as shown in Sec. 5.6.
- 3. From equipment specifications determine equipment maximum tolerable DGD<sub>max</sub> and PMD power penalty.
- 4. Using equipment maximum tolerable DGD<sub>max</sub> and total link PMD<sub>tot</sub> calculate link safety factor SF using Eq. (5.6).
- 5. Refer to Table 5.1 and determine probability of a DGD event affecting communications and circuit availability using calculated SF. If the probability of a DGD event occurring is unacceptable, refer to Sec. 5.11 for methods on how to reduce link PMD.
- 6. Determine the spectral bandwidth of a DGD event from Sec. 5.4.
- Measure or calculate link second-order PMD as shown in Sec. 5.7 and determine amount to be added to link total chromatic dispersion.
- 8. Refer to Sec. 5.8 to determine total PDL loss and include this amount in link optical power budget calculations.
- 9. Refer to Sec. 5.11 for ways to reduce PMD.

#### 5.13 PMD Examples

**Example 5.1** Find the total link PMD of three sections of fiber cable spliced together. For each section of fiber cable, the PMD was determined from field measurements before the cable sections were spliced together. Field measured PMD values of each section of cable are as follows:

Cable section 1:	2.0 ps
Cable section 2:	4.0 ps
Cable section 3:	0.7 ps

Equation (5.20) is used to calculate PMD total.

$$PMD_{tot} = \left(\sum_{i} PMD_{mi}^{2}\right)^{1/2}$$
$$PMD_{tot} = \sqrt{2^{2} + 4^{2} + 0.7^{2}}$$
$$PMD_{tot} = 4.5 \text{ ps}$$

Total link PMD is 4.5 ps.

**Example 5.2** Find the fiber link total PMD using maximum PMD and  $PMD_Q$  of 80 new 5.0 km sections of the same cable spliced together. The cable fiber specifications are as follows:

Maximum PMD coefficient:	≤0.2 ps/√km
PMD <sub>o</sub> :	≤0.06 ps/√km

From Eq. (5.18) we can determine total maximum link  $PMD_{tot}$  as follows [use Eq. (5.16) for dissimilar cables or cable lengths]:

$$PMD_{tot} = PMD_{max} \times \sqrt{L}$$
$$PMD_{tot} = 0.2 \times \sqrt{80 \times 5}$$
$$PMD_{tot} = 4_{ps}$$

From Eq. (5.17) we can determine the more realistic link statistical upper bound PMD (99.99th percentile) using  $PMD_Q$  as follows [use Eq. (5.19) for dissimilar cables or cable lengths]:

$$PMD_{tot} = PMD_Q \times \sqrt{L}$$
$$PMD_{tot} = 0.06 \times \sqrt{80 \times 5}$$
$$PMD_{tot} = 1.2_{ps}$$

**Example 5.3** Determine the total link PMD of a 200 km span of fiber cable with four embedded EDFAs, one embedded DCM (DCF), and 16 channel 100 GHz DWDM multiplexers at each end of the link. Cable and component PMD specifications are as follows:

Fiber PMD <sub>o</sub> :	≤0.06 ps/√km
EDFA PMD:	≤0.5 ps
DCM (DCF) PMD:	≤0.1 ps
16 ch. DWDM PMD:	≤ 0.15 ps

To determine the link PMD we use Eq. (5.23) as follows:

$$PMD_{tot} = \left(L \times PMD_Q^2 + \sum_i PMD_{Ri}^2 + \sum_j PMD_{Dj}^2\right)^{1/2} + PMD_{Dlast}$$
$$PMD_{tot} = (200 \times 0.06^2 + 0.1^2 + 4 \times 0.5^2 + 0.15^2)^{1/2} + 0.15$$
$$PMD_{tot} = 1.5_{ps}$$

Total link PMD is not expected to exceed 1.5 ps with 99.99% confidence.

**Example 5.4** Determine the minimum required measurement bandwidth to measure a fiber cable that has PMD of 4 ps at 1550 nm and to ensure a maximum intrinsic uncertainty of  $\pm 10\%$ .

Use Eq. (5.31) as follows:

$$\frac{\Delta PMD}{PMD} \approx \pm \frac{0.9}{\sqrt{PMD \times 2\pi \times \Delta f}}$$
$$0.1 \approx \pm \frac{0.9}{\sqrt{4 \times 2\pi \times \Delta f}}$$

Solving for  $\Delta f$ :

$$\Delta f \approx 3.2_{\text{THz}}$$
  
 $\Delta \lambda \approx 26 \text{ nm}$ 

Minimum measurement bandwidth is approximately 26 nm.

**Example 5.5** Determine the probability that a DGD event will affect communications for a 16-channel, 100 GHz DWDM, 200 km buried fiber cable link. Total link PMD<sub>tot</sub> of 2.3 ps has been determined from field measurements. A 40 Gbps transceiver that has a maximum tolerable  $DGD_{max}$  of 7.0 ps will be used for communications.

From Eq. (5.6):

$$SF = \frac{DGD_{max}}{PMD_{tot}}$$
$$SF = \frac{7.0_{ps}}{2.3_{ps}}$$
$$SF = 3.0_{ps}$$

Referring to Table 5.1, for an SF of 3.0 the probability that a DGD event will occur in a fiber is  $4.198 \times 10^{-5}$ , circuit availability is 99.992, and circuit unavailability is 44.2 min/year.

Also, DGD events were measured over a 15-day period and the Laplacian parameter  $\alpha_{L}$  was determined to be 0.3 hr/ps for each fiber. Determine the mean outage rate, MTBO, and MOD for a fiber.

From Eqs. (5.8), (5.11), and (5.12), the single fiber outage rate, MTBO, and MOD can be estimated as follows:

$$R_{out} = 8765.813 \frac{1}{2\alpha_{L}} P(\Delta \tau_{DG})$$

$$R_{out} = 1.44_{per year}$$

$$MTBO = \frac{1}{R_{out}}$$

$$MTBO = 8.3_{months}$$

$$T_{out} = \frac{P_{prob}}{R_{out}}$$

$$MOD = T_{out} \times 525948.8$$

$$MOD = 15.3 \text{ minutes}$$

At least one single fiber outage can be expected per year with the mean time between outages being 8.3 months and mean outage duration being 15.3 minutes.

If a DGD event should occur we can estimate the bandwidth that would be affected using Eq. (5.14).

$$BW = \frac{900}{<\Delta\tau>}$$
$$BW = \frac{900}{2.3_{\rm ps}}$$
$$BW = 391_{\rm GHz}$$

We can conclude that if a DGD event were to occur the disruption would likely affect four 100 GHz DWDM channels.

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# CHAPTER **6** WDMs and Couplers

#### 6.1 Description

Wavelength division multiplexing (WDM) is a technology used to combine or retrieve two or more optical signals of different optical center wavelengths in a fiber. It allows fiber capacity to be expanded in the frequency domain from one channel to more than 100 channels. This is accomplished by first converting standard, non-WDM optical signals to signals with unique WDM wavelengths that correspond to the available channel center wavelengths in the WDM multiplexer and demultiplexer. Typically, this is done by replacing non-WDM transceivers with the proper WDM channel transceivers. WDM channels are defined and labeled by their center wavelength or frequency and channel spacing. The WDM channel wavelength assignment is an industry standard defined in International Telecommunications Union (ITU-T) documentation, see App. C. Then the different WDM signal wavelengths are combined into one fiber by the WDM multiplexer, see Fig. 6.1. In the fiber, the individual signals propagate with little interaction assuming low signal power. For high powers, interchannel interaction can occur, refer to Chap. 7. Once the signals reach the fiber link end, the WDM demultiplexer separates the signals by their wavelengths, back to individual fibers that are connected to their respective equipment receivers. Optical receivers have a broad reception spectrum, which includes all of C band. Many receivers can also receive signals with wavelengths down to O band.

The process of combining and separating the different wavelengths in the fiber is the basis of WDM technology. As a rough analogy, a WDM demultiplexer can be thought of as a prism separating different colors of light from the incident white light ray. Each color of light can represent a unique WDM signal. The white light is the aggregate of all colors of light and represents all the WDM signals propagating in the fiber.

It should be noted that WDM wavelength and WDM channel have different meanings. WDM wavelength refers to the center wavelength of an optical signal or a WDM channel. WDM channel


FIGURE 6.1 WDM functional block diagram.

refers to an optical signal communications path that is defined by a center wavelength and a spectral passband. It can be full duplex, half duplex, or simplex. Most telecommunication systems require full duplex communication channels. All full duplex fiber communication channels require two optical signals, one in each direction, to work properly. For a two fiber full duplex WDM system, the two laser signals (one at both ends of the fiber link on different fibers) are assigned the same wavelength, which is referred to as the channel assignment. However, in cases where only one fiber is used for full duplex communications, both lasers will have different wavelength assignments and therefore communication channel uses two WDM channels. Typically, most WDM systems will use two fibers for a WDM link. Therefore, the WDM wavelength assignment is the same for both lasers for that channel and is referred to as the channel assignment.

The heart of any WDM system is the basic WDM (also referred to as passive WDM). The basic WDM only consist of glass optical filters without any electronics. Therefore, it is completely passive and highly reliable. The filters are designed to pass a selected light spectral range, referred to as a channel, with low loss and reject or reflect all other spectrum. A combination of these filters results in a multichannel WDM multiplexer or demultiplexer. At the transmit end, the multiplexer combines the unique wavelengths from each channel port into one common fiber and at the receive end the demultiplexer coupler separates the combined signals from the common fiber to their respective channel ports, see Fig. 6.1. For some systems, the multiplexer and demultiplexer units are the same and are interchangeable (universal units).

Basic WDMs are transparent to all optical protocols such as SONET, SDH, GigE, 10GigE, and so on. They are also transparent to transmission rates up to the WDM's specification limits. Rates above the limits may not pass or may pass with reduced performance. Basic WDMs are available for field deployment as stand-alone units. They are also integrated with other equipment and electronics to increase WDM system overall management, functionality, and expansion capability.

The two functional sides to a WDM are the common port (also known as aggregate port, network port, or trunk port) side and the channel port side. Two WDMs are required in any single fiber link, one at each end. Their common ports are connected together by the outside plant (OSP) fiber cable and their channel ports are connected to individual equipment optical transmit and receive fibers. In order for optical equipment to work in a WDM link, it is important to ensure that the equipment laser is the same wavelength as the WDM channel port to which it connects, see Fig. 6.2.



FIGURE 6.2 Half of a simple WDM link.

# 6.2 WDM Internal Technologies

Four competing technologies are available for WDMs: fiber Bragg grating (FBG), array waveguide grating (AWG), thin-film filter (TFF), and diffraction grating filter (DF). Fiber Bragg gratings have good filter shape but need to be used with circulators, which increases the WDM cost and size. Thin-film filters have excellent filter response and low cost. They are typically used for WDMs with less than 40 channels. Array waveguide gratings are suitable for larger channel counts and have good filter response.

William Lawrence Bragg was a physicist who in 1913 discovered that a change of a material's refractive index resulted in a small amount of X-ray wavelengths to be reflected. Then in 1978 at the Canadian Research Council (CRC), K.O. Hill, demonstrated the first in fiber Bragg grating. A short length of fiber with a periodic change in its refractive index (known as a grating) works as a highly reflective mirror to a narrow band of wavelengths and passes all other wavelengths. The distance between two adjacent maximum values of the refractive index is referred to as the grating period. The fiber grating reflects a narrow spectrum of wavelengths centered at  $\lambda_{B}$  and passes all the others,<sup>1</sup> see Bragg's law Eq. (6.1) and Fig. 6.3. The spectral width of the reflection depends on the grating layers, amplitude of the refractive index modulation,<sup>2</sup> and length of the grating.

$$\lambda_{\rm B} = 2\Lambda n_{\rm eff} \tag{6.1}$$

where  $\lambda_{B}$  = reflected wavelength,  $\mu m$  $\Lambda$  = grating period,  $\mu m$ 

 $n_{\rm eff}$  = effective group refractive index of the fiber's core

The fiber Bragg grating is analogous to an electrical notch filter. FBGs are combined with circulators to make a simple WDM. Figure 6.4*a* shows signal flow in a simple optical add/drop WDM constructed with one fiber Bragg grating and two circulators. The input signals of



FIGURE 6.3 Fiber Bragg grating filter.



c. Three-channel WDM demux



multiple channels  $\lambda_1$  to  $\lambda_n$  and channel  $\lambda_{B1}$  pass through the circulator and into the fiber Bragg grating. The grating reflects the  $\lambda_{B1}$  channel and passes all the others. The  $\lambda_{B1}$  channel re-enters the circulator and exits at the drop port. Similarly, an added channel  $\lambda_{B2}$  is coupled to the add port and enters the circulator where it is directed into the fiber Bragg grating. The grating reflects it back into the circulator and to the output port. A similar kind of signal flow occurs for WDM demux and mux fiber Bragg grating units, see Fig. 6.4*b* and *c* showing a three-channel unit.

Fiber Bragg grating WDM maximum insertion loss is often specified for the combined mux and demux units. This enables the fiber Bragg grating filters to be sequenced, resulting in a flatter and lower link insertion loss. The insertion loss of both combined mux and demux units is lower than double the maximum single-unit loss. It can be explained as follows, refer to example Fig. 6.4b. The insertion loss for the mux unit channel  $\lambda_1$  signal is the highest because the signal propagates through three circulators and three fiber Bragg gratings to get to the output port. Assuming 0.6 dB loss for a circulator and 0.1 dB for a fiber Bragg grating, the total insertion loss for the channel  $\lambda_1$ signal in the mux is 2.1 dB. Channel  $\lambda_{\gamma}$  signal loss is less because it propagates through two circulators and two fiber Bragg gratings for a total loss of 1.4 dB. Channel  $\lambda_2$  experiences the least amount of insertion loss in the mux, a total of 0.7 dB. The demux unit as shown in Fig. 6.4c is sequenced in the opposite order in order to achieve the lowest possible link loss when the mux and demux units are installed in a link. The demux channel  $\lambda_1$  signal loss is the least at 0.7 dB. Channel  $\lambda_2$ , signal loss is 1.4 dB, and channel  $\lambda_3$  signal loss is 2.1 dB. Therefore, for any channel, the total link loss due to the mux and demux pair will be 2.8 dB. If, however, the fiber Bragg gratings were not sequenced, then the maximum link loss due to the mux/demux pair can be as great as 4.2 dB ( $2 \times 2.1$ ) and as low as 1.4 dB ( $2 \times 0.7$ ).

Fiber Bragg gratings can be manufactured with good wavelength accuracy (better than  $\pm 0.05$  nm), low loss (0.1 dB), high channel cross talk (>30 dB), low channel ripple, and high reliability. They are commonly used in WDM, CWDM, and DWDM multiplexers. Notable characteristics of FBG technology are as follows:

- 1. FBGs have low temperature sensitivity,<sup>3</sup> ~0.5 pm/ $^{\circ}$ C.
- 2. FBGs are sensitive to strain. They are often used as strain gauges.
- 3. Apodised FBGs are directional in operation.
- 4. FBGs can be connected as a WDM or OADM.
- 5. FBGs filters are completely passive and when combined with fiber circulators they produce a passive WDM.
- 6. FBGs have low insertion loss, typically less than 1 dB per filter.
- 7. FBG filters in WDMs are connected in series, which increases insertion loss as channel count increases.
- FBG WDMs are available with channel spacing greater than 50 GHz.
- FBGs have higher dispersion than other filter types, which can be a concern for long links and/or transmission rates of 10 Gbps and above.<sup>3</sup>
- FBGs are suitable for WDMs with less than 40 channels and greater than 50 GHz channel spacing. This is primarily due to accumulated loss caused by serial filters.



FIGURE 6.5 Array waveguide grating simple WDM.

Array waveguide grating (AWG) WDM consists of an input and output coupler and an array of varying lengths of optical waveguides, see Fig. 6.5. The input coupler splits the optical signal arriving from the common fiber equally among the arrayed waveguides. Since the waveguides are of different lengths, each waveguide optical signal experiences a different phase shift. This creates an interference pattern at the output coupler with intensity maximums. The direction of the maximums is dependent on the optical wavelength that allows the individual wavelengths to be directed to separate channel fibers. Array waveguide gratings can be manufactured on a single substrate forming a photonic integrated circuit (PIC). This technology is cost effective for high channel counts. Notable characteristics of AWG technology are as follows:

- 1. AWG waveguides are birefringent and therefore add PMD to the link.
- 2. AWGs have a constant insertion loss of 4 to 5 dB relatively independent of the number of channels.<sup>4</sup>
- 3. AWG are very temperature sensitive,<sup>4</sup> ~10 pm/°C, and may require active thermal regulation.
- 4. Although AWG technology is passive, the need for thermal regulation results in an active WDM.
- 5. AWG can operate bidirectionally.
- 6. AWG can be connected as a WDM or OADM.
- 7. AWG WDMs are available with channel spacing of 12.5 to 200 GHz.
- 8. AWGs are suitable for WDMs with large channel counts (>40 channels).

A thin-film filter (TFF) is a glass filter that passes a narrow band of optical spectrum and reflects the rest, similar to a FBG, see Fig. 6.6a.





It contains multiple layers of very thin high- and low-refractive index materials on a glass base. The thickness of the layers determines which wavelengths will be reflected and which will be transmitted through the filter. As in FBG filters, thin-film filters are arranged in sequence as shown in Fig. 6.6b and c in a WDM to achieve the lowest possible link loss. TFFs have good overall characteristics for WDMs. Notable characteristics of TFF technology are as follows:

- 1. TFFs have low temperature sensitivity,<sup>5</sup> ~0.3 pm/°C.
- 2. TFFs can operate bidirectionally.

- 3. TFFs have low insertion loss, typically less than 1 dB per filter.
- 4. Simple TFF WDMs are completely passive.
- 5. TFFs in WDMs are connected in series, which increases insertion loss as channel count increases.
- 6. TFFs can be connected as a WDM or OADM.
- TFF WDMs are available with channel spacing greater than 50 GHz.
- 8. TFFs can be made tunable by changing the incident light angle of incidence.<sup>5</sup>
- 9. TFFs are suitable for WDMs with less than 40 channels and greater than or equal to 50 GHz channel spacing.

A diffraction grating filter (DF) has a periodic variation of a property that causes the incident light to be reflected or transmitted. For a reflective grating, periodic reflective ridges are formed on the surface filter's. The grating reflects incident light into its component wavelengths at different angles in accordance<sup>6</sup> with Eq. (6.2), see Fig. 6.7*a*. For a transmission grating, incident light passes through the grating and is diffracted in accordance with Eq. (6.3), see Fig. 6.7*b*. The channel fibers are properly positioned in the unit to receive the spatially separated wavelengths.

$$m\lambda_i f_s = \sin\theta + \sin\phi_i \tag{6.2}$$

$$m\lambda_i f_s = \sin \Phi_i \tag{6.3}$$



FIGURE 6.7 Diffraction grating simple WDM.

where  $\lambda_i$  = wavelength of the diffracted wave,  $\mu m$ 

- $f_s$  = spatial frequency of the grating, where  $f_s$  = 1/(grating period), lines/µm
- m = order of diffraction, typically 1 for telecom filters, integer
- $\theta$  = angle of incidence, measured CW from surface normal, rad
- $\phi_i$  = angle of reflection, measured CCW from surface normal, rad
- $\Phi_j$  = angle of transmission, measured CCW from surface normal, rad

Notable characteristics of DF technology are as follows:

- DFs have low temperature sensitivity.
- DFs can operate bidirectionally.
- DFs have low insertion loss at high channel counts (~4 dB for 56 channels at 100 GHz) and loss is relatively independent of the number of channels.
- Simple DF WDMs are completely passive.
- DF WDMs are available with channel spacing greater than or equal to 50 GHz.
- DFs can be connected as a WDM or OADM.
- DFs are suitable for WDMs with large channel counts.

## 6.3 WDM System Configuration and Transceivers

A simple WDM system consists of WDM multiplexers located at each end of a fiber link. The channel side of the WDM, also known as the drop side, connects to the transmission equipment such as SONET gear, routers, and switches that are fitted with the proper WDM transceivers, see Fig. 6.8. The WDM transceiver must have both the same channel assignment as the multiplexer port that it will connect to, and the same channel spacing as the multiplexer, such as 200, 100, 50 GHz, or CWDM. The common side of the multiplexer connects to the common fiber, also know as aggregate fiber.

Network equipment can be fitted for WDM transmission a number of different ways. The best way is to ensure the equipment comes with the proper WDM transceivers at the time of purchase. Equipment, such as routers, switches, and SONET gear commonly use pluggable transceivers such as SFPs, XFPs, GBICs, and Xenpaks. Exchanging the standard 1310 or 1550 nm pluggable transceiver with a proper WDM type is often easy and quick. If this is not possible, wavelength converters, referred to as transponders, can be deployed. They are designed to convert non-WDM optical signals to proper WDM signals. The transponders are inserted between the network equipment transceivers and WDM multiplexer. Many high-end



FIGURE 6.8 Typical basic 4-channel WDM link.

active DWDM systems come with integrated transponders. This eliminates the need for the network equipment to be fitted with proper WDM transceivers.

WDMs can be installed onto new fiber links or onto existing fiber links that need their capacity increased. They can eliminate or postpone the requirement for costly new outside plant (OSP) fiber cable builds in links where existing fiber capacities are full. In many cases, the addition of a properly designed WDM system to increase fiber capacity is much less costly than constructing new fiber cable links.

# 6.4 Simple WDM Systems

WDM systems are available as simple stand-alone or active systems. The active systems are a combination of simple WDM's and elaborate electronics that provide a rich set of features. They are deployed in both short- and long-haul applications. Simple stand-alone systems consist of the bare WDM that consists of a set of passive filters such as fiber Bragg gratings. Typically, a simple system contains no electronics, and therefore has no power or cooling requirements. They are generally limited by the WDM transceiver's optical budget to spans of less than 100 km (assuming equipment optical budget of 28 dB, fiber loss of 0.22 dB/km, and multiplexer pair insertion loss of 6 dB).

The advantages and disadvantages of this type of system are summarized in the following table.

Simple WDM Systems					
Advantages	Disadvantages				
Price for a set of basic WDMs is typically much less than active WDM systems. A typical set of 8-channel 200 GHz DWDMs can be purchased for under \$15,000 <sup>7</sup> plus the cost of appropriate WDM transceivers.	Their use is limited by transceiver optical budget and total link loss. Typically, simple WDM systems are deployed in spans of less than 100 km.				
Because simple WDM multiplexers are totally passive, they are highly reliable with very high MTBF.	Depending on the multiplexer, many have fixed channel counts and may be difficult to expand. For example, upgrading an 8-channel WDM multiplexer system to a 16-channel system may require the replacement of the 8-channel unit with a new 16-channel unit. Initial proper sizing of the WDM unit is important.				
Simple WDM systems are environmentally friendly that do not require electrical power to operate and do not require cooling.	Due to their simple nature, remote monitoring and configuration is not possible.				
Simple WDM systems are easy to install and provision. Typically they require no configuration, adjustment, or maintenance.					
Simple WDM multiplexers are fully transparent to all protocols such as SONET, SDH, Ethernet, fiber channel, and data rates up to specification limit. For example, one WDM multiplexer channel can be connected to a SONET system while the other channel is connected to a GigE system.					
Simple WDM multiplexer channels can be leased to others for additional revenue. As long as no amplifiers or other active equipment exists in the link between the two multiplexers (the link is completely passive), WDM transceivers are of the proper type, and each transceiver's launch power level is below +5 dBm (assuming standard single-mode fiber), then adding or removing individual wavelengths will not disrupt any of the other existing signal wavelengths in the fiber.					
Simple WDM multiplexers are available for full duplex operation over one- fiber or two-fiber spans.					

## 6.5 Basic WDM Types

The four basic WDM types are unidirectional, bidirectional, universal, and optical add/drop multiplexer (OADM). The unidirectional WDM allows transmission in the WDM in only one direction, channel ports to common port or common port to channel ports. The channel port(s) in a unidirectional multiplexer (mux) unit are designated as In port(s) and connect to the equipment laser(s). The channel port(s) in a unidirectional demultiplexer (demux) unit are designated as Out port(s) and connect to the equipment receiver(s), see Fig. 6.9a. A laser cannot be connected to the demultiplexer unit and a receiver fiber cannot be connected to the multiplexer unit. Unidirectional WDMs are always installed as a mux and demux pair with common ports connecting them by a single OSP fiber. Unidirectional WDM positions are not interchangeable; therefore, spares are required for both units. Figure 6.9a shows a 4-channel unidirectional WDM pair, which is half of the requirement for a full duplex communication system. Unidirectional WDMs are always used in two-fiber links for full duplex communications. Therefore, the WDM configuration shown in Fig. 6.9a needs to be duplicated but in the opposite direction in order to produce a full duplex, 4-channel WDM system. This is a common WDM type deployed with EDFAs because they are also unidirectional.

A common configuration of unidirectional WDMs is the dual unidirectional mux/demux unit. Here both multiplexer and demultiplexer are combined into one unit at each end of the fiber. This system uses two common OSP fibers for the link connection, see Fig. 6.9b. Each fiber can carry transmission in only one direction. Channel ports are marked In and Out on each unit. The units are referred to as Mux/Demux East and Mux/Demux West and are not interchangeable. Spares are required for both units. This WDM type is commonly available as a CWDM. The In and Out fiber port connections are typically mounted close together and labeled as a channel. Using a dual fiber jumper, a channel connection is easily made between the equipment pluggable transceiver such as an SFP and the WDM.

The bidirectional WDM allows transmission in both directions but equipment laser and receiver fiber must connect to the appropriate In and Out channel ports. The common port is bidirectional, see Fig. 6.9*c*. The units are referred to as Mux/Demux East and Mux/ Demux West. Bidirectional WDM positions are not interchangeable and therefore spares are required for both units.

The universal WDM allows transmission in both directions on any channel ports and on the common port. The units can operate as both mux or demux and can be used at either end of the fiber link, see Fig. 6.9d. This is a convenient feature that reduces complexity during design, ordering, and installation. Only one spare is required since it



FIGURE 6.9 Basic WDM types.

can be used at either end of the link. Although these units can be used in one-fiber links, they are typically used in two-fiber links.

Optical amplifiers cannot be used for single-fiber bidirectional DWDM transmission systems because most amplifiers are unidirectional. Therefore, for long-haul single-fiber applications, unidirectional DWDMs need to be used with red and blue band splitters, see Sec. 6.11.1.

The total number of bidirectional transmission channels depends on the number of channels the WDM can multiplex and the number of fibers that will be used in the transmission link. If one fiber is used. then the total number of transmission channels is half of the total number of the WDM's channels (assuming full duplex communication). If two fibers are used, the number of channels equals the number of WDM channels. This is because for full duplex (bidirectional) communication, two simultaneous transmission paths are required, one in each direction. If two fibers are used in a link, then each fiber is designated a transmission direction and the two fibers are referred to as the transmit fiber and receive fiber, see Fig. 6.10a. To accomplish full duplex communication in one fiber, the WDM wavelengths are divided in half to determine the number of transmission channels. Each half represents a transmission direction in the fiber. This is because two unique wavelengths are required in one fiber, one in each direction, for one full duplex channel of communication, see Fig. 6.10b. For example, an 8-channel universal DWDM can support only four full duplex transmission channels on a one-fiber link. Two of these DWDM 8-channel units are required, one at each end of the one-fiber link. However, if the same 8-channel universal DWDM is used in a two-fiber link, then it will support eight full duplex transmission channels and four DWDM units are required for the link, see Fig. 6.10.

The OADM is a multiplexer that is designed to drop (and/or add) specific WDM channels in the middle of a fiber link. All other WDM channels pass through the unit. The OADM has two common fiber ports, In and Out, for single-fiber OADM and four common fiber ports, In East, Out East, In West, and Out West for a two-fiber OADM, as well as drop ports, see Fig. 6.11b. OADM function can also be accomplished with back to back WDMs; however, the through channels loss will be much higher. For example, assuming a 4-channel DWDM has an insertion loss of 3 dB, then the total through channels link loss using two back to back DWDMs in a link to add/drop channels in Fig. 6.11*a* would be 12 dB and channel drop loss 6 dB, not including fiber losses. However, if a single-channel OADM with a 2 dB through and drop loss is used instead of the back to back DWDMs, as in Fig. 6.11b, then the total through channels link loss is 8 dB and drop loss is 5 dB, not including fiber losses. There is a significant saving in optical through and drop channels budgets when an OADM is deployed. An OADM is also typically less pricey than back to back WDMs, thereby reducing equipment costs.

Various OADM configurations are available to drop any number of channels for DWDM or CWDM systems. One to four channel OADMs in a two-fiber system are common. OADMs must match the WDM specifications of channel spacing and assignments in the



FIGURE 6.10 One- and two-fiber WDM channel count example.

link where they will be used. CWDM OADMs are deployed in CWDM links, and DWDM OADMs are deployed in DWDM links. DWDM OADMs must also match DWDM link channel spacing (50, 100, 200 GHz).

OADMs are also available as basic passive stand-alone units or active units that have additional functionality and wavelength management features. Figure 6.11*b* shows typical one-channel OADM link configurations for a CWDM or DWDM system. Manufacturer details should be consulted to determine the exact OADM configuration.



**FIGURE 6.11** Typical OADM configurations.

# 6.6 DWDM, CWDM, and Cross-Band WDMs

WDM technology can be broken down to three specific groups: DWDM, CWDM, and cross-band. Each will be discussed in detail in this chapter. The difference between these groups of WDMs is in their channel spacing. This loosely translates to system cost. The tighter the WDM channel spacing, the higher the WDM system price. This is primarily due to being more costly to manufacture WDMs with tightly spaced channels and to manufacture narrow spectra DWDM lasers that are temperature stabilized and will not drift outside of the narrower DWDM channel passband. DWDM is an ITU-T standard with channel spacing that is less than or equal to 1000 GHz (8 nm). Typically, DWDMs are available with channel spacing of 200 GHz and less, with the 200 GHz and 100 GHz being most common. With 200 GHz channel spacing a maximum of 22 channels are available in C band (two-fiber link) and with 100 GHz channel spacing a maximum of 44 channels are available in C band (two-fiber link), see App. C. CWDM is an ITU-T standard<sup>8</sup> with channel spacing of 20 nm (approximately 2500 GHz). Crossband WDMs have only two channels, one in the 1310 nm band (O band) and the other in the 1550 nm band (C band). Each group of WDMs has its own specific application.

# 6.7 DWDM

Dense wavelength division multiplexing (DWDM) is a WDM technology, where the channel spacing is less than or equal to 1000 GHz<sup>9</sup> (8 nm), typically 200 GHz (1.6 nm) or less. ITU-T<sup>10,11</sup> has assigned a standard DWDM grid with channel center frequencies for 200, 100, 50, 25, and 12.5 GHz spaced DWDM systems. Channel spacing of 25 GHz and less is referred to as Ultra-DWDM. The grid is centered around 193.10 THz reference frequency. To determine a DWDM channel, multiply the channel spacing (200, 100, 50, 25, 12.5 GHz) by a positive or negative integer *n* and add it to the reference frequency of 193.10 THz, see Eqs. (6.4) to (6.8). Then use Eq. (6.9) to convert the frequency to a wavelength. Note, the calculated wavelength is for free space propagation but is used as an industry standard to specify fiber lasers. Refer to App. C to see common ITU-T frequency and wavelength values.

$$f_c = 193.10 + n \times 0.20 \tag{6.4}$$

$$f_c = 193.10 + n \times 0.10 \tag{6.5}$$

$$f_c = 193.10 + n \times 0.05 \tag{6.6}$$

$$f_c = 193.10 + n \times 0.025 \tag{6.7}$$

$$f_c = 193.10 + n \times 0.0125 \tag{6.8}$$

$$\lambda_c = \frac{c}{f_c} \tag{6.9}$$

where  $f_c$  = ITU-T grid channel center frequency, THz

- $\lambda_{i}$  = channel center wavelength in free space, nm
- n =positive or negative integer including zero

c = speed of light in a vacuum, m/s

DWDM systems using 200 and 100 GHz channel spacing are very common. With 200 GHz channel spacing a maximum of 22 channels are possible in C band and using 100 GHz channel spacing 44 channels are possible, see App. C. More elaborate systems with higher channel counts are available with channel spacing of 50, 25, and 12.5 GHz using C, S, and L bands. Maximum channel counts that are known to the author currently exceed 200. DWDM technology is ideal for networks that require high fiber channel counts and future expansion capacity for short- or long-haul links.

### 6.7.1 DWDM Channel Capacity

The maximum data rate (maximum channel capacity) that can be transmitted error-free over a communications channel with a specified bandwidth and noise can be determined by the Shannon theorem,<sup>12</sup> see Eq. (6.10). This is a theoretical maximum data transmission rate for all possible multilevel and multiphase encoding techniques. As can be seen in Eq. (6.10), the maximum rate depends only on channel bandwidth and the ratio between signal power to noise power. There is no dependence on modulation method.

$$R_{\max} = B_0 \log_2(\text{OSNR} + 1) \tag{6.10}$$

where  $R_{max}$  = maximum data rate for the channel (also known as channel capacity), Gbps  $B_a$  = optical channel passband, GHz

OSNR = channel optical signal to noise ratio

For example, for a 62 GHz channel passband (for standard 200 GHz DWDM channel spacing) and an OSNR of 126 (21 dB) the maximum possible channel capacity is 433 Gbps. As channel bandwidth decreases so does maximum transmission rate. For a 30 GHz channel passband (100 GHz DWDM channel spacing) and OSNR of 126 (21 dB) the maximum possible channel capacity is 216 Gbps. These theoretical maximum transmission rates are much higher than are currently available. There are numerous reasons for this including encoding/ modulation technology and laser wavelength instability. To accommodate laser wavelength drift, a larger DWDM passband is required than is occupied by the signal itself. For an NRZ modulated DFB laser, a minimum bandwidth of  $0.75 \times$  transmission rate<sup>13</sup> is required to recover the signal information with a low BER. Therefore, a 10 Gbps signal requires approximately 7.5 GHz of bandwidth. However, due to laser drift and signal side band power, the DWDM channel passband (B) is much wider, typically 62 GHz for 200 GHz spaced lasers and 30 GHz for 100 GHz spaced lasers.

The amount of spectrum a signal occupies in a channel, for a given transmission rate, is referred to as information spectral density (also spectral efficiency) and is given by Eq. (6.11). It is a measure of how

WDM Spacing	2.5 Gbps 10 Gbps		40 Gbps	100 Gbps	
2500 GHz (CWDM)	0.001	0.004	0.16	0.04	
200 GHz	0.013	0.05	0.2	0.5	
100 GHz	0.025	0.1	0.4	1	
50 GHz	0.05	0.2	0.8	2	
25 GHz	0.1	0.4	1.6	4	
12.5 GHz	0.2	0.8	3.2	8	

 
 TABLE 6.1
 Information Spectral Density for Given DWDM Channel and Transmission Rate

much of the DWDM channel is used for the signal transmission and how much is wasted. Using current NRZ and RZ modulation techniques information spectra density of 0.4 bps/Hz<sup>14</sup> (spectral efficiency of 40%) and 0.8 bps/Hz using carrier suppressed return-to-zero CS-RZ modulation<sup>15</sup> is achievable. Other modulation techniques are required to achieve spectral density over 1 bps/Hz.<sup>16,17</sup>

Spectral densities for various DWDM and CWDM channel spacing and transmission rates are shown in Table 6.1. Spectral densities up to 0.4 bps/Hz for NRZ modulation are commercially available.

$$S = \frac{R}{B_s} \tag{6.11}$$

where S = information spectral density (spectral efficiency), bps/Hz R = signal transmission rate, Gbps

 $B_s = DWDM ITU$  channel spacing, GHz

**Note:** A 2.5 Gbps EM-DFB signal at -20 dB spectral width is 13 GHz,<sup>18</sup> 10 Gbps EM-DFB signal at -20 dB spectral width is 38 GHz, and 40 Gbps EM-DFB signal at -30 dB spectral width is 60 GHz.<sup>19</sup>

## 6.7.2 Expanding Fiber Capacity Using Basic DWDMs

Deployment of basic (passive) DWDMs can be a very cost-effective solution to expanding fiber capacity. Typical 8-channel basic 10G DWDM units can be acquired for under \$15,000 USD,<sup>20</sup> which would increase fiber link capacity to 80 Gbps. Sixteen-channel 10G DWDM units can be acquired for under \$20,000, which would increase fiber link capacity to 160 Gbps. Thirty-two-channel 10G DWDM units can be acquired for under \$40,000, which would increase fiber link capacity to 320 Gbps. In addition to the basic DWDM units, proper DWDM transceivers (SFP, XFP, Xenpak, GBIC, etc.) need to be acquired for each channel connecting to the DWDM units. The transceiver

must use a laser that matches a wavelength assigned to one of the DWDM's channels and has the same DWDM ITU-T grid spacing (200, 100, 50, 25 GHz) specification. For example, when deploying an 8-channel 200 GHz basic DWDM with channel wavelengths of 1547.72, 1549.32, 1550.92, 1552.52, 1554.13, 1555.75, 1557.36, 1558.98 nm, then each equipment laser transceiver must be the DWDM 200 GHz type with one of these listed channel wavelengths.

Additional costs include labor to install and test the units. Typical basic DWDM units require no (or very little) configuration or setup. Installation is usually just bolting the units to a rack and connecting the fiber jumpers.

Basic DWDMs can be deployed on fiber cable links that meet the below criteria:

- 1. The total link loss, including the DWDM insertion loss, is less than the transmission equipment optical budget. If intermediate OADMs are used then their insertion loss needs to be included in the link budget.
- 2. Standard single-mode fiber (G.652) is used and there are no dispersion issues.
- 3. There is no intermediate fiber switching device in the link that may increase fiber length and loss.
- 4. Optical launch power into the fiber (after DWDM loss) is less than +2 dBm per wavelength, to avoid any nonlinear distortions.

Table 6.2 estimates show maximum fiber cable lengths using G.652 fiber with attenuation of 0.25 dB/km @ 1550 nm for various transceivers and basic (passive) DWDMs. DWDM insertion loss (IL) is shown for one unit and is multiplied by two for total span IL. Cable lengths greater than these can be achieved by deploying optical amplifiers and dispersion compensation modules (where required).

DWDM Transceiver	4-Channel IL = 2.0 dB	8-Channel IL = 3.5 dB	16-Channel IL = 4.0 dB	32-Channel IL = 5.0 dB	
10 Gbps Budget is 23 dB	76 km	64 km	60 km	52 km	
2.5 Gbps Budget is 26 dB	88 km	76 km	72 km	64 km	
1 Gbps Budget is 26 dB	88 km	76 km	72 km	64 km	

 TABLE 6.2
 Basic DWDM System Maximum Fiber Cable Length Estimate Using

 G.652 Fiber at 0.25 dB/km Attenuation



FIGURE 6.12 Eight-channel DWDM typical configuration.

Figure 6.10*a* shows a basic 8-channel DWDM system using four unidirectional or universal 8-channel DWDMs, two DWDMs at each end of the two-fiber link. Each DWDM channel consists of Tx and Rx fiber that connects to the appropriate client transceiver, see Fig. 6.12. WDM West Tx and WDM West Rx units can often be enclosed in one package called Mux/Demux, see Fig. 6.13. Then connectors for both Tx and Rx channel fibers can be located next to each other. This makes WDM channel identification and connection easier and allows for dual type jumpers, such as dual SC or dual LC, to be used. Each dual jumper represents a channel.

**Example 6.1** Two dark fibers in a fiber cable are being leased by a company between its two offices. The fiber cable length L = 50 km. The dark fibers are currently connected to the company's 10 GigE switch, which is equipped with 1550 XFP transceivers, and provides high-speed intranet office communications. The company wants to expand its fiber link capacity without leasing additional fibers to meet current demands and future expansion requirements to at least eight 10 Gbps channels that can support various protocols including the current 10 GigE system, other GigE systems, SONET/SDH, and ATM systems. The solution needs to be highly reliable and be able to be installed quickly in one night with minimal disruption to the existing communications system. The measured dark fiber link loss on each fiber is 12.0 and 12.5 dB. Unfortunately, the company entered into the fiber lease not knowing any other specifications of the two dark fibers, such as chromatic dispersion or PMD that may affect



FIGURE 6.13 Eight-channel DWDM mux/demux typical configuration.

performance at rates of 1 Gbps and higher. What is the solution and what will it cost the company?

A good solution for this company is to deploy a basic (passive) DWDM system, see Fig. 6.13. It is protocol independent, rate independent, highly reliable and simple to install with typical down time of less than 30 minutes. It is always a good idea to determine the specifications of any dark fiber link before acquiring it or by fiber characterization testing. However, this link has been in operation for a number of years at 10 Gbps without any noticeable link errors using standard 1550 transceivers. Therefore, it can be safely concluded that using DWDM 10 Gbps transceivers will result in the same performance as long as optical budgets are met.

To determine the maximum number of channels this link can support, basic DWDM manufacturer's insertion loss specifications are obtained for 8-, 16-, and 32-channel DWDMs and are as follows:

8-channel IL: 3.5 dB 16-channel IL: 4.5 dB 32-channel IL: 7.0 dB

To determine the total link loss, Eq. (6.12) can be used. The DWDM insertion loss is multiplied by two because it is inserted at both ends of the fiber link.

$$\Gamma_T = 2 \times IL_{\text{DWDM}} + \Gamma_{\text{fiber}} \tag{6.12}$$

where  $\Gamma_{T}$  = total link loss, dB  $\Gamma_{fiber}$  = fiber loss, dB IL<sub>DWDM</sub> = DWDM insertion loss, dB



FIGURE 6.14 Basic 10 Gbps DWDM 50 km link with EDFAs.

Adding these DWDM units to the fiber link (worst-case fiber) would result in total link loss as follows:

8-channel IL plus fiber maximum link loss:

 $2 \times 3.5 + 12.5 = 19.5_{dB}$ 

16-channel IL plus fiber maximum link loss:

 $2 \times 4.5 + 12.5 = 21.5_{dB}$ 

32-channel IL plus fiber maximum link loss:

 $2 \times 7.0 + 12.5 = 26.5_{dB}$ 

In addition to the DWDMs, proper DWDM transceivers for all equipment that will connect to the DWDM link must be found and optical specifications reviewed. Worst-case optical budget for transceivers is determined to be for the 10 GigE switch, which requires DWDM XFPs and has an optical budget of 23 dB that includes a 2 dB dispersion penalty. Therefore, it is clear that either the 8-channel or 16-channel DWDM system can be used since they are both below 23 dB. Also, if the company wanted to use the 32-channel system, all that is required, in this case, is to deploy optical amplifier booster EDFAs with a gain of 5 dB or more. They are placed after the DWDMs on the DWDM common out fiber at both ends of the link to compensate for the high DWDM insertion loss, see Fig. 6.14. A 5 dB gain would decrease the total link loss from 26.5 to 21.5 dB, which is then within optical budget of the XFP.

The cost of such a system would include the purchase and installation of the DWDM units, the purchase and installation of the proper DWDM transceivers for all equipment, and a short amount of down time to insert this system into the link.

## 6.8 CWDM

Coarse wavelength division multiplexing (CWDM) is a WDM technology where the wavelength spacing is 20 nm (approximately 2500 GHz) as defined by ITU-T G.694.2. Eighteen channels are defined in the ITU standard, see Table C4 in App. C. The first two channels with center nominal wavelengths of 1271 and 1291 nm (hereafter referred to as channel numbers) may exhibit high loss and may be unusable in some fiber types. Channels 1351 to 1451 nm occur near the 1383 nm fiber water peak where fiber attenuation is high, typically >2 db/km, and may also be unusable. However, this high loss region is flattened



FIGURE 6.15 CWDM fiber spectrum.

in newer "full spectrum" type fiber conforming to standard ITU-T G.652.c/d<sup>21</sup> such as Corning SMF-28e\*, and OFS Allwave<sup>+</sup> fiber, see Fig. 6.15.

Because of lower fiber attenuation at higher wavelengths and water peak attenuation, 8-channel CWDM multiplexers typically use channels 1471 to 1611 nm and 4-channel units use channels 1611 to 1551 nm, see Table C4 in App. C.

CWDM transceivers are significantly less expensive than DWDM transceivers. This can be attributed to the factors listed below:

- 1. CWDM transceivers use simpler laser designs without elaborate temperature stabilization circuitry to keep the laser from drifting out of the DWDM narrow channel passband (60 GHz). The CWDM wider channel passband (1600 GHz) allows for laser drift without costly laser cooling and control circuitry.
- 2. Because of the large CWDM channel passband, transceivers have less stringent laser center wavelength and spectral width tolerances.
- 3. CWDM lasers use lower cost directly modulated DFB and VCSEL technology.

The CWDM lower cost technology is ideal for increasing fiber capacity up to 18 channels in metro fiber applications (<80 km).

<sup>\*</sup>Corning Incorporated trademark

<sup>&</sup>lt;sup>+</sup>Furukawa Electric North America Inc. trademark

It should be noted that non-CWDM transceivers that are labeled 1310 or 1550 nm will likely not work in CWDM channels 1311 or 1551 nm because of their large laser drift and wide manufacturing tolerances. The 1310 and 1550 designation on these transceivers indicates only that their laser will operate in the 1310 or 1550 bands (O and C bands) and not necessarily at that specific wavelength or CWDM channel. CWDM passband is  $\pm$  6.5 nm and these transceiver lasers may not fall into this spectrum or may drift out of this spectrum. It is best to acquire transceivers that are designated CWDM when using this WDM technology.

## 6.8.1 CWDM Channel Capacity

Due to the much wider channel spacing and broader passband of approximately 13 nm (1600 GHz), high transmission rates may be possible<sup>22</sup> (10, 40, and 100 Gbps) as can be calculated by Eq. (6.10) and seen in Table 6.1. Currently (at time of printing) up to 10 Gbps CWDM transceivers are commercially available.

## 6.8.2 Expanding Fiber Capacity Using Basic CWDMs

Deployment of basic (passive) CWDMs can be a more cost-effective solution than deploying DWDMs. Because of their wide channel spacing (20 nm), CWDM laser drift does not need to be controlled as vigorously as in DWDM systems. This significantly reduces the price of these units. Typical CWDM GigE pluggable transceivers can be acquired for under \$2000<sup>23</sup> and 8-channel basic CWDM units for under \$3500. Using these prices, an 8-channel CWDM single-span system costs \$7000 for two CWDM end units plus two times each pluggable transceiver price to equip each channel. This 8-channel system price is much less than comparable 8-channel DWDM systems. The advantages and disadvantages of deploying a CWDM system are summarized in the following table.

Deploying a CWDM System				
Advantages	Disadvantages			
Both CWDM multiplexers and pluggable transceivers are less expensive than DWDM products.	Due to the wider spectral width of CWDM lasers, chromatic dispersion distance limitation is typically less than 80 km for most pluggable transceivers.			
CWDM links are Ideal for shorter fiber spans.	Because CWDM band spans across the entire fiber spectrum, total fiber link loss and dispersion may change considerably between channels.			

CWDM lasers consume less power than DWDM lasers (approximately 20% less <sup>24</sup> ) because they use uncooled laser without any temperature stabilization circuitry.	For fiber that is not "full spectrum, G.652.c/d" (water peak at 1383 nm), channels 1351 to 1451 will suffer from high optical attenuation and it is likely unusable in 16-channel systems except possibly for very short links. Eight-channel CWDM systems are still possible (channels 1471 to 1611).
CWDM technology can be deployed in dispersion shifted fiber (DSF) type spans that currently could not support DWDM technology due to four-wave mixing (FWM) interference, see Section on FWM interference. FWM interference power levels depend on channel spacing. With CWDM wide channel spacing, FWM interference levels are much lower and inconsequential compared to DWDM systems. This technology can be used to increase capacity of existing DSF cable builds that could not be increased previously with DWDM technology.	Channels 1531, 1551, and 1571 use all of the C band spectrum that could be used to deploy a high channel count DWDM system.
	CWDM pluggable transceivers may have a worst maximum BER (typical $10^{-10}$ ) compared to most DWDM transceivers' maximum BER (typical $10^{-12}$ ). This higher BER may not be acceptable for some applications.
	To compensate for fiber loss, EDFA amplifiers cannot be used with this technology because of the EDFA restricted passband. However, Raman amplifier technology may be effective in some applications.

As in DWDM technology, CWDM lasers or CWDM pluggable transceivers (SFP, XFP, Xenpak, GBIC) need to be acquired for each channel connecting to the CWDM multiplexer unit. A proper CWDM laser or pluggable transceiver has a laser that matches a wavelength assigned to one of the CWDM channels. Since there are no channel spacing options for CWDMs, this is the only criterion needed to be matched to the CWDM multiplexer for compatibility.

Additional system costs can include labor to install and test the units. Many basic CWDM units require no or very little configuration or setup. Installation is usually just bolting the units to a rack and connecting the fiber jumpers.

Basic CWDMs can be deployed on fiber cable links that meet all of the below criteria:

- 1. The total link loss, including the CWDM insertion loss, is less than the transmission equipment optical budget. Because of the very wide fiber spectrum that may be used in CWDM deployment, see Fig. 6.15, fiber optical loss can vary greatly between channels. Loss measurements should be taken at every channel when designing the link to ensure optical budgets are met. If intermediate OADMs are used then their insertion loss needs to be included in the link budget.
- 2. Standard single-mode fiber (G.652) is used for 8-channel systems and "full spectrum" fiber (G.652.c/d) is used for 16-or 18-channel systems. It may be possible to use standard single-mode fiber (G.652) for short 16- or 18-channel deployments. However, loss measurements on channels affected by the fiber 1383 nm water peak high attenuation, such as 1351, 1371, 1391, 1411, 1431 nm, should be conducted to ensure link loss is within budget.
- 3. There are no intermediate fiber switching devices in the link that may increase fiber length and loss.
- 4. If the fiber type is unknown or if the fiber type is DSF, CWDM technology may still be feasible. Fiber link chromatic dispersion measurements should be obtained at each CWDM channel to ensure CD is within equipment budget.

Table 6.3 shows typical estimated maximum fiber cable lengths of G.652 fiber with attenuation of 0.37 dB/km @ 1311 nm, 2.5 dB/km @ 1391 nm, 0.25 dB/km @ 1551 nm, for various equipment optical budgets and channel counts using basic (passive) CWDMs and shown insertion losses (IL). Cable lengths greater than these may be achieved by deploying Raman optical amplifiers and dispersion compensation modules (where required). CWDM IL is shown for one unit and is multiplied by two for total span IL.

**Example 6.2** Two dark fibers in a fiber cable are being leased by a company between its two offices. The fiber cable length L = 40 km and the cable installation occurred 15 years ago. The dark fibers are currently connected to the company's GigE switch, which is equipped with 1550 SFP transceiver, and provides high-speed intranet office communications. The company wants to expand its fiber link capacity without leasing additional fibers to meet current demands and future expansion requirements to at least eight WDM 2.5 Gbps channels that can support various protocols including the current GigE system, other GigE systems, SONET/SDH, and ATM systems. The solution needs to be highly reliable and be able to be installed quickly in one night

CWDM	4-Channel		8-Channel			16-Channel			
	IL = 2.5 dB		IL = 3.5 dB			IL = 5.0 dB			
Fiber	1311	1391	1551	1311	1391	1551	1311	1391	1551
attenuation	nm	nm	nm	nm	nm	nm	nm	nm	nm
	0.37	2.5	0.25	0.37	2.5	0.25	0.37	2.5	0.25
	dB/km	dB/km	dB/km	dB/km	dB/km	dB/km	dB/km	dB/km	dB/km
100 Mbps to 2.7 Gbps transceiver with budget of 25 dB	54 km	8 km	80 km	48 km	7 km	72 km	40 km	6 km	60 km

 TABLE 6.3
 Basic Passive CWDM System Maximum Cable Length Estimate Using

 G.652 Fiber

with minimal disruption to the existing communications system. The measured dark fiber link loss at 1551 nm on each fiber is 10.0 and 9.5 dB. Unfortunately, the company entered into the fiber lease not knowing any other specifications of the two dark fibers. What is the solution and what will it cost the company?

Since this is an older fiber cable installation, it is safe to assume that the fiber cable does not use "full spectrum" fiber. Also since the fiber may be DSF, which is not suitable for DWDM, CWDM technology is selected. Because of the long length, 40 km, the water peak channels will be useless if a 16-channel CWDM system is deployed. For an 8-channel system, loss measurements should be conducted at each end of the 8-channel spectrum and the center channel. Measurement at 1551 nm resulted in worst-case fiber loss of 10.0 dB. Additional measurements at 1471 and 1611 nm result in worst-case fiber link loss reading of 11.5 dB. Therefore we will design to this maximum fiber loss.

To determine the maximum number of channels this link can support, manufacturer's insertion loss specifications are obtained for 8- and 16-channel CWDMs and are as follows:

8-channel IL: 3.5 dB 16-channel IL: 5.0 dB

To determine the total link loss, Eq. (6.13) can be used. The CWDM insertion loss is multiplied by two because it is added to both ends of the fiber link.

$$\Gamma_T = 2 \times IL_{CWDM} + \Gamma_{fiber} \tag{6.13}$$

where

$$\begin{split} & \Gamma_{_{T}} = \text{total link loss, dB} \\ & \Gamma_{_{\text{fiber}}} = \text{fiber loss, dB} \\ & \text{IL}_{_{\text{CWDM}}} = \text{CWDM insertion loss, dB} \end{split}$$

Adding these CWDM units to the fiber link (worst-case fiber) would result in total link loss as follows:

8-channel CWDM IL plus fiber maximum link loss:

$$2 \times 3.5 + 11.5 = 18.5_{dF}$$

16-channel CWDM IL plus fiber maximum link loss:

$$2 \times 5.0 + 11.5 = 21.5_{dB}$$

CWDM pluggable transceivers that work with transmission rates of 100 Mbps to 2.7 Gbps are available with optical budgets of 25 dB. Maximum link loss for both 8-channel and 16-channel CWDM designs are within optical budget for wavelengths 1471 to 1611 nm, 8-channel systems.

The 16-channel CWDM can be considered for use to obtain two or four more channels not in the water peak, 1331, 1311, 1291, and 1271 nm. Measuring losses at these wavelengths results in a maximum loss of 14.0 dB. Using Eq. (6.13) we obtain maximum link loss at these wavelengths as follows:

$$2 \times 5.0 + 14.0 = 24.0_{dB}$$

This is within the pluggable transceiver's optical budget of 25 dB. Therefore, as long as the high attenuation channels are avoided, a 16-channel CWDM can be used to achieve twelve usable channels.

Since cable fiber type is unknown, chromatic dispersion measurements were conducted across the usable CWDM band, which resulted in minimum CD of 0 ps/nm and maximum CD of  $\pm 300$  ps/nm. Equipment specifications CD limit is  $\pm 500$  ps/nm. Therefore, CD is not a concern for this deployment.

### 6.8.3 CWDM Capacity Expansion Using DWDMs

It is possible to cascade a DWDM multiplexer with a CWDM multiplexer system to increase link capacity, see Fig. 6.16. CWDM channel passband of  $\pm 6.5$  nm can pass up to sixteen 100 GHz channels and eight 200 GHz channels, see Table C5 in App. C. CWDM channel 1531 nm has a passband of 1524.62 to 1537.38 nm, CWDM channel 1551 nm has a passband of 1544.62 to 1557.38 nm, CWDM channel 1571 nm has a passband of 1564.62 to 1577.38 nm (assuming laser drift of  $\pm 0.12$  nm). These passbands fall within the DWDM S, C, and L bands, see Fig. 6.10, where DWDM lasers (SFP, Xenpaks, etc.) are available. However, two concerns need to be addressed for such a configuration to be practical.



FIGURE 6.16 DWDM multiplexers cascaded with CWDM multiplexers.

- 1. DWDM multiplexer insertion loss adds to the CWDM link loss decreasing the link optical budget and transmission distance.
- Total DWDM aggregate output power can interfere with other CWDM channels.

The first concern can be addressed by including DWDM insertion loss in total link loss calculations to ensure the equipment optical budget is not exceeded. The second concern can cause interference on adjacent CWDM channels if the aggregate DWDM channel power is too high. Typical DWDM laser output power is approximately 0 dBm. With eight DWDM channels feeding into one CWDM channel, the total aggregate DWDM power into that one CWDM channel is 9 dBm minus the DWDM insertion loss. This power is significantly higher than the other CWDM channel typical launch powers of approximately 0 dBm. DWDM signal spillover to the other CWDM channels can decrease CWDM channel OSNR, thereby affecting BER performance. Calculations can be made to determine the amount of spillover to adjacent channels as shown in the following example.

**Example 6.3** An 8-channel DWDM multiplexer will be cascaded with an existing 16-channel CWDM multiplexer system. The existing 16-channel CWDM adjacent channel isolation specification is 28 dB. Insertion loss of the DWDMs and CWDMs are 3 dB each. Equipment CWDM laser launched power is 0 dBm and receiver sensitivity is -23 dBm @  $10^{-10}$  BER and OSNR 21 dB. Equipment DWDM laser launched power is 0 dBm and receiver sensitivity is -25 dBm @  $10^{-12}$  BER. Fiber total loss is 10 dB.

CWDM channel total link loss is the total fiber loss plus two times the CWDM insertion loss, which calculates to 16 dB. DWDM channel total link loss is the total fiber loss, plus two times the CWDM insertion loss and plus two times the DWDM insertion loss, which calculates to 22 dB.

$$\Gamma_{T-CWDM} = 2 \times IL_{CWDM} + \Gamma_{fiber}$$
(6.14)

 $\Gamma_{T-CWDM} = 16_{dB}$ 

 $\Gamma_{T-\text{DWDM}} = 2 \times \text{IL}_{\text{DWDM}} + 2 \times \text{IL}_{\text{CWDM}} + \Gamma_{\text{fiber}}$ (6.15)

 $\Gamma_{T-{\rm DWDM}}=22_{dB}$ 

$$P_{Rx-CWDM} = P_{Tx-CWDM} - \Gamma_{T-CWDM}$$
(6.16)

 $P_{Rx-CWDM} = -16_{dBm}$ 

$$P_{Rx-DWDM} = P_{Tx-DWDM} - \Gamma_{T-DWDM}$$
(6.17)

$$P_{Rx-DWDM} = -22_{dBn}$$

where  $\Gamma_{T-DWDM}$  = total DWDM channel link loss, dB  $\Gamma_{T-CWDM}$  = total CWDM channel link loss, dB IL<sub>DWDM</sub> = DWDM insertion loss, dB IL<sub>CWDM</sub> = CWDM insertion loss, dB 
$$\label{eq:product} \begin{split} & \Gamma_{\rm fiber} = {\rm fiber\ link\ loss,\ dB} \\ & P_{Rx-{\rm DWDM}} = {\rm equipment\ receive\ power\ for\ a\ DWDM\ channel,\ dBm} \\ & P_{Rx-{\rm CWDM}} = {\rm equipment\ receive\ power\ for\ a\ CWDM\ channel,\ dBm} \\ & P_{Tx-{\rm CWDM}} = {\rm equipment\ DWDM\ laser\ transmit\ power} \\ & P_{Tx-{\rm CWDM}} = {\rm equipment\ CWDM\ laser\ transmit\ power} \end{split}$$

With CWDM laser launch power of 0 dBm, the signal is received at -16 dBm. CWDM signal maximum noise level is at -37 dBm (received signal level minus OSNR) for BER of  $10^{-10}$ . Assuming interference for a CWDM channel will be received from both adjacent channels, the signal noise level is decreased by 3 dB to -40 dBm.

Totaling the eight DWDM signals, each at 0 dBm (1 mW), total aggregate power is +9.0 dBm (8 mW). Power out of the DWDM is +6.0 dBm (DWDM IL subtracted) and into the CWDM channel. At the other end of the CWDM fiber link the CWDM channel signal power is now -10.0 dBm (DWDM out minus CWDM link loss). With a specified 28 dB CWDM channel isolation the adjacent channel noise maximum due to this aggregate DWDM signal is -38.0 dBm. This is hotter (greater) than the CWDM signal noise floor at -40 dBm and a degrade in adjacent CWDM OSNR can be expected.

If three DWDM channels are removed, the total aggregate power for five signals is 6.99 dBm (5 mW). Power out of the DWDM is 3.99 dBm. At the other end of the CWDM fiber link the CWDM channel signal power is now -12.0 dBm (DWDM output minus CWDM link loss). With a specified 28 dB CWDM isolation, the adjacent channel noise maximum is now -40 dBm. This is now at the specification noise limit for equipment OSNR -21 dB @ BER  $10^{-10}$ . The DWDM channel receive power is -22 dBm, which is determined from equipment DWDM laser signal launch minus DWDM channel link loss. This is within the equipment sensitivity limit of -25 dBm @ BER  $10^{-12}$ .

Instead of decreasing the DWDM channel count, another option would be to decrease each DWDM channel launch power equally. If we keep the 8-channel DWDM signals but decrease each DWDM signal launch power by 2 dB, from 0 to -2 dBm, the same result can be achieved. The total aggregate power for eight signals launching at -2 dBm is +7.0 dBm. Power out of the DWDM is 4.0 dBm. At the other end of the CWDM fiber link the CWDM channel signal power is now -12.0 dBm (DWDM output minus CWDM link loss). With a specified 28 dB CWDM isolation, the adjacent channel noise maximum is now -40 dBm. This is now at the specification noise limit for equipment OSNR -21 dB @ BER  $10^{-10}$ . The DWDM channel receive power is -24 dBm, which is determined from equipment DWDM laser signal launch minus DWDM channel link loss. This is still within the equipment sensitivity limit of -25 dBm @ BER  $10^{-12}$ .

## 6.9 Cross-Band WDM

Cross-band WDMs combine two channels from different bands into one fiber. One channel has an O-band passband (1260 to 1360 nm) and the other channel has a C-band passband (1530 to 1565 nm), see Fig. 6.15. Lasers with any wavelength in these two bands can be used with these WDMs. The lasers do not need to meet any specific standard (such as ITU) or spectral width because the WDM channel passband is very wide, the entire band. Therefore, any laser with wavelength in O or C bands can be used to double the fiber's capacity. Figure 6.17*a* shows a 2.5G SONET system with 1310 nm lasers and a GigE switch with 1550 nm lasers that normally would require four fibers for communication. By adding four cross-band WDMs as shown in Fig. 6.17*b* and *c*, the fiber count is reduced to two fibers using the same equipment lasers. The fiber capacity is double with



FIGURE 6.17 Cross-band WDM application.



FIGURE 6.18 Cross-band WDM and DWDM application.

these cross-band WDM units for a total price of approximately \$3000 for the cross-band WDMs. If both systems happened to have lasers with wavelengths in the same band, then one system's transceiver would need to be changed for lasers with wavelengths in the other band.

Two configurations are possible using cross-band WDMs. Figure 6.17*b* shows the most common where unidirectional cross-band WDMs are deployed and each system uses wavelengths in each band. In Fig. 6.17*c*, universal cross-band WDMs are deployed and each system uses one dedicated fiber for communications. Lasers at both ends of the same system must use different band lasers. Before implementing this configuration, optical receiver specification should be reviewed to ensure the receiver can accept signals with wavelengths from both bands (many can).

Cross-band WDMs can also be combined with DWDMs to allow O-band transmission in a DWDM system. Figure 6.18 shows a DWDM system combined with a 1310 nm SONET system using cross-band WDMs. Since the cross-band WDM passband is the entire C band, the DWDM can have channels only in C band. Note that the total link loss includes the sum of the DWDM and WDM insertion losses.

# 6.10 WDM Specification

## 6.10.1 Basic WDMs

The following WDM specifications are commonly used to define operating parameters. Additional definition and standard values can be obtained from ITU-T G.671<sup>25</sup> and Telcordia GR-1209.<sup>26</sup>



FIGURE 6.19 WDM insertion loss diagram.

#### **Insertion Loss (IL)**

This is the optical power loss measured between a WDM channel input and output ports, see Figs. 6.19*a* and 6.20. The measurement unit is dB. Maximum insertion loss for any WDM channel is provided in specifications. The maximum insertion loss may differ for DWDM multiplexer and demultiplexer units.

Maximum insertion loss for FBG and TFF WDMs can also be specified for a mux/demux matched pair. This is the total loss for both multiplexer and demultiplexer units in the fiber link. Internally the optical WDM signals propagate from one channel filter to the other in a sort of series fashion, see Figs. 6.4 and 6.6. The signal that matches the channel's wavelength is dropped or else it continues to the next channel filter. Hence, filters closer to the aggregate (common) fiber end have a lower insertion loss than filters further from it. Filter channels in matched multiplexer and demultiplexer pairs are sequenced in opposite directions from aggregate fiber such that the combined loss for each channel is more uniform and less than the combined loss of the two highest loss channels. This method provides a lower maximum insertion loss for the pair.

For OADMs, the insertion loss is divided into through loss and channel add/drop loss. The OADM through loss is measured between the two common ports. The OADM channel add/drop loss is measured from the common port and a drop port, see Fig. 6.19*b*.



FIGURE 6.20 WDM filter plot.

### **Channel (Passband) Ripple or Flatness**

This is the peak-to-peak difference in insertion loss in a channel's passband, see Fig. 6.20. Unit of measure is dB. Typically, value is less than 0.5 dB.

### **Channel Loss Uniformity**

This is the maximum insertion loss difference between all channels, see Fig. 6.20. Unit of measure is dB.

#### **Channel Wavelength**

This is the center wavelength of each channel, see Fig. 6.20. Unit of measure is nm.

### **Channel Spacing**

This is the ITU-T WDM channel spacing measured between center wavelengths of adjacent channels. DWDM values are 200, 100, 50, and 25 GHz, see Fig. 6.20. CWDM channel spacing is 20 nm.

### **Channel Passband**

This is the WDM channel filter passband measured 0.5 or 3 dB down from filter center, see Fig. 6.20. Unit of measure is nm or GHz. Passband value varies among manufacturers and with channel spacing. Typically values for a 0.5 dB down passband are 0.5 nm for 200 GHz spaced channels, 0.22 nm for 100 GHz spaced channels, and 0.1 nm for 50 GHz spaced channels.

## Adjacent Channel Isolation (Demultiplexer)

This is the maximum optical power leakage to adjacent channels referenced to launch channel power, see Fig. 6.21*a*. Unit of measure is dB. A value greater than 25 dB is common.

### Nonadjacent Channel Isolation (Demultiplexer)

This is the maximum optical power leakage to nonadjacent WDM channels referenced to the launch channel power, see Fig. 6.21*b*. Unit of measure is dB. A value greater than 45 dB is common.




## **Directivity (Multiplexer)**

This is the maximum channel power reflected back into other WDM channels referenced to the launched channel power, see Fig. 6.21*c*. Unit of measure is dB. A value greater than 50 dB is common.

## **Return Loss**

This is the maximum optical power reflected back onto itself in the same channel referenced to the launched power, see Fig. 6.21*d*. Unit of measure is dB. A value greater than 45 dB is common.

#### **Chromatic Dispersion**

This is the amount of chromatic dispersion added to the WDM channel. Unit of measure is ps/nm. See Chap. 4 for details. Specified as a maximum value.

#### **Polarization Mode Dispersion**

This is the amount of PMD added to the WDM channel. Unit of measure is ps. See Chap. 5 for details. Specified as a maximum value. Value less than 0.1 ps is common.

#### **Polarization Dependent Loss**

This is the amount of PDL added to the WDM channel. Unit of measure is dB. See Chap. 5 for details. Specified as a maximum value. Value less than 0.1 dB is common.

#### **Power Handling**

This is the maximum optical launch power into any channel. Unit of measure is dBm. Value of 300 mW (+25 dBm) is common.

## **Operating and Storage Temperatures**

This is the temperature range that the unit can operate within specification and be safely stored. Typical operating temperature for basic (passive) WDM is  $0^{\circ}$ C to + $60^{\circ}$ C, and for storage - $40^{\circ}$ C to + $80^{\circ}$ C.

# 6.11 Couplers and Splitters

A fiber optic coupler is a general term referring to a device that splits or combines optical power between three or more fibers. The device is commonly passive and is made by fusing fiber ends together in a specific manner to achieve the required results. Typically it splits or combines the entire optical band or bands. Couplers are available for single C/L or O band operation or all-band operation. The number of fiber inputs and outputs is expressed as  $M \times N$ . The letter M represents the number of input fibers and the letter N represents the number of output fibers. Common types are  $1 \times N$ ,  $2 \times 2$ ,  $4 \times 4$ ,  $8 \times 8$ , but can be any number of input and output fibers. The combined optical

input powers are split between the output fibers and each output fiber's total power is reduced.

WDMs are a type of  $1 \times N$  coupler that also contains channel filters.

# 6.11.1 Bidirectional Coupler (Circulator)

A bidirectional coupler is an optical passive device that couples light transmission, of any wavelength, in both directions (transmit and receive optical signals) into one fiber, see Fig. 6.22. The basic unit is comprised of a single passive optical circulator that is able to separate signal transmission by direction. Refer to Fig. 6.22*a*, when a signal enters one port of the circulator it is directed to the adjacent port, in cyclic order, and the other ports remain isolated. Signal entering port



FIGURE 6.22 Bidirectional coupler.

		1550	) nm	1310 nm		
Transmission Rate	Equipment OSNR (dB)	Fiber Loss (dB)	Distance @ 0.25 dB/km	Fiber Loss (dB)	Distance @ 0.35 dB/km	
10 Gbps	21	6	24 km	3	8 km	
2.5 Gbps or less	15	12	48 km	9	25 km	

 TABLE 6.4
 Bidirectional Coupler Maximum Transmission Distance

1 is directed to port 2, signal entering port 2 is directed to port 3, and signal entering port 3 is directed back to port 1. For a bidirectional coupler, port 1 is the common fiber port, port 2 is the signal out fiber port, and port 3 is the signal in fiber port. Typical insertion loss of a bidirectional coupler is less than 1 dB.

A two fiber link, see Fig. 6.22b, can possibly be reduced to a onefiber link, see Fig. 6.22c, without the need for any special laser changes. Transmission in both directions in one fiber at the same wavelength is possible with basic bidirectional couplers. But their use is limited by reflected optical power degrading receiver OSNR. Since the same fiber is used for both signal transmission and reception, signal back reflections due to Rayleigh scattering and Fresnel reflections (connector reflections) increase receiver noise and decrease signal OSNR. Typical fiber reflections back into the receiver (return loss) at the same end as the laser are approximately 30 dB (at 1550 nm) below laser launch power for a long terminated fiber, assuming clean ultra polish connectors (UPC). This reflected power is seen as noise to the receiver reducing signal OSNR and limiting transmission distance. Table 6.4 shows maximum bidirectional coupler transmission distances that may be achieved using G.652 fiber, attenuation of 0.25 dB/km @ 1550 nm, attenuation of 0.35 dB @ 1310 nm, maximum fiber link return loss of 30 dB @ 1550 nm, and clean UPC with 50 dB or better return loss.

When using this technology, it is important to ensure all fiber connectors are low reflectance UPC type and are clean. An unterminated fiber can cause strong signal reflections back to the same end receiver. This may cause certain receivers to lock onto this reflected signal tricking the receiver in showing it as a valid signal, when in fact the receiver is seeing its own signal looped back on to itself.

## 6.11.2 Red and Blue Band Coupler

A bidirectional coupler can be combined with red and blue band filters to provide red and blue band separation for bidirectional DWDM transmission in one fiber. See Table C2 in App. C. for red and blue band DWDM channel assignments. Each band is used for signal transmission in one direction. Reflected signal noise is filtered



FIGURE 6.23 Red and blue band splitter configuration.

out by the band filters, which eliminates limitation issues shown in Table 6.4. This configuration allows for optical amplification of each band to increase transmission distance over single-fiber facilities, see Fig. 6.23.

#### 6.11.3 Splitters

Fiber splitters divide optical power from one common port to two or more split ports and combine all optical power from the split ports to one common port ( $1 \times N$  coupler). They operate across the entire band or bands such as C, L, or O bands. The three port  $1 \times 2$  tap is a splitter commonly used to access a small amount of signal power in a live fiber span for measurement or OSA analysis. Splitters are referred to by their splitting ratio, which is the power output of an individual split port divided by the total power output of all split ports, see Eq. (6.18). Popular splitting ratios are shown in Table 6.5; however, others are available. Equation (6.19) can be used to estimate the splitter insertion loss for a typical split port. Excess splitter loss adds to the port's power division loss and is lost signal power due to the splitter properties. It typically varies between 0.1 to 2 dB, refer to manufacturer's specifications for accurate values.

It should be noted that splitter function is symmetrical. For example, if a 0 dBm signal is launched into the common port of a 25% / 75% splitter, then the two split ports, output power will be -6.2 and -1.5 dBm. However, if a 0 dBm signal is launched into the 25% split port, then the common port output power will be -6.2 dBm.

$$SR = \frac{P_i}{P_T} \times 100 \tag{6.18}$$

$$IL = -10 \times \log(SR/100) + \Gamma_e \tag{6.19}$$

where IL = splitter insertion loss for the split port, dB

 $P_i$  = optical output power for single split port, mW

 $P_{T}$  = total optical power output for all split ports, mW

SR = splitting ratio for the split port, %

 $\Gamma_{e}$  = splitter excess loss (typical range 0.1 to 2 dB), dB

Common splitter applications include

- Permanent installation in a fiber link as a tap with 2% 98% splitting ratio. This provides for access to live fiber signal power and OSA spectrum measurement without affecting fiber traffic. Commonly installed in DWDM amplifier systems.
- Video and CATV networks to distribute signals.
- Passive optical networks (PON).
- Fiber protection systems.

Туре	Split Ratio for Each Split Port (%)	Typical Insertion Loss (dB) (assumes 0.2 dB loss)
1×2	50 50	3.2 3.2
1×2	45 55	3.7 2.8
1×2	40 60	4.2 2.4
1×2	35 65	4.8 2.1
1×2	30 70	5.4 1.8
1×2	25 75	6.2 1.5
1×2	15 85	8.4 0.91
1×2	10 90	10 0.66
1×2	5 95	13 0.42
1×2	2 98	17 0.29
1×2	1 99	20 0.24
1×3	10 45 45	10 3.7 3.7
1×3	20 40 40	7.2 4.2 4.2
1×3	30 35 35	5.4 4.8 4.8
1×3	40 30 30	4.2 5.4 5.4
1×3	50 25 25	3.2 6.2 6.2
1×3	60 20 20	2.4 7.2 7.2
1×3	70 15 15	1.8 8.4 8.4
1×3	80 10 10	1.2 10 10
1×4	25 25 25 25	6.2 6.2 6.2 6.2

Note: Insertion loss does not include loss due to connectors.

## 6.12 Active WDM Systems

Active WDM systems can be described as basic passive WDM technology integrated with any combination of other components such as optical amplifiers, dispersion compensation modules, transponders, management and monitoring circuitry in order to provided a flexible high-capacity transmission system that can be deployed over short- or long-haul fiber links. Active systems can be deployed over any cable length but are most economical in long-haul applications.

Figure 6.24 shows the basic components of a typical active system. It contains three major components, the WDM/OADM unit, the transponder, and the optical amplifiers. The WDM/OADM units can be the basic passive type but more elaborate units are available. An advanced unit is called the reconfigurable optical add drop multiplexer (ROADM). ROADM functions include the ability to remotely add/ drop single or multiple channels at a site; equalize individual channel powers; and allow for remote access, monitoring, and control of DWDM channel assignments.

The transponder's function is to convert optical or electrical input signals to the proper ITU DWDM/CWDM wavelength. One transponder is used per channel and is typically a plug-in card or module. Client side and WDM side pluggable transceivers (SFP, XFP, GBIC, etc.) plug into the transponder card. Two pluggable transceivers are required for each channel, one for the client channel interface, which is usually a short range 1310 type, and the other for the WDM side which is the proper ITU DWDM/CWDM laser type.

Optical amplifiers are added to compensate for fiber link, WDM, dispersion compensation losses. Boosters are typically used but systems can also include pre-amplifiers and in-line amplifiers for higher loss or longer spans.



FIGURE 6.24 Typical active DWDM system block diagram.

Dispersion compensation modules are used for longer spans where dispersion exceeds equipment limits. They are typically integrated with the optical amplifier, but also can be placed before or after the amplifier depending on equipment specifications and link design.

All these components are tied together by the management unit. This unit provides for remote computer monitoring and control of each individual component. Typical remote computer interface to a management unit is by 10/100BaseT Ethernet protocol. Management units at different sites and/or nodes are connected together by a dedicated optical service channel (OSC). The OSC can be established as an in-band or out-of-band (EDFA band) communications channel. The out-of-band channel is a separate optical channel, outside of the EDFA band, assigned specifically for OSC communications. The 1510 nm channel is typically used for OSC communications. Alternately 1480 or 1310 nm channels are also suggested for OSC communications. The OSC at 1510 nm is just outside of EDFA band but may benefit from some lower level amplification. For in-band OSC communications, one of the DWDM channels are used. The benefit of method is that the channel is amplified along the entire link; however, it consumes one of the DWDM channels that could be used for traffic. Another method used to establish management communications, if an OSC is not available or possible, is to provide a dedicated Ethernet circuit to each node and site. Management communications typically have low bandwidth requirements and a 1 Mbps or less circuit may be adequate.

Although not shown in Fig. 6.24, channel power equalization is required for any DWDM system equipped with optical amplifiers. This is due to the EDFA wavelength-dependent gain and saturation characteristics. Wavelength-dependent gain can result in accumulated channel power and optical signal to noise ratio (OSNR) imbalances as the optical signal passes through multiple amplifiers. This limits the number of EDFA amplifiers that can be cascaded and limits the transmission distance. Equalization of the channel signal power or OSNR can increase the number of cascaded amplifiers and transmission distance.<sup>27</sup>

# 6.13 WDM Technology Selection

Table 6.6 can be used as a general guide for selecting WDM multiplexers and transceivers. The "yes 1" selections of laser and WDM/ coupler types is the standard choice for these technologies. The "yes 2" selections can function together but may not be the most economical choice or bandwidth efficient choice. For example, 100 GHz lasers can be used with 200 GHz DWDM multiplexers. However, a 200 GHz laser is a better choice since it is likely less expensive. With rapidly advancing technologies many manufacturers are phasing out 200 GHz lasers and producing only 100 GHz lasers. Therefore, the 100 GHz laser with the 200 GHz DWDM may be the only choice available.

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Transceiver	Cross- band	Bidirectional	CWDM 8-channel	CWDM 16-18- channel	DWDM 200 GHz	DWDM 100 GHz	DWDM 50 GHz
Non-WDM 1310 laser	yes 1	yes 1	no	no	no	no	no
Non-WDM 1550 laser	yes 1	yes 1	no	no	no	no	no
CWDM laser	no	yes 2	yes 1	yes 1 G.652. c/d	no	no	no
DWDM 200 GHz laser	yes 2	yes 2	yes 2	yes 2 G.652. c/d	yes 1	no	no
DWDM 100 GHz laser	yes 2	yes 2	yes 2	yes 2 G.652. c/d	yes 2	yes 1	no
DWDM 50 GHz laser	yes 2	yes 2	yes 2	yes 2 G.652. c/d	yes 2	yes 2	yes 1



Proper system design should always be completed to confirm selection.

Table 6.7 can be used as a general guide to help determine which WDM technology is best for a specific fiber cable length. The "yes 1" is a good choice for most systems. The "yes 2" selections can also work but may not be economical.

Operating					DWDM ≤ 32-channel	DWDM
Band and	Cross-	Single fiber	CWDM	CWDM	Basic	Active
Cable Length	band	Bidirectional	8-channel	16-channel	(passive)	System
O band ≤2 km	no	yes 1	no	no	no	no
All bands ≤2 km	yes 1	yes 1	yes 1	yes 1 G.652.c/d	yes 1	yes 2
All bands ≤40 km	yes 1	yes 1	yes 1	yes 1 G.652.c/d	yes 1	yes 1/2
All bands >40 km ≤80 km	yes 1	no	yes 1	yes 1 G.652.c/d	yes 1	yes 1/2
C band ≥80 km	no	no	no	no	no	yes 1

TABLE 6.7	Cable	Length	and	WDM	Selection	Guide
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# CHAPTER 7 Fiber Nonlinear Impairments

# 7.1 Fiber Nonlinear Impairments

In basic fiber transmission link design the assumption is made that an optical fiber acts as a linear medium. This means the fiber's properties do not change with optical signal power, the optical signal wavelength remains the same as it propagates in the fiber, and the signal does not interact with any other signals in the fiber. This assumption is true for low signal power levels (approximately less than +3 dBm). However, for high optical powers the fiber exhibits nonlinear properties (power-dependent properties). High optical signal power alters the properties of the fiber, which then affects the signal itself. This interaction causes the propagating optical signal to change and lose its signal power linearly, see Fig. 7.1. The optical power loss due to the nonlinear effect is referred to as the nonlinear power penalty.

Nonlinear effects are weak and of no consequence at low signal power levels but increase considerably at higher signal powers and higher power densities in the fiber core. High fiber power densities are achieved by increasing signal power and/or by reducing the fiber's effective area, see Eq. (7.1).

$$\Pi = \frac{P_{\text{sig}}}{A_{\text{eff}}} \tag{7.1}$$

where  $\Pi = \text{fiber's power density, } dBm/\mu m^2$ 

 $P_{\text{sig}} = \text{signal power, dBm}$  $A_{\text{eff}} = \text{fiber's effective area, } \mu \text{m}^2$ 

Nonlinear effects also depend on the fiber span length. The longer the fiber span, the more the signal can interact with the fiber, causing greater nonlinear effects. However, the longer the span the more the propagating signal is attenuated by the fiber, thereby diminishing the nonlinear effect because it is dependent on signal strength. Therefore, most of the nonlinear effects occur early in the fiber span, which is referred to as the effective length  $L_{\text{eff}}$ . The fiber's effective



FIGURE 7.1 Linear and nonlinear fiber input and output interaction.

length is the fiber length, where nonlinear effects no longer increase in severity, see Eqs.  $(7.2)^1$  to (7.5).

$$L_{\rm eff} = \frac{\int_{0}^{L} P(z) dz}{P_{\rm in}}$$
(7.2)

$$P(z) = P_{\rm in} e^{-\alpha z} \tag{7.3}$$

If there are no amplifiers in the link the effective length is shown as Eq. (7.4).

$$L_{\rm eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{7.4}$$

With optical amplifiers in link, the equation is

$$L_{\rm eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \frac{L_T}{L}$$

For long fiber spans where  $L >> \alpha^{-1}$  then

$$L_{\rm eff} = \frac{1}{\alpha} \tag{7.5}$$

where  $L_{eff}$  = fiber effective length, km

L =fiber span length, km

- $L_T$  = total link length,  $L_T = N \times L$
- P(z) = power at a distance z along the fiber length, mW
  - $P_{in}$  = signal launch optical power into the fiber, mW
    - $\alpha$  = fiber's attenuation coefficient (note  $\alpha_{dB}$  = 4.343 $\alpha$ ), 1/km

Typically  $\alpha$  is 0.048/km ( $\alpha_{dB} = 0.21 \text{ dB/km}$ ) at 1550 nm, then  $L_{eff}$  is approximately 21 km for very long (where L >> 21 km) nonamplified fiber links. Therefore, most nonlinear distortion effects for very long fiber spans occur in the first 21 km of the span. Increasing span lengths past the fiber's effective length does not significantly increase nonlinear



FIGURE 7.2 FWM component power and fiber length.

effect severity. Figure 7.2 shows that four-wave component power peaks at 21 km for long DSF fiber lengths and three +10 dBm DWDM signals.

Nonlinear effects in a fiber can be divided into two categories. The first category is the Kerr effect, which is the fact that a medium's refractive index is dependent on the propagating signal power. As shown in Eq.  $(7.6)^2$  a fiber's refractive index  $n(\omega, E)$  is the sum of two components, the effective refractive index at low signal power which is a function of frequency and the nonlinear-index coefficient times signal power density  $P/A_{\text{eff}}$ . At low signal power densities the second component is minimal. However, it becomes a significant concern at high signal powers. To reduce the Kerr effect, optical power needs to be kept low and/or the fiber's effective area should be increased.

$$n(\omega, E) = n_{\text{eff}}(\omega) + n_2 E^2 = n_{\text{eff}}(\omega) + n_2 \frac{P}{A_{\text{eff}}}$$
(7.6)

where  $n(\omega, E)$  = fiber's effective refractive index at high power levels, m<sup>2</sup>/W

E = electric field strength, V/m

- $n_{\rm eff}(\omega)$  = fiber's effective refractive index at low power levels, m<sup>2</sup>/W
  - $n_2$  = nonlinear-index coefficient (or the Kerr coefficient), varies  $2.0 \times 10^{-20}$  to  $3.5 \times 10^{-20}$  m<sup>2</sup>/W for silica, m<sup>2</sup>/W (typical is  $3.0 \times 10^{-20}$  m<sup>2</sup>/W)
  - P = optical signal power, W
  - $A_{\text{eff}}$  = effective area of the fiber core (available from fiber specifications), m<sup>2</sup>

Changes in the fiber's refractive index due to Kerr effect will also change the propagation parameter  $\beta$  introduced in Chap. 1, by a factor called the nonlinear coefficient  $\gamma$ , see Eq. (7.7). This will cause a nonlinear phase shift in the signal as it propagates in the fiber due to the Kerr effect. This is detrimental to the signal and causes various unwanted effects as discussed later in this chapter. It is important to maintain the nonlinear coefficient as small as possible. Typically nonlinear coefficient  $\gamma$  varies between 1 (Wkm)<sup>-1</sup> and 3 (Wkm)<sup>-1</sup>.

$$\beta_P = \beta_0 + \gamma P \tag{7.7}$$

where  $\beta_p$  = nonlinear propagation parameter, rad/m

 $\beta_0$  = linear propagation parameter, rad/m

 $\gamma$  = nonlinear coefficient, (Wm)<sup>-1</sup>

The nonlinear coefficient is defined by Eq. (7.8).

$$\gamma = \frac{2\pi n_2}{\lambda A_{\rm eff}} \tag{7.8}$$

where  $\lambda$  is the laser's center wavelength, m.

The main nonlinear effects in this category are four-wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM).

The second category is the nonlinear stimulated scattering of photons in a fiber to a lower energy level that results in the appearance of phonons. The effects are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).

# 7.2 Four-Wave Mixing

When two or more optical signals of different center frequencies (different DWDM channels) are propagating in a fiber, mixing of the signals can occur, which can result in the generation of new interfering optical signal components. Note that optical frequency can be converted to wavelength by  $\lambda = c/f$ . This effect is transmission rate independent and occurs in DWDM links where high signal powers are present. It is due to the dependence of the fiber's refractive index on the signal power causing a nonlinear medium of propagation, known as the Kerr effect, and creates conditions for signal mixing. The center frequencies of the newly generated signal components can be calculated by summing the positive or negative integer multiples  $N_i$  of all the contributing signal center frequencies, see Eq. (7.9). This mixing phenomena is similar to radio frequency mixing called intermodulation products.

$$f_{\rm IM} = N_1 f_1 + N_2 f_2 + N_3 f_3 \cdots$$
(7.9)

$$IM_{order} = \sum_{1}^{M} \left| N_{i} \right|$$
(7.10)

 $f_{IM}$  = generated signal component center frequency, THz  $f_i$  = DWDM signal center frequency where i = 1 to M, THz where  $N_i$  = any integer with + or – coefficients including zero, where i = 1 to M M = total number of DWDM signals in the fiber IM<sub>order</sub> = intermodulation order

In the case where N is 0, ±1, or ±2, the effect is referred to as fourwave mixing (FWM) because a combination of any three (or two) DWDM signals propagating in a fiber can generate a fourth signal component. It is also referred to as third-order intermodulation as defined by Eq. (7.10), where the sum of  $|N_i|$  is equal to 3. When only three DWDM signals are propagating in the fiber, up to nine signal components can be generated, see Eqs. (7.11) to (7.19). In FWM the generated signal components can interfere with the original signal channel as well as other adjacent or nearby DWDM channels.

$$f_{123} = f_1 + f_2 - f_3$$
 (same as  $f_{213} = f_2 + f_1 - f_3$ ) (7.11)

$$f_{321} = f_3 + f_2 - f_1$$
 (same as  $f_{231} = f_2 + f_3 - f_1$ ) (7.12)

$$f_{312} = f_3 + f_1 - f_2$$
 (same as  $f_{132} = f_1 + f_3 - f_2$ ) (7.13)

$$=f_1 + f_1 - f_2 \quad (\text{same as } f_{112} = 2f_1 - f_2) \tag{7.14}$$
$$= f_1 + f_2 - f_2 \quad (\text{same as } f_1 = 2f_1 - f_2) \tag{7.15}$$

$$f_{112} = f_1 + f_1 - f_2 \quad (\text{same as } f_{112} = 2f_1 - f_2) \quad (7.14)$$

$$f_{112} = f_1 + f_1 - f_3 \quad (\text{same as } f_{113} = 2f_1 - f_3) \quad (7.15)$$

$$f_{221} = f_2 + f_2 - f_1 \quad (\text{same as } f_{221} = 2f_2 - f_1) \quad (7.16)$$

$$f_{223} = f_2 + f_2 - f_3 \quad (\text{same as } f_{223} = 2f_2 - f_3) \quad (7.17)$$

$$f_{331} = f_3 + f_3 - f_1 \quad (\text{same as } f_{331} = 2f_3 - f_1) \quad (7.18)$$

$$\lambda_{exc} = f_c + f_c - f_c \quad (\text{same as } f_{acc} = 2f_c - f_c) \quad (7.19)$$

$$=f_2 + f_2 - f_1 \quad (\text{same as } f_{221} = 2f_2 - f_1) \tag{7.16}$$
  
$$= f_2 + f_2 - f_2 \quad (\text{same as } f_{222} = 2f_2 - f_2) \tag{7.17}$$

$$f_{223} = f_2 + f_2 - f_3$$
 (same as  $f_{223} = 2f_2 - f_3$ ) (7.17)

$$f_{31} = f_3 + f_3 - f_1$$
 (same as  $f_{331} = 2f_3 - f_1$ ) (7.18)

$$\lambda_{332} = f_3 + f_3 - f_2 \quad (\text{same as } f_{332} = 2f_3 - f_3) \tag{7.19}$$

where  $f_{1'}f_{2'}f_3$  = three DWDM signal center frequencies in a fiber, THz

 $f_{ijk}$  = a generated interfering signal center frequency, THz

If the DWDM signal frequencies are equally spaced, then the signal components will fall onto and interfere with the signal channels as shown in Fig. 7.3. For example, if three equally spaced signals in a 100 GHz DWDM system are  $\lambda_1 = 1550.12$  channel 34,  $\lambda_2 = 1550.92$  channel 33,  $\lambda_3 = 1551.72$  channel 32, then the following interfering FWM wavelengths may be generated (note use  $\lambda_m = c/f_m$  for conversion):

$\lambda_{113} = 1548.52$	channel 36
$\lambda_{123} = 1549.32$	channel 35
$\lambda_{112} = 1549.32$	channel 35
$\lambda_{223} = 1550.12$	channel 34
$\lambda_{312} = 1550.92$	channel 33



FIGURE 7.3 FWM effects of three equally spaced signals.

$\lambda_{221} = 1551.72$	channel 32
$\lambda_{_{332}} = 1552.52$	channel 31
$\lambda_{_{321}} = 1552.52$	channel 31
$\lambda_{_{331}} = 1553.32$	channel 30

where  $\lambda_{ijk}$  = generated interfering wavelength, nm \* $\lambda_{312}$ ,  $\lambda_{221}$ ,  $\lambda_{223}$  = wavelengths that directly interfere with the original signals, nm

The generated components with center wavelengths  $\lambda_{223}$  = 1550.12,  $\lambda_{312}$  = 1550.92,  $\lambda_{221}$  = 1551.72 fall directly into the original DWDM signal channels causing interference. The other generated components fall into adjacent and nearby DWDM channels interfering with those channels, see Fig. 7.3.

The total number of possible FWM components increases exponentially with the number of signals that are propagating in the fiber. The total number of FWM components (third-order components) can be estimated by Eq. (7.20) given the number of signals in the fiber. Table 7.1 lists maximum possible FWM components for common DWDM channel counts.

$$N_{\rm IM} = \frac{M^2(M-1)}{2}$$
(7.20)

where  $N_{IM}$  = maximum possible number of generated FWM components

M = number of signals propagating in the fiber

Number of Signals ( <i>M</i> )	Total Possible Number of Generated FWM Components ( $N_{IM}$ )	Total Possible Number of Generated Inband FWM Components
2	2	0
3	9	3
8	224	124
16	1920	1093
32	15872	9803
40	31200	19571
80	252800	167755

 TABLE 7.1
 Maximum Number of FWM Components for Various Sized

 DWDM Systems

Table 7.1 also shows the total possible number of FWM components that can appear in the same DWDM channels as the signals (inband FWM components).

As shown in Table 7.1, as the number of signals propagating in the fiber increases the possible number of FWM generated components increases exponentially. However, not all of these components will be strong enough to cause interference. This is because for FWM to occur certain conditions need to exist in the fiber as follows:

- 1. The phase of the DWDM signals propagating constants needs to match, this occurs for zero or low values of chromatic dispersion.
- 2. Narrow WDM channel spacing (DWDM).
- 3. High channel signal power density levels.

FWM results in two detrimental effects on the transmission performance:

- 1. Generation of FWM components that interfere with the original signal and other DWDM signals causing interchannel crosstalk interference, which reduces OSNR and increases BER.
- 2. To a lesser extent optical power transferred from the original DWDM signal to the generated interfering components.

It should be noted that higher order mixing, such as fifth- or seventh-order, may occur<sup>3</sup> and cause interference. However, higher order component power is lower than FWM (third-order) component power. In some cases where very high signal powers and/or close channel spacing are encountered these components may be a concern. This can occur with unevenly spaced channels where FWM components do not appear in a certain channel but a higher order component may appear. A few examples of fifth- and seventh-order equations are shown in Eqs. (7.21) to (7.23). Other higher order wave-lengths can be determined by using intermodulation software such as F-Intermod.<sup>4</sup>

$$f_{1234} = f_1 + f_2 + f_3 - 2f_4$$
 fifth order (7.21)

$$f_{12345} = f_1 + f_2 + f_3 - f_4 - f_5$$
 fifth order (7.22)

$$f_{1234} = 2f_1 + f_2 - f_3 - 3f_4$$
 seventh order (7.23)

## 7.2.1 Methods to Reduce the Effects of FWM

One method to reduce FWM effects is to use transmission fiber that has high chromatic dispersion coefficient at the signal wavelength such as standard single-mode fiber SSMF (ITU-T G.652). The typical chromatic dispersion coefficient of SSMF is 18 ps/nm · km @ 1550 nm which helps to significantly reduce FWM from occurring. Even a lower chromatic dispersion coefficient significantly helps in reducing FWM such as NZ-DSF fiber (ITU-T G.655). This fiber is specially designed with low chromatic dispersion coefficient (~4 ps/nm · km @ 1550 nm) for extended transmission distance but high enough to significantly reduce FWM effects. Using these fiber types will help reduce the FWM effects but may not totally eliminate them. Table 7.2 shows how fiber chromatic dispersion can affect FWM. One fiber type that exhibits high FWM effects even for moderately powered signals is called dispersion shifted fiber DSF (ITU-T G.653). Its zero dispersion wavelength is at 1550 nm and therefore exhibits high FWM effects for signals at or near this wavelength. DSF was deployed in the past for some links before it was known that FWM was a concern at zero dispersion. It is no longer deployed but still may be encountered in the field.

Another method to reduce these effects is to lower signal power in the fiber or use fiber with a larger cross sectional area to reduce the signal power density. Table 7.2 shows estimated maximum input signal powers for a 3-channel equally spaced DWDM system given fiber

Fiber Type	NDSF G.652 $CD_c = 18 \text{ ps/(nm \cdot km)}$ $A_{eff} = 80  \mu\text{m}^2$			2 NZ-DSF G.655 s/(nm · km) $CD_c = 4 \text{ ps/(nm · km)}$ $A_{eff} = 72 \mu m^2$		DSF G.653 $CD_c = 0 \text{ ps/(nm \cdot km)}$ $A_{eff} = 50 \mu\text{m}^2$			
DWDM channel spacing	100 GHz	50 GHz	25 GHz	100 GHz	50 GHz	25 GHz	200 GHz	100 GHz	50 GHz
Signal power (dBm)	17	11	5	13	8	2	3	-3	-4

TABLE 7.2Maximum Signal Launch Power for a 3-Channel System to Achieve anFWM Interference Cross Talk of 25 dB



FIGURE 7.4 FWM effects of three unequally spaced signals.

types, and channel spacing to avoid FWM cross-talk interference. It assumes a 100 km link with 0.21 dB/km attenuation,  $n_2 = 3 \times 10^{-20} \text{ m}^2/\text{W}$ , all signals have the same polarization (worst case), there are no optical amplifiers and minimum tolerable FWM cross talk is 25 dB. The table was constructed using Eq. (7.24).

A third method to help reduce FWM effects is to space signal channels unevenly. The worst channel interference occurs when evenly spaced DWDM signals cause coherent interference in the same signal channels, see Fig. 7.3, and wavelengths  $\lambda_{223}$ ,  $\lambda_{312'}$ ,  $\lambda_{221}$ . When signals are spaced unevenly this interference can be avoided to some extent, see Fig. 7.4. For example, if three unequally spaced (100 GHz spacing) DWDM signal channels are at  $\lambda_1 = 1549.32$  channel 35,  $\lambda_2 = 1550.92$  channel 33,  $\lambda_3 = 1551.72$  channel 32, then the following nine interfering FWM wavelengths can be generated and none would fall on the signaling channels.

$\lambda_{113} = 1546.92$	channel 38
$\lambda_{112} = 1547.72$	channel 37
$\lambda_{123} = 1548.52$	channel 36
$\lambda_{_{312}} = 1550.12$	channel 34
$\lambda_{223} = 1550.12$	channel 34
$\lambda_{_{332}} = 1552.52$	channel 31
$\lambda_{221} = 1552.52$	channel 31
$\lambda_{321} = 1553.32$	channel 30
$\lambda_{331} = 1554.12$	channel 29

where  $\lambda_{iik}$  is the generated interfering wavelength, nm.

However, in modern densely packed DWDM systems, this method is inefficient because channel space is wasted. Also, this method only moves the interference over to adjacent channels.

A fourth method to reduce FWM effects is to use DWDM systems with wide channel spacing. The magnitude of FWM effect is dependent on channel spacing. Wider spaced DWDM channels generate weaker FWM components, see Table 7.2. Systems with CWDM channel spacing of 20 nm (~2500 GHz) are unlikely to encounter this effect.

Another method that may help reduce FWM effects is to use fiber with high PMD values. Pachnicke<sup>5</sup> has shown that a reduction in FWM power can be achieved by increasing link PMD for low chromatic dispersion fibers such as NZ-DSF and DSF. However, note that too much link PMD can also reduce channel availability and increase BER, refer to Chap. 5.

Hansryd<sup>6</sup> has shown that using polarization-multiplexed DWDM channels can reduce FWM component power<sup>7</sup> and cross talk. This involves polarizing the DWDM channels such that each channel's polarization state is orthogonal to the adjacent channel's polarization. It may be possible to suppress FWM components by a factor of 4 with this technique.<sup>8</sup>

## 7.2.2 Estimating Generated FWM Component Power

FWM component powers can be accurately determined by solving Schrödinger wave equations for all DWDM signal wavelengths in the fiber, see Eq. (1.40). A solution for three DWDM signal has been determined by Song<sup>9</sup> and is shown in Eqs. (7.24) to (7.27). The assumptions are that all signals have the same polarization (worst case), FWM component power is much less than the signal power  $P_{ijk} << P_{i'}, P_{j'}, P_{k'}$  and no optical amplifiers are used in the link.

$$P_{ijk} = \frac{\eta}{9} d^2 \gamma^2 P_i P_j P_k L_{\text{eff}}^2 \exp(-\alpha L)$$
(7.24)

where  $P_{i'}P_{j}$ ,  $P_{k}$  = channel peak signal power input into the fiber (assuming perfect extinction ratio, the average NRZ power is  $P_{max} = P_{max}/2$ ), W

power is  $P_{ave} = P_{peak}/2$ ), W  $P_{ijk}$  = generated FWM component peak power at frequency  $f_{ijk}$  and at fiber length L (note:  $f_{ijk} = f_i + f_j - f_k$ ), W

- $\eta = FWM$  efficiency factor
- *d* = degeneracy factor equals 3 for degenerate and 6 for nondegenerate FWM
- $\gamma$  = nonlinear coefficient, (Wm)<sup>-1</sup>
- $\alpha$  = fiber attenuation coefficient, m<sup>-1</sup>
- L =fiber length, m
- $L_{\rm eff}$  = effective fiber length, m



FIGURE 7.5 Degenerate FWM.

Two types of mixing are defined for this equation, degenerate and nondegenerate FWM. Degenerate involves two DWDM signals (of different frequencies) which generate FWM components that do not lie in the original signal channels. A factor of 3 is used for degenerate class ( $f_i = f_{i'}, f_i \neq f_k$ ), see Fig. 7.5. Nondegenerate involves three DWDM signals (of different frequencies), generating FWM components that can lie in the same channel as the original signals. A factor of 6 is used for the nondegenerate class ( $f_i \neq f_i \neq f_k$ ), see Figs. 7.3 and 7.4.

The nonlinear coefficient  $\gamma$  can be calculated by Eq. (7.25).

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \tag{7.25}$$

where  $\gamma = \text{nonlinear coefficient, } (Wm)^{-1}$ 

 $n_2$  = fiber nonlinear refractive index, which varies for different fibers between  $2.0 \times 10^{-20}$  to  $3.5 \times 10^{-20}$  m<sup>2</sup>/W, (typical is  $3.0 \times 10^{-20}$  m<sup>2</sup>/W)

 $\lambda$  = FWM component wavelength, m

 $A_{\rm eff}$  = fiber core's effective area, m<sup>2</sup>

The FWM efficiency factor  $\eta$  can be calculated<sup>8</sup> by Eq. (7.26).

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left[ 1 + \frac{4 \exp(-\alpha L) \sin^2(\Delta\beta L/2)}{(1 - \exp(-\alpha L))^2} \right]$$
(7.26)

where  $\eta$  = FWM efficiency factor

 $\Delta\beta$  = phase matching factor, m<sup>-1</sup>



FIGURE 7.6 FWM efficiency for different channel spacing.

The FWM efficiency is shown in Fig. 7.6 as a function of channel spacing and fiber dispersion coefficient for a 100 km fiber span with attenuation at 0.21 dB/km at 1550 nm. As the fiber's dispersion coefficient increases or channel spacing increases, the FWM efficiency decreases, thereby reducing FWM component power.

The phase matching factor  $\Delta\beta$  depends on channel spacing, fiber dispersion, and signal power; it can be calculated<sup>8</sup> by Eq. (7.27).

$$\Delta \beta = \frac{2\pi \lambda_k^2}{c} \Delta f_{ik} \Delta f_{jk} \left[ CD_c + \frac{\lambda_k^2}{2c} (\Delta f_{ik} + \Delta f_{jk}) S_{fc} \right] - \gamma (P_i + P_j - P_k) \left[ \frac{1 - \exp(-\alpha L_{eff})}{\alpha L_{eff}} \right]$$
(7.27)

where

 $\Delta\beta$  = phase matching factor, 1/m

$$\Delta f_{ik}$$
,  $\Delta f_{jk}$  = channel spacing  $\Delta f_{ik} = |f_i - f_k|$  and  $\Delta f_{jk} = |f_j - f_k|$ , Hz

 $\lambda_k$  = wavelength of channel k, m

c = speed of light in a vacuum, m/s  $CD_c$  = fiber's chromatic dispersion coefficient at FWM wavelength  $\lambda_k$ , s/m<sup>2</sup> (to convert (ps/(nm \cdot km)) × 10<sup>-6</sup>  $S_{fc}$  = chromatic dispersion slope coefficient at FWM

wavelength  $\lambda_{k}$ , s/m<sup>3</sup> (to convert (ps/(nm<sup>2</sup>·km)) × 10<sup>3</sup>

If optical amplifiers are deployed in a fiber link as seen in Fig. 7.7, Inoue<sup>10</sup> indicates that FWM component power can be estimated by including the number of spans term N and span length term l in Eqs. (7.24) to (7.27) as shown in Eqs. (7.28) to (7.30). The following assumptions are made for these equations: all signals have the same polarization, FWM component power is much less than the signal



FIGURE 7.7 Fiber link EDFA placement to estimate FWM.

power, the fiber link is made up of a number of *N* spans, each span ends with an optical amplifier with gain that exactly compensates for the previous span's loss except for the last span, the number of amplifiers in the link is N - 1, all spans are the same length  $l_{o'}$  and the same fiber characteristics apply to each span's fiber.

$$P_{mijk} = N^2 \frac{\eta_{\rm m}}{9} d^2 \gamma^2 P_i P_j P_k l_{\rm eff}^2 \exp(-\alpha l_{\rm o})$$
(7.28)

$$l_{\rm eff} = \frac{1 - \exp(-\alpha l_{\rm o})}{\alpha} \tag{7.29}$$

- where  $P_{mijk}$  = generated FWM component power at center wavelength  $\lambda_{ijk}$  and at end of fiber link when optical amplifiers are deployed, W
  - N = number of spans in the fiber link
  - $l_{o}$  = fiber span length (amplifier spacing), m
  - $l_{\rm eff}$  = effective span length, m

The FWM efficiency and phase matching factors for a link with multiple amplifiers become Eqs. (7.30) and (7.31). Note that the linear version of the phase matching factor is used here instead of Eq. (7.27) as defined by Inoue.

$$\eta_{\rm m} = \frac{\alpha^2}{N^2(\alpha^2 + \Delta\beta_{\rm m}^2)} \left[ 1 + \frac{4 \exp(-\alpha l_{\rm o}) \sin^2(\Delta\beta_{\rm m} l_{\rm o}/2)}{(1 - \exp(-\alpha l_{\rm o}))^2} \right] \\ \times \left[ \frac{\sin^2(N\Delta\beta_{\rm m} l_{\rm o}/2)}{\sin^2(\Delta\beta_{\rm m} l_{\rm o}/2)} \right]$$
(7.30)

$$\Delta\beta_{\rm m} = \frac{2\pi\lambda_k^2}{c} \Delta f_{ik} \Delta f_{jk} \left[ CD_c + \frac{\lambda_k^2}{2c} (\Delta f_{ik} + \Delta f_{jk}) S_{\rm fc} \right]$$
(7.31)

where  $\eta_m = FWM$  efficiency factor when optical amplifiers are deployed  $\Delta\beta_m =$  phase matching factor, linear version, 1/m



FIGURE 7.8 FWM efficiencies for nonamplified and amplified links.

Figure 7.8 compares calculated FWM efficiencies  $\eta$  using Eq. (7.26) for the nonamplified link and using Eq. (7.30) for the amplified link for various channel spacing. For the nonamplified link, the link length is 50 km. The amplified link consists of ten 50 km spans (N = 10). In both cases the fiber attenuation is 0.2 dB/km, chromatic dispersion is 4 ps/(nm·km), core effective area 50  $\mu$ m<sup>2</sup> and signal wavelength 1550 nm.

The total FWM interference power generated in a channel is equal to the sum of all the generated FWM component powers in that channel,<sup>11</sup> see Eq. (7.32). For example, assume three DWDM signals exist in a fiber and nine FWM components are generated as shown in Fig. 7.3 and Eqs. (7.11) to (7.19). Then one FWM component is generated in channels C36, C34, C33, C32, and C30, and two FWM components are generated in channels C35 and C31. The total FWM component power for channel C35 is the sum of the two component powers in this channel.

$$P_{\rm FT.m} = \sum_{f_{\rm K}} \sum_{f_{\rm I}} \sum_{f_{\rm J}} P_{ijk}(f_i, f_j, f_k)$$
(7.32)

where  $P_{\text{FT.m}}$  = total of all FWM component average powers in channel m, W

 $P_{ijk}$  = individual FWM average component power for a channel given by Eq. (7.24) or Eq. (7.28), generated by signal wavelength combinations *i*,*j*,*k* given by Eqs. (7.11) to (7.19), W

Total FWM component power as shown in Fig. 7.3 at channels C35 and C31 is given by Eqs. (7.33) and (7.34).

$$P_{\rm FT.C35} = P_{112} + P_{123} \tag{7.33}$$

$$P_{\rm FT.C31} = P_{332} + P_{231} \tag{7.34}$$

However, DWDM systems do not stop at three channels. Common DWDM channel counts are 8, 16, 32, 40, and 80. As can be seen from Table 7.1 the total possible combinations of inband FWM components generated for 8 channels is 124, for 16 channels is 1093. Each channel can have many components that may need to be considered in determining total channel FWM component power and cross talk.

Neokosmidis<sup>12</sup> has simulated FWM effects using the Monte Carlo method for DWDM channel counts of 8, 16, and 32 channels in an 80 km fiber link. Maximum signal launch power results to achieve a link BER of  $10^{-13}$  (considering only noise due to FWM components) are listed in Table 7.3. Assumptions made are that all signals have the same polarization (worst case), FWM component power is much less than the signal power  $P_{ijk} << P_i$ ,  $P_j$ ,  $P_k$ , center channel wavelength is 1550 nm, nonlinear coefficient is  $\gamma = 2.4$  (Wkm)<sup>-1</sup>, fiber attenuation is 0.2 dB/km, and the fiber link length, is 80 km. Since most FWM

<b>DWDM Channels</b>		Fiber Chromatic Dispersion Coefficient			
Channel		2 ps/(nm⋅km)	5 ps/(nm⋅km)	10 ps/(nm $\cdot$ km)	
Number of Channels	Spacing (GHz)	Max Signal Power (dBm)	Max Signal Power (dBm)	Max Signal Power (dBm)	
	10	-11	-6	-4	
0	25	-3	1	4	
8	50	3	7	10	
	100	9	13	15	
	10	-13	-10	-6	
10	25	-5	-1	1	
10	50	0	4	8	
	100	6	10	14	
	10	-14	-10	-6	
32	25	-6	-1	1	
	50	0	4	8	
	100	6	10	13	

 TABLE 7.3
 Average Signal Launch Power Limits to Achieve BER 10<sup>-13</sup> due to FWM

 Interference
 Interference

components are generated over the fiber's effective length, which is much less than 80 km, maximum launch power limits will not change significantly for fiber lengths greater than 80 km. This chart can be used to help estimate channel maximum fiber launch power level assuming the following conditions:

- 1. Fiber link lengths 80 km or longer.
- 2. Fiber link chromatic dispersion of 2, 5, or  $10 \text{ ps/(nm \cdot km)}$ .
- 3. Fiber attenuation of 0.2 to 0.21 dB.
- 4. Fiber nonlinear coefficient  $\gamma$  of 2.4 (Wkm)<sup>-1</sup> or less.
- 5. DWDM channel spacing of 10, 25, 50, or 100 GHz.
- 6. DWDM systems with 8, 16, and 32 channels.
- 7. NRZ signal modulation.
- 8. Noise generated by optical amplifiers is not considered in this table. Amplifier noise effect is discussed in Chap. 3.

As can be seen in Table 7.3, signal launch power limits for 16- and 32-channel systems are very similar. This is because after 16 channels, the component powers from channels further than 16 channels away contribute very little interference. Therefore, this chart can provide estimated launch power limits for higher count DWDM systems.

# 7.3 Self-Phase Modulation and Cross-Phase Modulation

Both self-phase modulation (SPM) and cross-phase modulation (XPM) occur because a nonlinear medium is created when high optical powers propagate in a fiber (Kerr effect). The fiber's refractive index varies with the power intensity as shown in Eq. (7.6). This effect limits the maximum transmission rate possible in the fiber.

In self-phase modulation, the nonlinear refractive index causes a phase shift in the propagating pulse's optical wavelength, which is proportional to its own optical intensity,<sup>13</sup> see Eq. (7.35).

$$\Delta \Phi_{\rm SPM} = \gamma P_0 L_{\rm eff} \tag{7.35}$$

From Eq. (7.8):

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}$$

where  $\Delta \Phi_{\text{SPM}}$  = phase shift of the optical signal after propagating a distance *L* 

- $\gamma$  = nonlinear coefficient, (Wm)<sup>-1</sup>  $P_0$  = input signal power, W
- $L_{\text{eff}} = \text{fiber's effective length, m}$

The phase shift is a function of time  $\Phi_{\text{SPM}}(t)$  and knowing that frequency is the derivative of phase shift with respect to time, Eq. (7.35) can be expressed as Eq. (7.36).

$$\Delta \omega = -\frac{d\Delta \Phi_{\rm SPM}}{dt} = -\gamma \frac{dP}{dt} L_{\rm eff}$$
(7.36)

where  $\Delta \omega$  is the change in frequency caused by the change in phase shift at location *L*, s<sup>-1</sup>.

Equation (7.36) shows the relationship between the change in signal power and frequency shift around the carrier frequency, see Fig. 7.9.

The reason for this is explained as follows. As an optical pulse propagates in a fiber, the leading edge of the pulse's amplitude causes the refractive index of the fiber to increase, resulting in a shift to a lower frequency for the beginning of the pulse. The falling edge of the pulse's amplitude causes the refractive index to decrease, resulting in



FIGURE 7.9 Pulse frequency change due to SPM.

a shift to a higher frequency for the end of the pulse. Over the pulse width, in the time domain, its frequency changes as shown in Fig. 1.9*a* and *b*. This is referred to as positive frequency chirp. Since different optical frequencies travel at different speeds in a fiber, the pulse width expands or compresses. Pulse width expansion leads to intersymbol interference and worst BER. Refer to Chap. 1 for more details on chirped pulse propagation. The pulse's frequency change is a modulation caused by a phase shift induced by itself and therefore the effect is called self-phase modulation. This effect caused by high optical power limits the maximum transmission rate possible in the fiber. It should be noted that this wavelength chirping is not linear in time as the pulse propagates in the fiber, which is different from laser frequency chirping.

Solving the nonlinear Schrödinger equation [Eq. (1.40)] using only the Kerr nonlinear term and with the Gaussian pulse Eq. (1.45) where chirp  $C_0 = 0$ , Cvijetic<sup>14</sup> shows that the pulse width broadening factor due to SPM and chromatic dispersion can be estimated with Eq. (7.37).

$$\frac{\partial A}{\partial z} + \underbrace{\beta_1 \frac{\partial A}{\partial t}}_{\text{Group velocity}} + \underbrace{\frac{j\beta_2}{2}}_{\text{CD effect}} \frac{\partial^2 A}{\partial t^2} - \underbrace{\frac{\beta_3}{6}}_{\text{CD slope}} \frac{\partial^3 A}{\partial t^3} + \underbrace{\frac{\alpha}{2}}_{\text{Attenuation}} = \underbrace{j\gamma |A|^2 A}_{\text{SPM}}$$
$$\frac{\sigma_{\text{SPM}}}{\sigma_{\text{o}}} = \left[1 + \frac{\sqrt{2}L_{\text{eff}}L\beta_2}{2L_{\text{NL}}\sigma_{\text{o}}^2} + \left(1 + \frac{4}{3\sqrt{3}}\frac{L_{\text{eff}}^2}{L_{\text{NL}}^2}\right)\frac{L^2\beta_2^2}{4\sigma_{\text{o}}^4}\right]^{1/2}$$
(7.37)

Here the nonlinear length  $L_{\rm NL}$  term is introduced and is defined as the fiber length required to produce one radian of nonlinear phase rotation at power  $P_{a,r}$  see Eq. (7.38).

$$L_{\rm NL} = \frac{\lambda A_{\rm eff}}{2\pi n_2 P_{\rm o}} \tag{7.38}$$

The group-velocity dispersion (GVD) parameter  $\beta_2$  is defined in Eq. (4.17) and is shown below.

$$\beta_2 = -\frac{\lambda^2}{2\pi c} CD_c$$

where  $\sigma_{\text{SPM}}$  = signal RMS pulse width (Gaussian pulse shape) at location *L*, s

- $\sigma_{o}$  = signal RMS pulse width (Gaussian pulse shape) at the beginning of fiber, s
- $\sigma_{\text{SPM}}/\sigma_{\text{o}}$  = pulse width broadening factor due to SPM

$$\tilde{L}$$
 = fiber link length, m

- $L_{\rm NL}$  = fiber nonlinear length, m
- $L_{\rm eff}$  = fiber effective length, m
- $P_0$  = pulse peak power at launch, W
- $\beta_2$  = group-velocity parameter, s<sup>2</sup>/m

 $\lambda$  = center wavelength of the optical signal, m

- $CD_c$  = chromatic dispersion coefficient, s/(m · m)
- $n_2$  = nonlinear-index coefficient which varies for different fibers between  $2.0 \times 10^{-20}$  to  $3.5 \times 10^{-20}$  m<sup>2</sup>/W, (typical is  $3.0 \times 10^{-20}$  m<sup>2</sup>/W)  $A_{off}$  = fiber core's effective area, m<sup>2</sup>

Equation (7.37) shows that SPM effect is dependent on

- 1. Signal wavelength (the higher the wavelength the lesser the SPM)
- 2. Transmission rate, ≥10 Gbps (the higher the rate the greater the SPM effect)
- 3. Fiber core effective area (the larger the area the lesser the SPM)
- 4. Fiber dispersion (the lower the dispersion the lesser the SPM)
- 5. Fiber nonlinear index coefficient

For transmission rates of 2.5 Gbps and less, SPM is not a limiting factor for NRZ and other OOK modulation formats. The below discussion concentrates on NRZ modulated 10 Gbps and higher rates.

For 10 Gbps and higher transmission rates, we assume that optical signal pulses have a Gaussian shape as they propagate in a fiber. A commonly used fit criteria for Gaussian pulses is that the pulse's RMS width needs to be less than 1/4 of the bit time slot *T* for at least 95% of the optical pulse power to fit within the time slot, see Eq. (4.29) and Eq. (7.39).

$$\sigma_{o} = \frac{1}{4R} \tag{7.39}$$

where *R* = transmission rate, bps

 $\sigma_0$  = Gaussian pulse initial launch RMS width, s

As a Gaussian pulse propagates in a fiber, it undergoes compression and expansion in the presence of SPM. For example, assume a 10 Gbps signal with Gaussian-shaped pulses is launched into a standard single-mode fiber (G.652). Pulse width changes due to SPM occur as the signal propagates in the fiber as shown in Fig. 7.10. When SPM is present, positive chirp occurs and the pulse initially undergoes compression, then expansion as it propagates further in the fiber. This compression is helpful in extending the propagation limit for a distance up to ~100 km as shown in the example. Comparing this effect to a pulse launched in a fiber with no SPM [Eq. (1.60),  $C_0 = 0$ ], the pulse only expands as it propagates in the fiber. Eventually, the SPM pulse width surpasses the non-SPM pulse width at ~100 km. Therefore, in



FIGURE 7.10 SPM pulse broadening example.

this example, SPM is beneficial to pulse propagation for short distances under 100 km, but it is limiting in longer transmission distances.

A pulse width  $\sigma_{_{SPM}}$  at location *L* that is different from the launched pulse width  $\sigma_{_{0}}$  results in some amount of associated optical power penalty due to the pulse energy spreading out of its time slot. A simple calculation can be made to estimate this power penalty due to SPM broadening factor  $\sigma_{_{SPM}}/\sigma_{_{0'}}$  as shown in Eq. (7.40). This power penalty is shown on the right axis in Fig. 7.10.

$$\delta_{\text{SPM}} \approx 10 \log \left\{ \frac{\sigma_{\text{SPM}}}{\sigma_{o}} \right\}$$
 (7.40)

where  $\delta_{\text{SPM}}$  is the power penalty due to SPM, dB.

Cvijetic also suggests that to roughly estimate maximum possible launch powers, the pulse phase shift given by Eq. (7.35) needs to be less than 1 radian. Equation (7.35) can then be written as a limiting condition, see Eq. (7.41).

$$P_{\text{Max}} < \frac{1}{\gamma L_{\text{eff}}} \tag{7.41}$$

$$P_{\text{Max}} < \frac{\alpha \lambda A_{\text{eff}}}{2\pi n_2 [1 - \exp(-\alpha L)]}$$
(7.42)

where  $P_{\text{Max}}$  is the maximum launch peak power, W.

Table 7.4 lists estimated SPM launch average NRZ power limits calculated using Eq. (7.42) assuming  $n_2 = 3.0 \times 10^{-20} \text{ m}^2/\text{W}$ , signal wavelength of 1550 nm, and single fiber span with no dispersion compensation.

Maximum Launch Power (dBm)	Fiber Core Effective Area $A_{\rm eff}(\mu m^2)$	Fiber Attenuation (dB)
12	80	0.20
13	80	0.25
10	55	0.20
11	55	0.25

 TABLE 7.4
 Estimated Single-Channel Average Signal Launch Power

 SPM Limits for Uncompensated Span

For links where each span's dispersion is fully compensated except for the last span, which is undercompensated, SPM limits for 10 and 40 Gbps NRZ links over G.652 fiber attenuation of 0.2 dB/km, maximum launch powers are available from a publication<sup>15</sup> as shown in Table 7.5. For optimum suppression of SPM effects, 800 ps/nm of net link residual dispersion is suggested for standard G.652 fiber and 300 ps/nm of net link residual dispersion is suggested for NZ-DSF G.655 fiber.<sup>16</sup>

Cross-phase modulation (XPM) is the same basic effect of the refractive index dependence on the signal intensity except that the optical power causing the effect is produced not only by the original signal but also from all other optical signals propagating in the fiber. This occurs for multichannel WDM, DWDM, and CWDM systems. The nonlinear Schrödinger equations written for interaction between two channels<sup>17</sup> can be shown as Eqs. (7.43) and (7.44). Solving the

Maximum Launch Power (dBm)	Transmission Rate (Gbps)	Distance (km)	
15	10	350	
12	10	700	
10	10	1,100	
7.5	10	2,000	
7	40	170	
5	40	270	
2	40	540	
0	40	855	
-2	40	1,350	

 TABLE 7.5
 Estimated Single-Channel Average Signal Launch

 Power SPM Limits in Compensated Spans

nonlinear Schrödinger equations for multiple channels will provide accurate XPM effect results.

$$\frac{\partial A_1}{\partial z} + \underbrace{\frac{j\beta_2}{2}}_{\text{CD effect}} \frac{\partial^2 A_1}{\partial t^2} - \underbrace{\frac{\beta_3}{6}}_{\text{CD slope}} \frac{\partial^3 A_1}{\partial t^3} + \underbrace{\frac{\alpha}{2}}_{\text{Attenuation}} = j\gamma_1 \left( \underbrace{|A_1|^2}_{\text{SPM}} + \underbrace{2|A_2|^2}_{\text{XPM}} \right) A_1 \quad (7.43)$$

$$\frac{\partial A_2}{\partial z} + \underbrace{\frac{j\beta_2}{2}}_{\text{CD effect}} \frac{\partial^2 A_2}{\partial t^2} - \underbrace{\frac{\beta_3}{6}}_{\text{CD slope}} \frac{\partial^3 A_2}{\partial t^3} + \underbrace{\frac{\alpha}{2}}_{\text{Attenuation}} A_2 = j\gamma_2 \left( \underbrace{|A_2|^2}_{\text{SPM}} + \underbrace{2|A_1|^2}_{\text{XPM}} \right) A_2 \quad (7.44)$$

The amount of signal phase shift due to XPM from multiple channels is estimated by Cvijetic<sup>14</sup> by adding a channel quantity term to Eq. (7.35), see Eq. (7.45). Launch power maximum limit for multichannel systems can be roughly estimated by Eq. (7.46) assuming the maximum pulse phase shift  $\Delta \Phi_{\rm XPM,i}$  is 1 radian. This equation assumes all channel powers are equal, the fiber has zero dispersion, and optical pulses from all the different channels propagate at the same velocity. It also assumes that all the different channel signals' one-bit level patterns line up, which results in the worst-case XPM effect (no channel walk-off). These conditions are unrealistic, but provide the reader with a general idea of the possible severity of this effect.

$$\Delta \Phi_{\text{XPM},j} = \gamma P_0 L_{\text{eff}} (2M - 1) \tag{7.45}$$

$$P_{\text{Max},j} < \frac{\alpha}{\gamma [1 - \exp(-\alpha L)](2M - 1)}$$
(7.46)

where  $\Delta \Phi_{\text{XPM},j}$  = nonlinear phase shift of the *j*'th channel after propagating a distance *L* 

- $P_{Max,j}$  = maximum peak launch power for channel *j* assuming all channel powers are equal and the fiber has zero dispersion, W
  - M = number of channels

Table 7.6 lists estimated maximum launch powers for typical multichannel systems derived from Eq. (7.46) using the following

Channel Maximum Launch Power (dBm)	Number of Channels (M)		
0	8		
-3	16		
-6	32		
-7	40		

**TABLE 7.6**XPM Limited DWDM Average SignalLaunch Power Assuming Worst-Case Conditions

fiber parameters, L = 80 km,  $A_{eff} = 80$  pm<sup>2</sup>, CD = 0 ps/nm and fiber attenuation = 0.22 dB/km.

In reality, signal bit patterns from different channels do not line up as they propagate in the fiber because their group velocities differ for each channel signal, see Eq. (1.30). They drift in relation to each other, which is referred to as channel walk-off. The faster the walkoff, the lower the XPM induced fluctuations. Walk-off increases as channel spacing increases and as dispersion increases which in turn decreases XPM. Fibers with low dispersion coefficient such as NZ-DSF cause a higher XPM effect due to the lower channel walk-off. However, as dispersion accumulates the phase to intensity modulation conversion effect strengthens which increases XPM.

XPM effect is dependent on

- 1. Input channel power (the higher the power the greater XPM)
- 2. Channel spacing (the greater the channel spacing the lesser the XPM due to walk-off effect)
- 3. Fiber dispersion (locally greater to reduce walk-off but lower overall to reduce phase conversion)
- 4. Fiber core effective area (the larger the area the lesser the XPM)

XPM acts as noise like variations in amplitude and jitter in copropagating signals. It has been shown that using effective dispersion compensation, XPM can be significantly reduced and launch power levels increased considerably as shown in Table 7.7. Two compensation methods that are common in fiber links are full optimized compensation scheme (FOCS) and distributed under compensation scheme (DUCS). The most effective compensation is DUCS where every span is equally under compensate<sup>18</sup> by placing compensation modules at all midspan optical amplifier positions and at the receiver as shown in Fig. 4.9*a*. Each span's compensation is less than the total span's accumulated dispersion such that a small optimum amount of span

Channel Spacing (GHz)	Fiber Type	Optimum Link Net Residual Dispersion (ps/nm)	P <sub>MC</sub> (mW)	1-Span Link P <sub>in</sub> (dBm)	2-Span Link P <sub>in</sub> (dBm)	3-Span Link P <sub>in</sub> (dBm)
100	NDSF	800	112	20	17	15
100	NZ-DSF	100–300	40	16	13	11
50	NDSF	200–1000	32	15	12	10
50	NZ-DSF	100–300	16	12	9	7

 TABLE 7.7
 Estimated XPM Average Signal Launch Power Limits for 8-Channel

 10 Gbps NRZ System with DUCS Compensation

residual dispersion remains. This optimum span residual dispersion helps in reducing the local XPM due to channel walk-off and remains low enough to keep phase to intensity conversion effect tolerable.

To determine optimum dispersion compensation for suppression of XPM effects, a simple scaling equation can be used that states the total transmission distance represented as the number of equal length spans N, times the maximum channel input power  $P_{in'}$  equals a constant, see Eq. (7.47). This equation is dependent on fiber type, channel spacing, number of channels, and transmission rate.

$$P_{\rm MC} = P_{\rm in} \times N \tag{7.47}$$

where  $P_{\rm MC}$  = maximum power constant, mW · span

 $\tilde{P}_{in}$  = maximum channel, average signal, launch power, mW N = number of optical amplifier spans in the link

 $P_{\rm MC}$  is estimated by Fürst<sup>19</sup> for 8-channel DWDM NRZ signaling systems with 100 GHz and 50 GHz channel spacing and the following parameters: for G.655 (NZ-DSF) fiber  $\gamma = 1.3 \text{ km}^{-1}$ , CD<sub>c</sub> = 2.8 ps/ (nm · km) and for G.652 fiber (NDSF) fiber  $\gamma = 1.5 \text{ km}^{-1}$ , CD<sub>c</sub> = 17 ps/ (nm · km).  $P_{\rm MC}$  is defined for a 10 Gbps system with an OSNR penalty (or Q) of less than 1 dB for an OSNR of 16 dB. For a 100 GHz channel spaced system over NZ-DSF fiber and using dispersion under compensation scheme (DUCS) with net residual dispersion between 100 and 300 ps/nm,  $P_{\rm MC}$  is estimated to be 40 mW (16 dBm). The net residual dispersion is equally distributed in each span's residual dispersion, see Eq. (7.48). Therefore, for a 2-span link, the maximum (average signal) launch power is 20 mW (13 dBm) per channel.

$$CD_{span} = CD_{net}/N \tag{7.48}$$

where  $CD_{span}$  = span residual dispersion, ps/nm  $CD_{net}$  = net residual dispersion, ps/nm N = number of optical amplifier spans in the link

For a 50 GHz spaced system over NZ-DSF fiber with dispersion under compensation and net residual dispersion between 100 and 300 ps/nm,  $P_{\rm MC}$  is 16 mW (12 dBm). For a 3-span link maximum launch power is 7 dBm per channel. For a 100 GHz system over NDSF, the XPM walk-off effect is not limiting due to the high fiber dispersion. Therefore, it requires 800 ps/nm net residual dispersion compensation for optimum SPM suppression. For a 50 GHz spaced system over NDSF with dispersion under compensation and net residual dispersion between 200 and 1000 ps/nm, the  $P_{\rm MC}$  is estimated to be 32 mW (15 dBm). For a 3-span link maximum launch power is 10 dBm per channel. Table 7.7 tabulates these average signal power limits for a 1 dB XPM penalty. Although these maximum launch powers are estimated for 8-channel DUCS systems, Fürst<sup>20</sup> indicates that for channel counts over eight for NZ-DSF or NDSF the change in  $P_{\rm MC}$  is less than 1/2 dB. This is due to the decrease in walk-off effect from the outer channels as channel count increases. Therefore Table 7.7 is also a good estimate for higher channel count systems.

# 7.4 Stimulated Raman Scattering and Stimulated Brillouin Scattering

Stimulated scattering effect is the nonlinear scattering of light photons of an incident wave to another lower energy wave at a lower frequency (longer wavelength) in the fiber. This results in energy being released causing the appearance of phonons (molecular vibrations). The incident optical wave is the optical signal, also referred to as the pump wave and the scattered lower frequency waves are referred to as Stoke's waves. This effect reduces the signal's power as it propagates in the fiber. Note that linear scattering of light in a fiber is referred to as Rayleigh scattering and causes signal power loss in a fiber but the frequency of the scattered light remains unchanged. The main difference between Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) is that for SRS the phonons created in the fiber by the effect are optical and for SBS they are acoustical.

For SRS the high signal power interacts with atomic oscillations, which results in resonance at a lower frequency, peaking about 13.2 THz (100 nm) below the signal frequency. This peak occurs at approximately 180.21 THz (1660 nm) for an optical signal at 193.41 THz (1550 nm). For signals in the 1550 and 1660 nm bands SRS can cause energy to transfer from the 1550 nm signals to the 1660 nm signals resulting in cross-band interference. SRS spectral width (FWHM) is approximately 6 THz (48 nm). This effect is also the basis for Raman signal amplification.

For SBS, the phonons created by this effect generate an acoustical pressure wave due to electrostriction traveling at the speed of sound in the fiber in the same direction as the signal. This periodic change in fiber density changes the fiber's refractive index, since it is dependent on material density, and creates a sort of moving refractive index Bragg grating effect. This effect diffracts some of the signal power in the backward direction which reduces the signal power traveling in the forward direction, see Fig. 7.11. The backward signal changes to a lower frequency by 11 GHz (+0.1 nm) due to the Doppler shift caused by the signal diffracting from the moving grating. The backward propagating wave can interfere with laser operation causing instability, which can lead to bit errors, or if it is strong enough can damage the laser. SBS scattering effect is primarily in the backward direction; for SRS it is in the forward direction (direction of the signal or pump wave). Special fiber designs are available that reduce SBS to some degree by optimizing the core/cladding index profile and core dopants.


FIGURE 7.11 Brillouin scattering effect.

In single-channel systems, the SRS threshold power, which is the signal power level that causes a loss of 3 dB over the fiber length due to SRS effect, can be estimated<sup>21</sup> by Eq. (7.49).

$$P_{\rm th}^{\rm SRS} \approx \frac{16A_{\rm eff}}{g_{\rm R}L_{\rm eff}}$$
 (7.49)

where  $P_{\text{th}}^{\text{SRS}} = \text{SRS}$  threshold power, W

 $g_{\rm R}$  = Raman peak gain coefficient approximately<sup>22</sup> 4.7 × 10<sup>-14</sup> m/W (this value varies for different fiber types<sup>23</sup> from 3 × 10<sup>-14</sup> to 8 × 10<sup>-14</sup> m/W)

$$L_{off}$$
 = fiber effective length, m

 $A_{off}^{eff}$  = fiber's effective area, m<sup>2</sup>

Therefore, if the fiber's effective area is  $55 \,\mu\text{m}^2$  and the fiber length is longer than 50 km, then the maximum signal launch power is limited to 29 dBm. For most single-channel systems the signal launch powers are considerably lower than this and therefore likely not a concern.

In WDM systems, because of multiple signals existing in a fiber, the SRS optical power is transferred between the multiple signals causing SRS cross talk and degrading system performance. Making this effect worse is the fact that SRS can transfer power to signals spaced as much as 125 nm apart. This encompasses much of C- and L-band channels. Power coupling between the channels occurs from the signals with shorter wavelengths to the signals with the longer wavelengths, see Fig. 7.12. This results in an increase in noise for the higher wavelength channels and reduction in signal power in the lower channels. This occurs only if the signal's 1-bit levels overlap as they propagate in the fiber. When chromatic dispersion is present, the signals propagate at different speeds, which results in less probability the 1 bits will overlap due to the walk-off effect. Therefore, chromatic dispersion reduces SRS effect.

The fraction of power loss in a given WDM signal due to SRS can be estimated<sup>24</sup> by Eq. (7.50). This equation assumes the worst-case scenario where chromatic dispersion is zero and all the channel's 1 bits overlap. Additional assumptions are that all the channels are



FIGURE 7.12 SRS effect.

launched with the same power, all the channels have the same spacing, all polarizations are scrambled, and all the channels fall within the Raman gain  $\Delta\lambda_{R}$ .

$$\delta_{\rm SRS} = \frac{\Delta \lambda_{\rm ch} g_{\rm R} P_{\rm ch} L_{\rm eff} N(N-1)}{4 \Delta \lambda_{\rm R} A_{\rm eff}}$$
(7.50)

where  $\delta_{SRS} =$  fraction of power loss due to SRS  $\Delta \lambda_{ch} =$  WDM channel spacing, assuming constant channel spacing, m  $\Delta \lambda_{R} =$  Raman interaction bandwidth, approximately 125 nm  $P_{ch} =$  channel peak signal launch power, assuming all chan-

- nels are the same, W
- $L_{\rm eff}$  = fiber effective length, m

 $\ddot{N}$  = number of channels

The power penalty in dB for a channel can be estimated by Eq. (7.51).

$$\delta_{\rm SRS}^{\rm dB} = -10 \log(1 - \delta_{\rm SRS}) \tag{7.51}$$

Maximum channel launch power can be estimated with Eqs. (7.50) and (7.51). For less than 0.5 dB signal power loss due to SRS,  $\delta_{SRS}$  needs to be 0.1 or less from Eq. (7.51). Using 0.1 for  $\delta_{SRS}$  results in Eq. (7.52), which estimates maximum channel launch power for this power penalty.

$$P_{\rm ch} \le \frac{0.4\Delta\lambda_{\rm R}A_{\rm eff}}{\Delta\lambda_{\rm ch}g_{\rm R}L_{\rm eff}N(N-1)}$$
(7.52)

Inserting the Raman gain and bandwidth values into Eq. (7.52) it can be simplified to Eq. (7.53). Equation (7.52) assumes the fiber has zero chromatic dispersion. To account for chromatic dispersion of 3 ps/nm km or greater, which increases the walk-off effect, a factor of 2 is included in Eq. (7.53).

$$P_{\rm ch} \le \frac{2.11 \times 10^6 A_{\rm eff}}{\Delta \lambda_{\rm ch} L_{\rm eff} N(N-1)}$$
(7.53)

Table 7.8 shows maximum channel launch powers for various WDM channel counts and spacing into a NZ-DSF (G.655) where  $A_{\rm eff}$  = 55 µm<sup>2</sup>, attenuation is 0.21 dB/km, and length is 100 km. It should be noted the Raman gain coefficient (4.7 × 10<sup>-14</sup> m/W) can vary significantly for different fiber types and manufacturers, which would affect this table's values.

The wide, 20 nm, channel spacing in CWDM systems also limits launch powers. Typical SRS bandwidth is approximately 125 nm, which includes six CWDM channels. Using Eq. (7.53) average CWDM signal launch power limit is 6.7 dBm per channel for G.655 fiber.

	Maximum Launch Power (dBm)						
Channel Count	200 GHz	200 GHz 100 GHz 50 GHz CWD					
8	15	18	21	6.7			
16	8.6	11.6	14.7	6.7			
32	2.5	5.5	8.5	N/A			
40	0.5	3.6	6.6	N/A			
80	-5.5	-2.5	0.5	N/A			

TABLE 7.8Estimated Average Signal Launch Power Limit for 0.5 dBPenalty due to SRS in G.655 fiber



FIGURE 7.13 SRS power penalty for various DWDM channel counts.

Figure 7.13 plots SRS power penalties calculated using Eq. (7.53) for various channel counts, channel spacing, and signal launch powers. It shows that as channel spacing decreases or channel count decreases the SRS power penalty decreases for the same channel launch power. Figure 7.14 shows that as channel spacing decreases the channel maximum launch power increases for a given channel count and 0.5 dB SRS penalty.

Therefore, to launch a signal at the highest possible SRS threshold power, the DWDM channels are spaced together as closely as possible.

In stimulated Brillouin scattering (SBS) power can also be transferred across multiple channels creating cross-talk interference. For this to occur, the channel spacing must be less than 20 MHz (0.02 GHz).<sup>25</sup> For current and any foreseeable future DWDM systems SBS crosstalk is not a concern. However, due to the scattering effect, SBS effect does deplete the laser launch power significantly. Figure 7.15 shows



FIGURE 7.14 Maximum peak launch power for SRS power penalty of 0.5 dB.



FIGURE 7.15 Launch power versus reflected power near the SBS threshold.

laser launch power versus reflected power plot. Here it can be seen as laser launch power increases, reflected power increases linearly to a certain point referred to as the SBS threshold. After the SBS threshold, reflected power no longer increases linearly with launch power.

Equation (7.54) estimates<sup>26</sup> the maximum signal SBS threshold power for limiting SBS effect to 10% of launch power (–10 dB).

$$P_{\rm th}^{\rm SBS-CW} = \frac{21A_{\rm eff}}{g_B L_{\rm eff}} \left( \frac{\Delta f_B \otimes \Delta f_s}{\Delta f_B} \right)$$
(7.54)

The convolution term can be approximated giving Eq. (7.55).

$$P_{\rm th}^{\rm SBS-CW} \approx \frac{21A_{\rm eff}}{g_B L_{\rm eff}} \left( 1 + \frac{\Delta f_s}{\Delta f_B} \right)$$
(7.55)

where  $P_{\text{th}}^{\text{SBS-CW}} = \text{SBS}$  threshold power for an unmodulated CW (continuous wave) laser, W

- $g_{\scriptscriptstyle B} = {\rm SBS}$  gain approximately  $^{27}$  2.2  $\times$  10  $^{-11}$  , m/W
- $L_{\rm eff}$  = fiber effective length, m
- $\Delta f_s =$  unmodulated CW laser spectral width, typically DFB 10 MHz to 200 MHz
- $\Delta f_{\rm B}$  = SBS interaction bandwidth approximately 20 MHz at 1550 nm
- $A_{\rm eff}$  = fiber's effective area, m<sup>2</sup>

Equation (7.55) can be written<sup>28</sup> as Eq. (7.56) for an SBS threshold power of 0.01% of launch power (-20 dB).

$$P_{\rm th}^{\rm SBS-CW} \approx \frac{18A_{\rm eff}}{g_B L_{\rm eff}} \left( 1 + \frac{\Delta f_s}{\Delta f_B} \right)$$
(7.56)

As can be seen in Eq. (7.55) the wider the laser width the higher the threshold. This is because of the very narrow interaction bandwidth of 20 MHz for this effect. Amplitude shift keying (ASK) such as used in RZ and NRZ modulation broadens laser width and increases the SBS threshold. The ASK modulated laser threshold power can be estimated<sup>22</sup> using Eq. (7.57).

$$P_{\rm th}^{\rm SBS} = \frac{P_{\rm th}^{\rm SBS-CW}}{1 - \frac{R}{2\Delta f_B} [1 - \exp(-\Delta f_B/R)]}$$
(7.57)

where  $P_{\text{th}}^{\text{SBS-CW}} = \text{SBS}$  peak signal threshold power for a modulated laser, W

R =transmission rate, bps

If 100 km of fiber is used for signal transmission with an effective core area of 55  $\mu$ m<sup>2</sup>, and the CW laser spectral width is 100 MHz modulated at 10 Gbps, the NRZ signal threshold peak signal power is calculated to be 14 dBm (11 dBm average signal power). If a laser is used with a CW spectral width of 10 MHz, then the threshold peak signal power drops to 8 dBm (5 dBm average signal power). Lasers are available with phase modulation circuitry that broadens the laser's line width and therefore decreases SBS. SBS limits are listed in many transceiver specifications.

SBS can be very detrimental to high-power transmission systems. Not only is the signal attenuated by the effect, the backward scattering of power can contribute to noise if it enters the transmitting lasers. Also, interferometric noise can be created at the receiver if the signal reflects at the laser back to the receiver end. In order to achieve a high SBS threshold, signal spectral width is kept as wide as possible, and fibers with larger effective area and/or special core designs are deployed.

#### 7.5 Intrachannel Nonlinear Effects

For transmission rates of 40 Gbps and higher, intrachannel nonlinear effects (INLE) can be a concern in high-power transmission systems. These effects occur because of the nonlinear interaction between overlapping ultra-short pulses (widths 25 ps and less) within the same channel. INLE leads to an increase of timing jitter, amplitude jitter, and noise in the channel.<sup>29</sup> The two main effects are intrachannel cross-phase modulation (IXPM) and intrachannel four-wave mixing (IFWM) distortion. IXPM occurs when adjacent pulses overlap and the time derivative of the pulse edge causes a shift in frequency of the adjacent pulse, see Fig. 7.16.

IFWM occurs when frequency components of adjacent pulses overlap and mix. This generates new components within the same channel, see Fig. 7.17. The result is power transfer from the signal to the components and an increase in channel interference.

Both of these effects can be reduced considerably by chromatic dispersion precompensation optimization. Killey<sup>30</sup> has shown that Eq. (4.67) can be used to calculate the optimum span precompensation to minimize these effects. Precompensation results in symmetrical dispersion maps similar to Fig. 4.10, which helps in canceling the effects along the span.

$$CD_{pre-DCM} = -\frac{N \times CD_{res}}{2} - \frac{CD_c}{\alpha_0} ln \left[\frac{2}{1 + exp(-\alpha_0 L_{span})}\right]$$



FIGURE 7.16 Intrachannel cross-phase modulation (IXPM) process.



FIGURE 7.17 Intrachannel four-wave mixing (IFWM) process.

#### 7.6 Summary

Four-wave mixing occurs in closely spaced multichannel WDM systems, such as DWDM, and results in the generation of interfering optical components. These components lower channel OSNR and increase link BER. To help reduce FWM effects, the following points can be considered:

- 1. DWDM channel spacing can be kept as wide as possible, preferably 100 GHz or more.
- 2. Uneven channel spacing helps reduce the effect.
- 3. Maintain signal launch power below recommended threshold, estimated values shown in Table 7.3.
- 4. Use fibers with higher chromatic dispersion and larger effective core area.
- 5. Do not use fiber with a zero dispersion wavelength at the operating wavelength such as DSF fiber.

Self-phase modulation occurs when changes in signal power (between 1 and 0 bits) cause a change in its own optical frequency. This is referred to as frequency chirp and hastens pulse broadening, which decreases transmission distance. It is a concern only for transmission rates of 10 Gbps and higher. To help reduce SPM effects, the following points can be considered:

- 1. Maintain channel launch power below recommended threshold, estimated values shown in Tables 7.4 and 7.5.
- 2. Use fibers with lower chromatic dispersion and larger effective core area.
- 3. Decrease transmission rate below 10 Gbps.

Cross-phase modulation is the same basic effect as SPM but occurs in WDM systems and affects other channels in the fiber. To help reduce XPM effects, the following points can be considered:

- 1. Maintain channel launch power below recommended threshold estimated values shown in Table 7.7.
- 2. Increase channel spacing.
- 3. Increase fiber dispersion to increase walk-off effect.
- 4. Increase fiber core effective area.

Stimulated Raman and Brillouin scattering is the nonlinear scattering of light photons of an incident wave to another lower energy wave at a lower frequency (longer wavelength). The effect reduces signal power and can cause interference. To help reduce SRS effects the following points can be considered:

- 1. Maintain channel launch power below recommended threshold, estimated values given by Table 7.8 and Eq. (7.53).
- 2. Decrease channel spacing or channel count.
- 3. Increase fiber dispersion to increase walk-off effect.
- 4. Increase fiber core effective area.

To help reduce SBS effects the following points can be considered:

- 1. Maintain channel launch power below recommended threshold, estimated values given by Eq. (7.57).
- 2. Increase DFB laser spectral width.
- 3. Increase fiber core effective area.

The common action in the above points to decrease nonlinear distortions is to decrease signal power in the fiber. This is because nonlinear distortion is a function of fiber power density as described at the beginning of this chapter and Eq. (7.1). Therefore, using a fiber with a larger effective core area  $A_{\text{eff}}$  will help to reduce all nonlinear distortion effects. Typical effective core areas range between 50 to 85 µm<sup>2</sup>. A few selected fibers are available with core areas greater than 100 µm<sup>2</sup>.

A method to help reduce launch powers but still achieve long transmission spans is to deploy Raman amplifiers in a counter pump configuration. The Raman amplifiers placed at the end of a span pump light backward into the span using the fiber itself as a gain medium. The technique allows for the signal launch power to be reduced, which is compensated by the gain of the Raman amplifier.

Another technique to minimize nonlinear effects is to provide effective dispersion compensation in each span as described in this chapter. Maintaining an optimized low, but not zero, residual dispersion level along the entire link helps to reduce all nonlinear effects. To do this effectively dispersion under compensation with DCF fiber or dispersion compensating gratings, as shown in Fig. 4.9, are deployed for each span and/or NZ-DSF fiber is used instead of standard NDSF fiber.

A technique that can be partially helpful in reducing FWM and XPM effects in DWDM systems is to orthogonally polarize adjacent DWDM channels.<sup>31</sup> This technique is only partially effective because of the polarization mode scrabbling that occurs along the fiber length. It can also be helpful in reducing intrachannel FWM and XPM effects for 40 Gbps and higher transmission rates.

Table 7.9 summarizes nonlinear effect maximum launch powers. SBS is a serious limitation if laser line width is 10 MHz. Increasing laser line width to 200 MHz can significantly improve launch power but may decrease the transceiver's chromatic dispersion limit. Also, SRS can be significant for large channel counts.

NL Effect	Maximum Launch Power NDSF $A_{eff} = 80 \ \mu m$	Maximum Launch Power NZ-DSF $A_{_{eff}} = 55 \ \mu m$	Transmission Rate	Channels	Channel Spacing	Notes
FWM	15 dBm	13 dBm	N/A	8	100	
FWM	13 dBm	10 dBm	N/A	32	100	
SPM	12 dBm	10 dBm	10 Gbps	1	N/A	CD uncompensated
XPM	15 dBm	11 dBm	10 Gbps	8	100 GHz	3-span link, CD compensated
SBS	7 dBm	5 dBm	10 Gbps	N/A	N/A	10 MHz line width
SBS	15 dBm	13 dBm	10 Gbps	N/A	N/A	200 MHz line width
SRS	19 dBm	18 dBm	10 Gbps	8	100 GHz	
SRS	5 dBm	3.5 dBm	10 Gbps	40	100 GHz	

 TABLE 7.9
 Nonlinear Impairment Estimated Average Signal Launch Power Summary

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# CHAPTER **8** Fiber Characterization

# 8.1 Description

Fiber characterization can be defined as the field measurement and recording of fiber span parameters that affect signal transmission over all or selected operating wavelengths. These measured parameters provide a true picture of the fiber span's transmission limitations. They are used in network planning to ensure transmission limits are designed within transceiver operating budgets and limits. Full fiber characterization is often necessary in modern high-speed link designs, where optical budgets are stretched to their maximum with little or no margin for error. Fiber quality can also be assessed with these parameters. Fiber characterization is performed after new fiber cable link construction, dark fiber purchase, or lease. This helps to ensure the fiber quality meets or exceeds required specifications and expectations. It also documents fiber parameters at the time of construction or acquisition for comparison with future measurements to determine fiber degradation due to aging, damage, and repair.

The field measurable fiber span parameters are span loss (includes connector loss, splice loss, other span losses), chromatic dispersion (CD), polarization mode dispersion (PMD), return loss (RTL), span length, and nonlinear effects. These parameters are available from fiber cable specification sheets (except nonlinear effects). However, they are specified as maximum values for when the fiber cable is still on the cable reel. After cable installation they can change significantly. Cable spans can be made up of numerous and different concatenated fiber types. This makes it difficult to accurately calculate the total span parameter from individual cable section specifications. Also, fiber cable installation records and specifications are often misplaced and the only way to determine the span parameters is by measurement. In addition to measuring fiber parameters, determining signal latency through one or more active fiber links can help characterize the communication channel. Latency is the signal delay through a channel. This may be required for some service level agreements.

Fiber characterization consists of the measurement and recording of a single span parameter or multiple parameters. It depends on the transmission system, design margins, and reason for the measurements. At a minimum, for most system designs, fiber loss measurements over all operating wavelengths are necessary. Table 8.1 can help in determining which parameters need to be considered when deploying various transmission systems. It assumes standard single-mode fiber (G.652) is used for the span fiber and transceiver specifications are available. A "yes" cell suggests the measurement is likely required for most designs. A cell with a condition in it suggests that the measurement may be required for that condition. A "no" cell suggests that the measurement is not likely required for most typical designs.

Table 8.2 indicates the measurement units and practical precision for field measurements.

#### 8.2 Span Loss

The most important parameter in planning any fiber system is fiber span loss. It includes loss due to the fiber, all connectors, all splices, and any fiber anomalies. Total span loss can be estimated by multiplying the fiber's specified attenuation by the span length and adding all other estimated fiber span losses to it such as connector and splice loss. However, this result is only an estimate and may miss lossy fiber events or anomalies that can occur due to poor installation practice or other environmental stresses. To be certain of the span loss, field measures are required. An optical power meter with test laser source set to the signal operating wavelength, 1310 nm and 1550 nm for non-WDM systems, and a tunable laser for WDM systems will provide the best results. If a test laser source at the proper wavelength is not available, the channel transceiver laser can also be used as a source. Refer to Chap. 2 for more details about optical loss and measurement.

Measurement results are total span loss (dB) at all operating wavelengths and fiber span attenuation (dB/km) at all operating wavelengths (if an OTDR is used). Fiber attenuation varies across the fiber's transmission spectrum as shown in the typical fiber attenuation plot, see Fig. 6.15. C band has the lowest attenuation, typically about 0.23 dB/km, and the water peak (1383 nm) area can exhibit the highest attenuation at over 2 dB/km. But these values depend on the fiber type and other span losses. As seen in Fig. 6.15 it is clear that for a CWDM system, fiber loss can vary greatly over all 18 CWDM

Transmission Systems	Span Loss	CD	PMD	RTL	Span Length	NL Effects	OTDR	OSNR	BER
Under 1 Gbps	yes	no	no	laser	no	no	no	no	yes
1 to 5 Gbps	yes	no	no	yes	yes	no	no	no	yes
1 to 5 Gbps amplified	yes	yes	no	yes	yes	SBS	no	yes	yes
≥10 Gbps	yes	yes	yes	yes	yes	yes	no	no	yes
≥10 Gbps amplified	yes	yes	yes	yes	yes	no	no	yes	yes
WDM passive	yes	≥10 Gbps	≥10 Gbps	yes	≥1 Gbps	no	no	no	yes
WDM amplified	yes	yes	≥10 Gbps	yes	yes	yes	no	yes	yes
Overall fiber span quality	yes	yes	yes	yes	yes	yes	yes	yes	yes

 TABLE 8.1
 Fiber Characterization Measurement Suggestions

	Span Loss	CD	PMD	RTL	Span Length	Non- linear	OTDR	OSNR	BER
Measurement unit	dB	ps/ nm	ps	dB	km	dBm	dB	dB	ratio, no unit
Practical precision	0.1	1	0.01	0.1	0.001	0.1	0.1	0.1	10 <sup>-10</sup> 10 <sup>-12</sup>

 TABLE 8.2
 Fiber Characterization Field Measurement Units and Precision

channels ranges. Span loss can be quite high around the fiber's water peak wavelength; however, for short fiber lengths it still may be within the acceptable transceiver optical budget. Measurements at each CWDM channel is important to accurately assess channel loss. DWDM channel fiber loss in C and L bands is flatter than other bands, but here too, loss varies with signal wavelength. For accurate loss values, measurement at each DWDM channel is suggested. Test equipment measurement accuracy should be reviewed to ensure equipment will provide results within acceptable limits. Practical precision for field loss measurements is one or two decimal places.

Although an OTDR can be used to measure fiber span loss and attenuation, the best accuracy is obtained by using a calibrated optical power meter and laser source (tunable laser for DWDM/CWDM channels). An OTDR is best used to locate and determine the loss of single anomalies in a fiber link, such as bad bends, high connector loss, or broken fibers.

# 8.3 Chromatic Dispersion

Chromatic dispersion (CD) distorts signal waveforms making it more difficult for the receiver to distinguish between transmission protocol symbols (1s and 0s). It accumulates along the fiber increasing with fiber length. Since chromatic dispersion varies with fiber length, increasing fiber length also increases total chromatic dispersion, which results in increased signal distortion. This produces more errors and increases the transmission BER. A point is reached where the transmission errors reach a maximum acceptable BER level, typically at a BER of  $10^{-12}$ . This is referred to as the chromatic dispersion limit for the transceiver and is specified in units ps/nm, refer to Chap. 4 for more details. In order to ensure acceptable transmission BER, total fiber link chromatic dispersion must be within the transceiver's dispersion limit.

Fiber chromatic dispersion can be estimated from fiber specifications if total fiber length and fiber type are known, as shown in Chap. 4. However, often the fiber type is not known, or the fiber link is constructed of numerous different fiber types concatenated, making calculation difficult. Therefore, for the best accuracy field measurement is required.

Span chromatic dispersion is measured in units ps/nm (where nm refers to the spectral width of the laser) at the signal operating wavelength. Chromatic dispersion varies with wavelength, refer to Fig. 4.5; therefore, measurements are taken at all operating wavelength(s). For single-wavelength non-WDM systems, measurements are taken at 1310 and 1550 nm. For WDM systems, measurements are required for the entire WDM band. Many chromatic dispersion field test sets will measure the chromatic dispersion at three or four specific wavelengths across the fiber band and then interpolate to determine the chromatic dispersion at all other wavelengths, see Chap. 4. This method can produce acceptable results as long as high accuracy is not required. These test sets are often combined with an OTDR, which adds dual functionality to the units for a reasonable price. Measurement with this type of test set requires access to only one end of the fiber span. However, the far end must have a highly reflective end. More accurate units require access to both fiber ends and use a tunable laser as the source. Test equipment measurement accuracy should be reviewed to ensure equipment will provide results within acceptable limits. Practical precision for most field measurements is 1 ps/nm.

#### 8.4 Polarization Mode Dispersion

High fiber link polarization mode dispersion (PMD) values can increase transmission bit errors and reduce link availability. Total fiber link PMD should be ascertained for all transmission systems with rates of 10 Gbps or higher. Field measurements provide the most realistic results because manufacturer specified PMD values can and do change after cable installation. PMD can vary between fibers in the same cable and therefore measurement of each fiber is common. PMD test sets calculate span PMD by averaging measured instantaneous differential group delay values over a wavelength range, over time or both. They typically require connection to both fiber ends. PMD measurement results are in ps units. Test equipment measurement accuracy should be reviewed to ensure equipment will provide results within acceptable limits. Practical precision for most field measurements is 0.01 ps. Refer to Chap. 5 for further information regarding maximum PMD thresholds and testing.

# 8.5 Optical Return Loss

Optical return loss (ORL) is the logarithmic ratio of the launch (incident) power divided by the total reflected power seen at the launch point. It is measured in decibel units. A return loss value lower than transceiver specification can cause laser instability, wavelength drift, and an increase in laser noise, which can worsen the bit-error rate. If the reflective power is high enough, the laser can also be permanently damaged.

To measure ORL an optical continuous wave reflectometer (OCWR) test set or an OTDR is used. A simple OCWR can be assembled using a laser source, power meter, and three-port circulator. Refer to Chap. 2 for ORL test method details. The OCWR will typically provide better accuracy than an OTDR. Measurements should be made at both fiber ends. If the fiber length is less than 50 km and the far end is not connected to any equipment, it should be terminated with a non-reflective end so that its reflected power does not add to the ORL measurement. A simple non-reflective end may be achieved by wrapping a fiber jumper around a pencil.

For WDM systems, OCWR measurements are performed using a tunable laser source tuned to the measurement channel center wavelength. Practical precision for these measurements is 0.1 dB.

#### 8.6 Fiber Span Length

Fiber span length is commonly measured by an OTDR in km units. Since other parameters such as loss, CD, and PMD depend on fiber span length, it is important to measure and record the length for current design work. Note, for most loose tube fiber cables, fiber length is slightly longer than cable jacket length due to the cable design. Refer to cable specifications for multiplication factors used to determine fiber length if cable jacket length is known. OTDR measures fiber length in the cable and not cable jacket length.

Test equipment accuracy should be reviewed to ensure equipment will provide results within acceptable limits. OTDR accuracy depends on entering an accurate effective group index of refraction  $(N_{eff})$  value at the measurement wavelength for the fiber to be measured. It is available from cable manufacturer's fiber specification documents. Precision of the index of refraction should be at least four decimal places  $\pm 0.0001$  (example 1.4682). This will result in an index of refraction error of  $\pm 0.007\%$  or  $\pm 3.5$  meters for a 50 km measurement. If the precision of the index of refraction is only three decimal places  $\pm 0.001$  then the error would be  $\pm 0.07\%$  or  $\pm 35$  meters for a 50 km measurement.

#### 8.7 Nonlinear Impairments

Nonlinear (NL) effects impair transmission when high optical powers are launched into a fiber. Refer to Chap. 7 for details about these effects. Two of the NL effects that can be field measured are stimulated Brillouin scattering (SBS) and four-wave mixing (FWM). These measurements can help in determining launch power limits.

#### 8.7.1 Stimulated Brillouin Measurement

Stimulated Brillouin Scattering (SBS) manifests itself as optical power that is reflected back to the laser source. It adds to other reflected power produced by Rayleigh scattering and Fresnel reflections, which in total decreases the fiber's ORL. If the reflected power is high enough, laser stability can be affected, which can lead to bit errors or laser failure. As shown in Table 7.9, a launch power over the SBS threshold of 5 dBm can produce significant SBS reflected power for certain transmission conditions. A simple test using the ORL measurement technique can be performed to determine the SBS threshold.

The setup for this measurement is shown in Fig. 8.1. The laser used for this measurement should be the actual transmission laser that is normally used for communications. This provides for a more realistic measurement since laser spectral width affects SBS. The booster EDFA can be the network EDFA or test EDFA used for the measurement. It is used to boost the laser launch power high enough to measure significant SBS levels. The variable optical attenuator (VOA) is connected after the EDFA in order to be able to adjust launch power levels from –5 to +15 dBm. A three-port circulator is connected to the VOA output, fiber under test, and a power meter. It directs reflected power in the fiber under test to the power meter for measurement. At the end of the fiber under test is a non-reflective end that prevents fiber end reflections from corrupting the recorded data. This can be easily made by tightly winding an old fiber jumper around a pencil.

The measurement begins with adjusting the VOA to an output, into the circulator, of -5 dBm. This level can be measured by attaching the power meter to the VOA output. The power meter is reconnected to the circulator and the reflected power is recorded. This process is repeated in 1 dBm increments up to +15 dBm. The recorded launch and reflected powers are used to plot a graph similar to Fig. 7.15. From this graph the SBS threshold can be easily spotted. It is the



FIGURE 8.1 SBS power measurement setup.

launch power value where an increase in launch power no longer results in a linear increase in reflected power.

The ORL at any point in the plot can be calculated from the measured data using Eq. (2.12).

$$ORL = 10 \log \left(\frac{P_i}{P_R}\right)$$

where ORL = optical return loss, dB  $P_{R}$  = total reflected power, mW  $P_{i}$  = launch power, mW

In order to meet or exceed transceiver specification, signal launch power is limited to the measured fiber ORL that is greater than the transceiver laser's specified ORL limit. Typical laser ORL limit specification is 24 dB. Refer to the manufacturer's specification for the correct value.

#### 8.7.2 Four-Wave Mixing and Nonlinear Coefficient Measurement

Four-wave mixing (FWM) is a nonlinear distortion that can occur in DWDM fiber spans where high power levels are encountered. It manifests itself as new interfering wavelengths created from the energy of the original DWDM signals, refer to Chap. 7 for details. For DWDM systems where channel wavelengths are near the fiber's zero dispersion wavelength or where high signal powers are used, significant FWM effects can be encountered.

FWM component power can be measured<sup>1</sup> and the nonlinear coefficient estimated using a simple test setup. Test equipment required includes two DFB lasers with adjacent channel wavelengths (or tunable lasers), two polarization controllers (PC), two variable optical attenuators (VOAs), a DWDM multiplexer (or 50/50 coupler), two EDFAs, and an optical spectrum analyzer (OSA). The two lasers are unmodulated continuous wave (CW) lasers, not transceiver lasers, in order to increase accuracy. Setup is shown in Fig. 8.2. If a DWDM is not available then two narrow band optical filters and a 50/50 coupler are used. The DWDM or narrow band filters help reduce noise



FIGURE 8.2 Nonlinear coefficient measurement using FWM and two CW lasers.

Fiber Characterization

generated by the EDFAs. If the noise level is too high it may be difficult to see the FWM components with the OSA.

The OSA is connected to the output of the DWDM and the VOAs are adjusted until both laser powers are equal. The launch powers into the fiber are recorded as  $P_0$ . Then the OSA is connected to the opposite end of the fiber span. If the FWM components are not visible at wavelengths given by Eqs. (8.1) and (8.2) then both EDFA gains are equally increased until they are visible next to the fundamental laser powers. The variable polarization controllers are adjusted until the FMW components peak at maximum power. This point corresponds with parallel launch polarizations. The OSA is reconnected at the DWDM output end and both lasers' launch powers are checked to be equal. If they are not equal, the VOAs are readjusted. The laser launch power is recorded as  $P_0$ . Then the OSA is reconnected to the opposite end of the fiber span and the two FWM component powers are measured with the OSA and recorded as  $P_{iv}$ .

$$\lambda_{112} = \lambda_1 + \lambda_1 - \lambda_2 \tag{8.1}$$

$$\lambda_{221} = \lambda_2 + \lambda_2 - \lambda_1 \tag{8.2}$$

where  $\lambda_1, \lambda_2$  = DWDM laser center wavelengths, nm  $\lambda_{ijk}$  = newly created interfering signal wavelengths, nm

Next the nonlinear Schrödinger wave equations are solved for two fiber signals. Equation (7.24) can be used as an estimate, see Eq. (8.3).

$$P_{ijk} = \frac{\eta}{9} d^2 \gamma^2 P_i P_j P_k L_{\text{eff}}^2 \exp(-\alpha L)$$
(8.3)

where

 $P_{iik}$  = peak power of an FWM component

 $\dot{P}_0$  = peak laser launch power into the fiber of the laser

 $P_i, P_i, P_k$  = peak laser launch power into the fiber of the laser

 $L_{\rm eff}$  = fiber effective length, m

 $\eta$  = FWM efficiency factor, see Chap. 7

d = degeneracy factor equals 3 for two lasers

 $\gamma$  = nonlinear coefficient, (Wm)<sup>-1</sup>

- $\alpha$  = fiber attenuation coefficient, m<sup>-1</sup>
- L = fiber length, m

Equation (8.3) is solved to give the nonlinear coefficient, see Eq. (8.4). For a two-laser test the degeneracy factor is set to 3 and all launch powers are equal  $P_0 = P_i = P_j = P_k$ . The measured laser launch power  $P_{0'}$  measured FWM component power  $P_{ijk}$ , and other required fiber parameters for Eq. (8.4) are used to solve for the fiber's nonlinear coefficient, refer to Chap. 7 for details. The other fiber parameters required are attenuation, length, chromatic dispersion, chromatic



FIGURE 8.3 EM FWM nonlinear coefficient measurement.

dispersion slope, and center frequencies of the two lasers. These are measured using appropriate test sets.

$$\gamma = \sqrt{\frac{P_{ijk}}{\eta P_0^3 L_{\text{eff}}^2 \exp(-\alpha L)}}$$
(8.4)

Once the nonlinear coefficient is known for the fiber, it can be used to calculate the fiber's nonlinear effects FWM, SPM, and XFM. Accuracy of this nonlinear coefficient measurement method is reported<sup>1</sup> to be 15% assuming accurate measurement of optical powers, laser frequencies, fiber length, fiber attenuation, and fiber chromatic dispersion.

A similar but more accurate and simpler method to measure nonlinear coefficient uses an external modulator (EM) and only one CW DFB laser. The laser is modulated with a high-frequency RF carrier that is pulse modulated with a square wave, see Fig. 8.3. The EM output is an optical carrier with two sidebands. The spectral separation of the side bands is twice the RF carrier frequency.<sup>2</sup> The output is then amplified with one EDFA and fed into the span fiber. The modulation frequency needs to be high enough so that the OSA can separate the sidebands for accurate power measurement. The launched side bands into the fiber have the same optical power ( $P_0$ ), the same polarization, and the same phase, which results in better calculation accuracy. The nonlinear coefficient is then calculated using Eq. (8.4).

#### 8.8 Signal Latency

Signal latency is the end to end information delay or pulse delay in a communication channel. It is an important parameter to measure and record because many protocols, such as Ethernet, require low latency for proper operation. Network providers often sign service level agreements (SLAs) that specify a maximum channel latency. However, this parameter is easily neglected in link planning. Latency depends on signal propagation delay in the transmission equipment and in

the transmission medium. Equipment propagation delay various greatly for various equipment. Exact delay times are often available from the equipment manufacturer or can be measured. Medium delay depends on the medium type and the propagation distance. For example, optical fiber transmission systems experience higher latency than wireless systems over the same distance because light travels significantly slower in glass than in air. Both media will experience higher latency if the transmission distance is increased.

The speed of an optical signal in a fiber, such as a data pulse, is known as group velocity and can be calculated<sup>3</sup> knowing the fiber's effective group refractive index using Eq. (8.5). This effective group refractive index is listed in manufacturer's fiber data sheets.

$$v_g = \frac{c}{n_g} \tag{8.5}$$

where  $v_g$  = group velocity of a signal, m/s

 $\ddot{c}$  = speed of light in a vacuum, m/s

 $n_g$  = fiber's effective group refractive index at operating signal wavelength  $\lambda$ 

Knowing the length of the fiber link and group velocity, the time delay can be calculated using Eq. (8.6).

$$t_f = \frac{L}{v_g} \tag{8.6}$$

Equation (8.5) and (8.6) can be combined into one as Eq. (8.7).

$$t_f = \frac{Ln_g}{c} \tag{8.7}$$

where  $t_f$  = fiber latency, the time required for information (pulse) to travel the length of the fiber, s

L =length of the fiber, m

For example, if a 100 km fiber link has an effective group refractive index of  $n_g = 1.4682$  what is the signal latency in the fiber?

$$t_f = \frac{100 \times 10^3 \times 1.4682}{2.9979 \times 10^8}$$
$$t_f = 4.8974 \times 10^{-3} \,\mathrm{s}$$

The fiber's latency or time required for the signal to propagate 100 km in this fiber link is 4.8974 ms.

A fiber link component that will increase signal latency if it exists in the link is the dispersion compensating module (DCM) that uses dispersion compensating fiber (DCF). For each DCF DCM deployed in the link, the latency due to its dispersion compensating fiber is calculated using Eq. (8.7) and is added to the fiber link latency. To avoid this additional latency, the DCF DCM can be replaced with a DCM that uses only a fiber Bragg grating (FBG). FBG does not add any significant latency to a link.

To obtain total end to end channel latency, the latency due to all link contributors is summed as shown in Eq. (8.8).

$$t_T = t_f + \sum t_{\text{DCM}} + \sum t_e \tag{8.8}$$

 $t_{T}$  = total link latency, s where

 $t_{i}$  = latency due to the link fiber, s

 $t_{\rm DCM}$  = latency due to a DCF DCM, s

 $t_{e}^{n}$  = latency due to electronic equipment in the signal path, s

Continuing with the above example, two DCF DCMs each with 20 km of DCF fiber and with a group refractive index of 1.4732 are added to the link. The delay due to the two end terminals is 7 ms each. What is the total channel latency?

The delay due to one DCF DCM is as follows:

$$t_f = \frac{20 \times 10^3 \times 1.4732}{2.9979 \times 10^8}$$
$$t_{\rm DCM} = 98.282 \times 10^{-6} \, {\rm s}$$

Total delay is calculated as follows:

 $t_{\tau} = 4.8974 \times 10^{-3} + 2 \times 98.282 \times 10^{-6} + 2 \times 7 \times 10^{-3}$  $t_T = 19.291 \times 10^{-3}$ 

The calculated channel latency is 19.291 ms. The accuracy of this latency depends on the accuracy of the measured fiber distance, DCM lengths, delay in electronic equipment, and group refractive index at the operating wavelength.

Signal latency can also be easily measured with some BER testers. For IP systems, the internet control protocol (ICMP) ping test can be used to estimate round-trip latency.

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# **CHAPTER 9** Testing Ethernet and Synchronous Optical Networks

# 9.1 Bit Error Ratio Test

A bit error ratio (BER) test is a common method of assessing the performance of a new or existing digital circuit. It is the standard test used in assessing the quality of SONET/SDH circuits. The test is an out-ofservice test that can be easy to perform by one technician who has access to both ends of the circuit. Typically one BER test set is used, which is connected at one end of the circuit. At the other end, a hardware or software loopback is installed. A fiber hardware loopback consists of a short fiber jumper with an attenuator that connects the laser output port to the receiver input port, see Fig. 9.1. The attenuator is sized to ensure the receiver is not overloaded by the local laser. For an electrical hardware loopback the data output to input wires are properly connected together and other control/handshaking wires may also need to be properly connected. For a software loopback, access is required to the far end interface software configuration and loopback option selected if available. Once the far end interface is in loopback, a BER test pattern sent to the far end of the link will be returned (looped back) to the BER tester. Upon receiving the signal, the BER tester compares the received bit pattern against the transmitted bit pattern to detect any bit errors. A bit error is defined as a transmitted one bit that is received as a zero bit or transmitted zero bit that is received as a one bit. A detected error is recorded as a bit error. The bit error ratio is calculated as the number of bits received in error divided by the total number of bits sent, see Eqs. (3.43), (3.44) and (9.1).

$$BER = \frac{E}{n}$$
(9.1)  
$$BER = \frac{E}{TR}$$

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FIGURE 9.1 Hardware loopback.

where *BER* = bit error ratio

E = number of erroneous bits received

n = number of bits transmitted

T =time to transmit n bits, seconds

*R* = transmission rate, bits/second

The most realistic BER test that represents the actual BER of a circuit is one that runs indefinitely. Since this is not practical, the BER test must run long enough to achieve a high level of confidence that the recorded BER is the actual circuit BER. This length of time can be calculated and is described in detail in Chap. 3. For example, to test a 10 Gbps circuit to a BER of 10<sup>-12</sup>, confidence level of 99%, and two-digit accuracy, the test needs to run for at least 3 hours and 30 minutes and 100 or less errors need to be recorded. For the same BER of 10<sup>-12</sup> and confidence level of 99%, a 2.5 Gbps circuit needs to be tested for at least 13 hours and 36 minutes, and 100 or less errors need to be recorded.

#### 9.2 RFC-2544 Test

The Internet Engineering Task Force (IETF) body established the RFC-2544 test standard<sup>1</sup> to provide a method of performance criteria for Ethernet networks. Since Ethernet is a layer 2 (data link) packet switched protocol, testing using a BER test may not provide useful results. A single bit error will result in the entire frame being discarded and the bit error will not be received by the tester. Instead it will receive a frame loss error and the actual number of bit errors will not be known. Therefore, the RFC-2544 test standard was created to better assess the Ethernet link throughput, frame loss, back to back frame loss, and latency. The test is conducted on an Ethernet channel that is out of service.

The link throughput test is the maximum frame rate in frames per second that the Ethernet link can support with zero frame loss. The Ethernet IEEE 802.3\* standard<sup>2</sup> defines four transmission rates, 10 Mbps, 100 Mbps (IEEE 802.3u), 1 Gbps (IEEE 802.3ab/z), or 10 Gbps (IEEE 802.3.ae). However, these rates are not maximum frame rates or actual data throughput rates. This is because the standard defines the transmission rate for a continuous stream of bits, or one over the bit

<sup>\*</sup>IEEE and 802.3 are registered trademarks belonging to the Institute of Electrical Engineering, Inc.

	-	i					
Preamble	Framing & MAC	Data	CRC	IFG			
8 bytes	14 bytes	46 to 1500 bytes	4 bytes	12 bytes			
	Frame 64 to 1518 bytes						
Total size 72 to 1526 bytes							

a. Ethernet 802.3 MAC frame

Preamble	Framing & MAC	Data	CRC	IFG
8 bytes	18 bytes	42 to 1500 bytes	4 bytes	12 bytes

b. Ethernet 802.3 MAC frame with VLAN tagging



period where  $R_r = 1/T$ . Ethernet protocol is a packet technology where frames of data are sent and not a continuous stream as in synchronous protocols (SONET/SDH). The maximum frame rate is determined by calculating the frame packet size, which is divided into the standard transmission rate, see Eq. (9.2). Each frame consists of MAC address, data, and cyclic redundancy check (CRC) fields. Also added to the frame is a preamble and interframe gap (IFG), see Fig. 9.2. The interframe gap is the gap between sequential frames that has a minimum size of 12 bytes. The data field has a minimum size of 46 bytes and maximum of 1500 bytes, or minimum of 42 bytes if virtual LAN (VLAN) is supported in the frame. Minimum frame packet size is then 84 bytes and maximum is 1538 bytes for non-VLAN frames.

RFC-2544 defines eight frame sizes for testing, 64, 128, 256, 512, 1024, 1280, 1518, and 1522 bytes. The maximum frame rate is tested for each frame size. The test begins with a low frame rate, which is increased until an error occurs. If the maximum frame rate is reached without error then the link can support the maximum rate. Otherwise the link supports the last error-free frame rate.

The actual data throughput rate is much less than the standard transmission rate because of the frame's nondata overhead bytes. Data throughput varies with frame size and can be calculated using Eq. (9.3). Data transmission efficiency can be calculated with Eq. (9.4).

$$R_F = \frac{R_S}{N_F} \tag{9.2}$$

$$R_{\rm data} = R_F \times N_{\rm data} \tag{9.3}$$

$$T_{\rm eff} = \frac{R_{\rm data}}{R_{\rm S}} \times 100 \tag{9.4}$$

where  $R_F =$  frame rate, fps  $R_S = 802.3$  standard transmission rate, bps  $R_{data} =$  actual data throughput rate, Mbps  $N_F =$  total length of the frame plus preamble and interframe gap, bits  $N_{data} =$  length of the data in the frame, bits  $T_{off} =$  data transmission efficiency, %

**Example 9.1** For example, if a 100 Mbps Ethernet link is sending the smallest frames with 46 data bytes, the maximum frame rate is calculated using a frame length of 64 bytes plus preamble of 8 bytes and IFG of 12 bytes.

$$R_F = \frac{100 \times 10^6}{(64 + 8 + 12) \times 8}$$
$$R_F = 148809_{\rm fps}$$

The maximum frame rate is 148,809 fps. The actual maximum data throughput rate is 54.76 Mbps and is calculated using Eq. (9.3) and 46 data bytes.

$$R_{data} = 148809 \times 46 \times 8$$
$$R_{data} = 54.76_{Mbps}$$

The data transmission efficiency is 54.76% and is calculated using Eq. (9.4).

$$\begin{split} T_{\rm eff} &= \frac{54.76 \times 10^6}{100 \times 10^6} \times 100 \\ T_{\rm eff} &= 54.76\% \end{split}$$

Table 9.1 lists the practical maximum frame rates and data throughput rates for various frame sizes.

As can be seen in Table 9.1 the highest transmission efficiency is achieved with the largest frame rate.

Frame loss tests measure the percentage of frames that were successfully transmitted by the source but never received tested over all frame rates. Frames can be lost due to a number of reasons including errors, excessive delay, and lack of resources.

Back to back frame loss tests (also known as burst or full rate) involve the transmission of back to back frames with minimum IFG (12 bytes) over a short period of time through the link. It measures the maximum number of frames that can be transmitted at maximum frame rate without any frame loss. The test assesses the buffering capability of end and intermediate equipment. It can validate the link's excess information rate (EIR) above the committed information rate (CIR) often specified in a service level agreement (SLA).

A signal latency test measures the total time for a frame to propagate through the link. The time is dependent on the medium (fiber) delay and electronic equipment delay. Refer to Chap. 8 for more details on latency. Latency can vary over time and should be completed at different times. Long latency times can degrade Ethernet service quality as well as real time applications such as VoIP.

It should be noted that the actual optical transmission rate in a fiber (also known as line rate) is slightly different from the standard rate. This is because

			100 Mbps		1 GigE		10 GigE	
Frame Size (byte)	Data Size (byte)	Efficiency (%)	Frame Rate (fps)	Throughput (Mbps)	Frame Rate (fps)	Throughput (Gbps)	Frame Rate (fps)	Throughput (Gbps)
64	46	54.8	148,809	54.8	1,488,095	0.548	14,880,952	5.48
128	110	74.3	84,459	74.3	844,594	0.743	8,445,946	7.43
256	238	86.2	45,289	86.2	452,898	0.862	4,528,986	8.62
512	494	92.8	23,496	92.8	234,962	0.929	2,349,624	9.29
1024	1006	96.4	11,973	96.4	119,731	0.964	1,197,318	9.64
1280	1262	97.1	9,615	97.1	96,153	0.971	961,538	9.71
1518	1500	97.5	8,127	97.5	81,274	0.975	812,744	9.75
1522	1504	97.5	8,106	97.5	81,063	0.975	810,636	9.75

 TABLE 9.1
 Maximum Ethernet Frame and Data Throughput

encoding is added to the transmission, which ensures DC balance using NRZ optical modulation. For 10 GigE standard, the actual fiber transmission rate is 10.3125 Gbps for 10GBase-R, which is used in LAN networks and 9.95328 Gbps for 10GBase-W, which is used in SONET/SDH transmission. For 1 GigE the actual optical rate is 1.25 Gbps.

RFC-2544 test sets are available from many manufacturers. Many have a simple default configuration that allows for all the above measurements to be run and results tabulated with one push of a button. The test set typically requires a matching remote unit for link end to end testing. The remote unit is configured with its own IP address and is connected to the far end of the Ethernet circuit.

# References

- 1. Internet Engineering Task Force; www.ietf.org.
- 2. Institute of Electrical Engineering, Inc.; www.ieee.org.

# CHAPTER 10 Network Elements

#### 10.1 Description

Most fiber communication links are deployed in point-to-point physical topologies. Other topologies such as ring, mesh, and star are various configurations of numerous point-to-point links. The basic elements of a point-to-point topology are the end terminals, fiber cable, WDM equipment, signal regeneration and/or amplification equipment, and other signal conditioning equipment.

The end terminal's basic function is to provide the electrical-tooptical and optical-to-electrical signal conversion, which is performed by the terminal's transceiver. The transceiver is either embedded in the terminal equipment or a pluggable that can be easily removed from the terminal for replacement or upgrade. Pluggable transceivers are very common; types include XFP, SFP, Xenpak, and GBIC. Many terminals also perform additional functions such as aggregating multiple signals into one such as SONET terminals or Ethernet switches and/or providing protection path switching.

Many different types of fiber optic cable and cable fiber are available on the market. The cable type is selected to best fit the installation environment and the fiber type is selected for the transmission system. Common cable types are direct burial, aerial, indoor, and optical ground wire. The most common fiber type is standard single-mode fiber (SSMF), which conforms to ITU-T G.652 standard. Other fiber types are non-zero dispersion shifted fiber (NZ-DSF ITU-T G.655) and dispersion shifted fiber (DSF ITU-T G.653). DSF is no longer deployed because its 1550 nm zero dispersion wavelength significantly increases four-wave mixing interference.

WDM equipment is deployed in local, metropolitan, or long-haul links, where all existing fiber strands are in use and additional link capacity is required. WDM deployment is typically much less costly than new fiber cable plant construction for most situations. DWDM solutions are available from 2 to over 80 channels on two fibers.

Regeneration equipment is deployed in a fiber link where the optical signal needs to be re-amplified, retimed, and reshaped (3R regeneration). Equipment that only re-amplifies and reshapes the

optical signal is called a 2R type regenerator. Regeneration equipment can regenerate only one optical signal. Therefore, in DWDM links, they are only used where signal retiming and reshaping are required. If the signal power only needs to be increased, then an optical amplifier is deployed instead. Optical amplifiers are commonly deployed in DWDM links to re-amplify multiple optical signals in the fiber.

Other conditioning equipment often found in a fiber link include attenuators and dispersion compensation modules.

# **10.2 Optical Transceivers**

An optical transceiver is an electronic device that converts an electrical signal to an optical signal and an optical signal to an electrical signal. The transceiver consists of two main parts: the light source (transmitter) and receiver. The light source consists of a solid state laser and associated circuitry that generates coherent light that can be modulated by the electrical signal and launched into a singlemode fiber. For multimode fiber systems, the light source is typically a light emitting diode (LED). The receiver consists of a photo diode or avalanche photo diode and associated circuitry that converts the modulated fiber light to an electrical signal. Both transmitter and receiver are commonly integrated into one small package called a pluggable transceiver (XFP, SFP, etc.).

#### 10.2.1 Lasers

The laser's generation of coherent light is similar to an electronic oscillator. In order for lasing to occur, a clear cavity is created in a semiconductor crystal. Both ends of the cavity are plane and parallel to each other forming a semi-reflective surface at the air interface, see Fig. 10.1*b*. This cavity structure is referred to as a Fabry-Perot resonator. As current passes through the semiconductor material, electrons in an atom are excited and move from the low-energy (valence) band to a temporary high-energy (conduction) band. After a time period (a.k.a. carrier recombination lifetime, 1 ms <  $\tau$  < 1 ns) the high-energy electrons drop back down to the low-energy band giving off energy in the form of photons (light) in all directions, see Fig. 10.1*a*. This is referred to as spontaneous emissions, see Fig. 10.2. This is the basis for light generation in an LED. The modulation bandwidth<sup>1</sup> of an LED is limited by the carrier lifetime and is the reciprocal of the carrier lifetime, see Eq. (10.1)

$$BW = \frac{1}{\tau}$$
(10.1)

where BW = -3 dB bandwidth, Hz  $\tau$  = carrier (electron) recombination lifetime, s



FIGURE 10.1 LED and laser emissions.

As the photons travel in the cavity they reflect off the end surfaces and travel back through the cavity. These photons stimulate other electrons that are in the high-energy band, to also drop back down to the lower energy band, which releases more photon energy. The newly generated photons acquire the same phase, frequency, polarization, and direction as the incoming photons (known as coherent radiation). This is referred to as stimulated emissions and is the basis for laser light generation, see Fig. 10.2. The stimulated emissions occur in the Fabry-Perot (FP) cavity. As the photons travel back and forth reflecting off the two mirror ends, resonance occurs at certain


FIGURE 10.2 Laser electron energy diagram.

optical frequencies (also known as standing wave) due to the cavity length, see Fig. 10.1*d*. Other photon nonresonant frequencies are not supported in the FP cavity and do not occur, see Fig. 10.1*c*. Optical power is concentrated at the resonance frequencies<sup>2</sup> and is referred to as longitudinal modes, see Fig. 10.3. The longitudinal modes occur at frequencies that are integer multiples of twice the cavity length, see Eq. (10.2).

This type of laser generates numerous longitudinal modes and is referred to as a multiple-longitudinal mode (MLM) laser. The name should not be confused with multimode fiber, which refers to a different type of fiber mode. Spacing between each mode is given by Eq. (10.3) or Eq. (10.4).

$$f_m = \frac{mc}{2nL_{\rm FP}} \tag{10.2}$$



FIGURE 10.3 Unmodulated Fabry-Perot laser diode spectrum.

#### Network Elements

$$\Delta f = f_m - f_{m-1} = \frac{c}{2nL_{\rm FP}}$$
(10.3)

$$\Delta \lambda \approx \frac{\lambda^2}{2nL_{\rm FP}} \tag{10.4}$$

where  $\Delta f$  = spacing between modes, Hz

 $f_m$  = resonance frequency, Hz

- $\Delta\lambda$  = spacing between modes, m
  - $\lambda$  = mode wavelength, m
- $L_{\rm FP}$  = laser FP cavity length, m
  - n = refractive index of the cavity material
  - m = a positive integer, typically in the range of 1280

c = speed of light in a vacuum, m/s

The amplitudes of the longitudinal modes are determined by the gain curve characteristic of the FP cavity which is dependent on the type of material and doping used for the laser. The mode that is generated at the gain peak becomes the dominant mode. The number of generated modes depends on the width of the gain curve. The end of the cavity that is semi-reflective is where the laser light is emitted. The total laser output power is the summation of powers of each mode.

For example, if an FP laser has a cavity length of 300  $\mu$ m and a cavity refractive index of 3.3, then the mode spacing is calculated to be 151.4 GHz. If the gain curve peak is at 193.77 GHz then the dominant mode frequency is calculated at 193.81 GHz (1546.12 nm). The number of modes that will appear will depend on the spectral width of the gain curve.

The FP laser has a relatively large spectral width of approximately 1 to 10 nm (120 to 1200 GHz). This significantly reduces its use in long-haul and high data rate transmissions because of fiber chromatic dispersion. The wide bandwidth also prevents it from being used in DWDM systems. However, it can be an economical choice for short reach non-DWDM links.

FP lasers and other MLM lasers cause mode partition noise (MPN). The noise occurs because of random variations of individual laser modes even though the total laser output power remains constant. The noise is generated in fibers where the signal dispersion wavelength is not zero. The fluctuating modes travel at different group velocities due to chromatic dispersion, which results in mode desynchronization and added receiver noise. The power penalty<sup>3</sup> due to this effect can be calculated as shown in Eqs. (10.5) and (10.6).

$$\delta_{\rm mpn} = -5\log(1 - Q^2 \sigma_{\rm mpn}^2) \tag{10.5}$$

$$\sigma_{\rm mpn} = \frac{k}{\sqrt{2}} [1 - \exp(-(\pi R L \sigma_{\lambda} C D)^2)]$$
(10.6)

where  $\delta_{mpn} = MPN$  noise penalty, dB Q = Q-factor [refer to Eq. (3.63) for relationship to BER]  $\sigma_{mpn} = RMS$  received noise power due to MPN, W k = MPN factor between 0 and 1 R = signal transmission rate, Tbps  $\sigma_{\lambda} = laser's RMS$  spectral width  $[\sigma_{\lambda} = 0.425\lambda_{FWHM}, see Eq. (E.4)]$ , nm CD = chromatic dispersion coefficient, ps/(nm · km) L = fiber length, km

The *k* factor is difficult to determine but can be estimated at 0.8 as a conservative value for MLM lasers. MPN can also occur for SLM lasers that have significantly large side nodes and where the side mode suppression ratio (SMSR) is less than 20 dB.

Another common laser type is called the distributed feedback (DFB) laser. Its basic function is the same as the FP laser. However, the DFB resonance cavity is a Bragg grating tuned to the dominant longitudinal mode frequency, see Eq. (6.1). The effect is that all nondominant mode frequencies are suppressed, resulting in a single-mode laser, see Fig. 10.4.

The DFB laser is referred to as a single longitudinal mode (SLM) laser. The laser's spectral width now becomes the same as the laser's line width and is very narrow. A variation of this laser type is when the Bragg grating is placed at the ends of the resonance cavity replacing the mirrors. The resulting effect of one single longitudinal mode output is the same. This type of laser is referred to as a distributed Bragg reflector (DBR) laser. Typical DFB and DBR lasers' unmodulated spectra widths are from 5 to 50 MHz. This laser type has a much



FIGURE 10.4 Unmodulated DFB laser diode spectrum.

longer dispersion limit than the FP laser and is better suited for longhaul and DWDM applications. This laser type is more complex than an FP laser and therefore higher priced. Another manufacturing concern is that the SLM laser's operating wavelength tends to drift with temperature. This is corrected by incorporating complex temperature compensation circuitry, which is necessary for DWDM applications but further increases the unit's price.

A third laser type is the vertical-cavity surface-emitting laser (VCSEL). It also operates as an SLM laser. It was introduced as a lower cost alternative to the DFB lasers. VCSEL lasers emit light perpendicular to the semiconductor wafer plane surface as opposed to the edge emitting lasers (FP, DFB, DBR) discussed previously. The resonance cavity is much shorter than that of DFB lasers, approximately 1  $\mu$ m. This results in wide mode spacing of approximately 45 THz. At the ends of the resonance cavity are Bragg gratings similar to the DBR laser. The resulting spectral width of the gain curve is much less than 45 THz, at approximately 400 GHz. Therefore, only one mode can exist and the laser operates as an SLM laser. Wide spectral widths of the gain curve can result in MLM laser operation. The advantage of this laser type is its small size and low power consumption. It is available for both long-haul transmissions and DWDM systems.

Laser diodes have a much larger modulation bandwidth than LEDs. This is because the LED bandwidth is determined by the spontaneous emission carrier recombination lifetime of the semiconductor material, see Eq. (10.1). This is the average time the electrons exist in the conduction band before spontaneously moving back to the valence band. In a laser the stimulated emission carrier recombination lifetime is the average time the electrons exist in the conduction band before being forced back to the valence band by photon stimulation. For laser stimulation emission to occur, the stimulation lifetime needs to be less than the spontaneous emission lifetime. Otherwise, the electrons will recombine during spontaneous emissions and no electrons will be left in the conduction band to be stimulated. This results in a much larger laser modulation bandwidth.

### 10.2.2 Laser Parameters

The following lists typical laser parameters and parameter explanations.

- 1. *Minimum output power:* This is the minimum laser output power that the laser can be expected to launch into a fiber over its life span. This is an average power for a modulated laser that can be measured with a power meter. Unit is dBm.
- Maximum output power: This is the maximum laser output power that the laser can be expected to launch into a fiber over its life span. This is an average power for a modulated laser that can be measured with a power meter. Unit is dBm.

- 3. *Spectral width:* This is the modulated or unmodulated spectral width of the laser measured at –3 dB down from peak optical power (FWHM), –20 dB down from peak optical power, or the RMS spectral width. Units are nm, GHz, or MHz. For DFB lasers it is very narrow, typically 30 MHz or less (unmodulated).
- 4. *Line width:* This is the width of a single longitudinal mode of a laser. For a DFB laser it is the same as the spectral width. Units are GHz or MHz.
- 5. *Wavelength:* This is the center wavelength of the laser's output power spectrum curve. Unit is nm.
- 6. *Wavelength or channel spacing:* For WDM lasers this is the spacing between center wavelengths of adjacent channels. Unit is GHz.
- 7. *Side-mode suppression ratio (SMSR):* This is the power difference between the main longitudinal mode and the largest side mode, see Fig. 10.4. Unit is dB.
- 8. *Extinction ratio:* It is the average optical power of a one bit divided by the average optical power of a zero bit, see Eq. (3.68) and Fig. 3.17. Units are linear or dB.
- 9. Dispersion penalty: This is the chromatic dispersion penalty that is included in optical budgets to account for signal power depletion. It is always stated with a dispersion limit transmission distance with unit km, or dispersion limit value with unit ps/nm. Also it is stated for a specific BER.
- 10. Tolerable back reflection or ORL: This is the maximum amount of reflected power back into the laser that the laser can accommodate and still operate within specification. Power above this amount can increase laser noise and laser instability. Excessively high reflected power can damage the laser. Unit is dB.
- 11. *Wavelength drift:* The wavelength of a laser will drift with a change in its case temperature. The relationship between wavelength and temperature change is linear approximately 0.08 nm/C. DWDM type lasers contain special cooling circuitry to reduce this drift to acceptable levels.
- 12. *Relative intensity noise (RIN and RIN OMA):* This is a measure of the intensity noise generated in an unmodulated laser. It is mostly due to random photons emitted with spontaneous emissions. RIN is defined<sup>4</sup> as the ratio of time averaged optical noise power normalized to a 1 Hz resolution bandwidth and laser power see at the photodiode in the electrical domain. Here we show the equation in the optical domain because typically it is measured with an OSA, see

Eq. (10.7). Unit is 1/Hz. It can also be specified in dB units, see Eq. (10.8).

$$\operatorname{RIN} = \frac{P_n^2}{P_L^2 \times B_m} \tag{10.7}$$

$$RIN_{dB} = 10 \log(RIN) \tag{10.8}$$

- where  $P_n$  = average optical noise power measured at the photodiode with no laser modulation, W
  - $P_{L}$  = optical laser power measured at the photodiode with no modulation, W
  - $B_m$  = measurement noise equivalent bandwidth, Hz
  - RIN = relative intensity noise, 1/Hz
  - $RIN_{dB}$  = relative intensity noise, dB/Hz

A slightly different definition is specified for RIN OMA. RIN OMA is defined by IEEE 802.3ae and can be stated as the ratio of time averaged optical noise power normalized to a 1 Hz resolution bandwidth and average laser power modulated by a square wave measured at the photodiode in the electrical domain. Here again we show the equation in the optical domain because typically it is measured with an OSA, see Eq. (10.9). Therefore, RIN OMA is defined for a modulated laser. Note that noise power at the high pulse can be different from at the no pulse time. Therefore, an average noise power is calculated for noise power at both locations  $P_{n1}$  and  $P_{n0}$ , see Eq. (10.10). The decibel value for RIN can be calculated with Eq. (10.11).

$$\text{RINOMA} = \frac{P_{\text{nm}}^2}{P_s^2 \times B_m} \tag{10.9}$$

$$P_{\rm nm} = \frac{(P_{n1} + P_{n0})}{2} \tag{10.10}$$

$$RINOMA_{dB} = 10 \log(RINOMA)$$
(10.11)

where

- $P_{nm}$  = average optical noise power with laser modulation, W
  - $P_{n1}$  = average optical noise power measured during a pulse, W
  - $P_{n0}$  = average optical noise power measured during no pulse, W
    - *P<sub>s</sub>* = average electrical modulated laser power measured at the photodiode, W
  - $B_m$  = measurement noise equivalent bandwidth, Hz

RINOMA = relative intensity noise with a modulated laser, 1/Hz

 $RINOMA_{dB} = RIN OMA$  relative intensity noise, dB/Hz

RIN OMA can be thought of the inverse of the OSNR and can be related to the OSNR with Eq. (10.12). An assumption for Eq. (10.12) is that spontaneous emission is the dominant noise contributor.

$$OSNR = \frac{\alpha_{ss}}{RINOMA \times B_r}$$
(10.12)

where OSNR = optical signal to noise ratio of the laser

- $\alpha_{ss}$  = a factor that depends on the amount of polarization correlation there is between photon stimulated emissions and spontaneous emissions. A factor of 1 is for no polarization correlation and 4 is when both are 100% polarized with the same orientation. This factor can be difficult to determine but can be estimated for worst case as 1.
- $B_r$  = measurement resolution bandwidth, Hz

The dB form of Eq. (10.12) is Eq. (10.13).

$$OSNR_{dB} = 10 \log(\alpha_{ss}) - 10 \log(B_r) - RINOMA_{dB}$$
(10.13)

For example, if a laser has an RIN OMA of 160 dB/Hz, its OSNR is estimated using Eq. (10.13) as 49 dB for a 1 nm (124.8 GHz) measurement resolution bandwidth.

### 10.2.3 Laser Modulation

Modulation can be defined as the process of encoding signal information onto a carrier by changing the carrier's amplitude (light intensity), frequency, or phase. In fiber optic communication the carrier is light produced by the laser or LED source. The most common modulation scheme is light intensity (IM) modulation where the transceiver light source intensity is modulated in a digital or analog format. The most common digital modulation format is called on-off keying (OOK). This is where information is represented by the carrier as a sequence of high and low light intensities. A high light intensity (pulse) represents a logic one and a low or extinguished light intensity (no pulse) represents a logic zero (or vice versa depending on the line coding), see Fig. 1.4. This sequence of high and low light intensities represents data information transmitted by the light source. Analog modulation format is used often in the video and cable TV industry. In this modulation scheme the varying amplitude of the electrical analog signal modulates the light source resulting in a similar varying light intensity signal.



b. Externally modulated laser block diagram FIGURE 10.5 Direct and external laser modulation.

Two methods are used in modulating a light source, direct modulation laser (DML) and external modulation laser (EML), see Fig. 10.5.

Direct modulation is more common, simpler and less expensive. This method involves varying the laser's or LED's drive current the same as the signal. For OOK digital modulation the effect results in a sequence of many on and off light pulses. The major disadvantages of this modulation technique is that it causes significant frequency chirp and limits modulation speed in lasers. Chirp is the effect where the carrier frequency of a pulse varies with time. This broadens the laser's spectral width and decreases the transmission dispersion limit. Chirp can be reduced by increasing the power to the laser during the zero bit. This however reduces the signal's extinction ratio, which also degrades system performance. For an electrical step input current, the laser responds with a dampened-oscillation optical output with frequency  $\omega_{,,}$  see Fig. 10.6. This results in a time delay between the step input and the time the laser's light output reaches maximum. This is referred to as the laser's relaxation frequency and limits the laser's maximum modulation transmission rate. It can be approximated<sup>5</sup> by Eq. (10.14).

$$BW \approx \frac{\omega_r \sqrt{3}}{2\pi}$$
(10.14)

where BW = laser's -3 dB bandwidth, Hz  $\omega_r$  = laser's relaxation frequency, rad/s

Due to this limitation, most directly modulated lasers operate at data rates of 10 Gbps and below.



FIGURE 10.6 Laser relaxation oscillation.

External modulation involves placing a device at the light output of a continuously on laser to modulation the laser's light, see Fig. 10.5b. The device is an external modulator and is available separate from the laser or integrated within the laser package. The advantage of this modulation technique is that it significantly reduces laser chirp and thereby extends dispersion limits much further than DML lasers. It also eliminates the step-input time delay due to laser relaxation oscillation and therefore higher modulation rates are possible. Two types of external modulators are currently on the market, Mach-Zehnder (MZ) lithium niobate (LiNbO<sub>2</sub>) interferometer and electro-absorption modulator (EAM). The MZ modulator is the better of the two. It offers a high extinction ratio, high modulation speed, and chirp control. It operates on the principle that as a voltage is applied to certain materials the material's refractive index changes. This causes a 180-degree phase shift between two laser light paths in the material resulting in constructive (logical one) or destructive (logical zero) interference when the two light paths are recombined. The EAM modulate laser light by absorbing optical energy when a negative voltage is applied to the device. It is a lower cost solution and can be integrated within the laser package. When an EAM is integrated with a DFB laser, it is referred to as an electroabsorptive modulated laser (EML). Chirp in an EA modulator is not completely eliminated but is much better than a DML laser.

Table 10.1 lists typical optical source parameters. LED parameters are also listed here but are not commonly used in single-mode applications because of their wide optical spectrum and poor power coupling efficiency with single-mode fiber.

Parameter	LED	DML FP Laser	DML DFB Laser	DML VSCEL	EML	MZ DFB
Output power	<–16 dBm	<10 dBm	<16 dBm	<7 dBm	<9 dBm	<10 dBm
Spectral width*	6 THz	370 GHz	20 MHz	25 GHz	20 MHz	20 MHz
Transmission rate max	622 Mbps	3 Gbps	30 Gbps	15 Gbps	>10 Gbps	>10 Gbps
Common wavelengths	850 and 1310 nm	1310 and 1550 nm	1310 and 1550 nm	850 and 1310 nm	1310 and 1550 nm	1310 and 1550 nm
Reach <sup>†</sup> @ 2.5 Gbps	N/A	20 km	200 km	40 km	600 km	600 km
DWDM compatible	no	no	yes	yes	yes	yes
Cost	least	low	medium	low	high	highest

Notes: \*Unmodulated spectral width. <sup>†</sup>Dispersion limit assuming G.652 fiber.

 TABLE 10.1
 Typical Optical Source Parameters

### 10.2.4 Receivers

A fiber optic receiver converts the light signal to an electrical signal using a semiconductor called a photodiode. This operation is similar to the reverse of light generation by an LED. Note that electrons in the atom's valence band are bonded to the atom and cannot move to another atom. Electrons in the conduction band can move if a voltage is applied to the material resulting in current. Photons striking the semiconductor are absorbed by electrons in the atom's low energy valence band. This results in excited electrons with a higher energy level that jump to the atom's conduction band. This leaves behind electron holes in the valence band. When a voltage is applied to the amount of photons striking the photodiode,<sup>6</sup> see Eq. (10.15). Consequently, the varying intensity optical signal is reproduced as a varying photocurrent.

$$I_p = R_p P \tag{10.15}$$

where  $I_n$  = photocurrent, A

 $\dot{P}$  = incident optical power, W  $R_p$  = photodiode responsivity, A/W

The two types of photodiodes are PIN and avalanche photodiodes (APD). The PIN photodiode operates in the manner described above but has a lightly doped intrinsic material between the P and N semiconductors. This increases the efficiency and responsivity of the material. In a PIN photodiode, each photon excites only one electron to move to the conduction band. In an APD the semiconductor electrons are subjected to a high electric field. When a photon excites an electron its movement is accelerated by the electric field. This causes the excited electron to hit other electrons in the valence band causing them to also jump to the conduction band. This process starting with one photon generates many more electron-hole pairs. This multiplicative gain effect where one photon generates multiple electron-hole pairs is referred to as avalanche multiplication. The multiplier value is typically between 10 and 100. Because of this avalanche gain effect these diode types are much more sensitive to weak optical signals than PIN diodes.

The optical bandwidth of a photodiode depends on the semiconductor material. Most photodiodes use Indium-Gallium-Arsenide (InGaAS), which results in a wide optical bandwidth between 1000 and 1700 nm. The photodiode's maximum transmission rate depends on the photodiode type and load resistor  $R_{_{I}}$ , see Fig. 10.7 and Eq. (10.16).<sup>7</sup>

$$BW_E = \frac{1}{2\pi C_T R_L}$$
(10.16)



FIGURE 10.7 Optical receiver major components.

where  $BW_E$  = photodiode's maximum 3 dB bandwidth, Hz  $C_T$  = total photodiode's capacitance, F  $R_L$  = load resistance,  $\Omega$ 

There is a trade-off when selecting an appropriate load resistance. Increasing the load resistance increases the input voltage to the amplifier and therefore the output. It also reduces thermal noise and improves sensitivity. However, a larger load resistance decreases the signal bandwidth and dynamic range, see Eq. (10.16). PIN Photodiodes are available with very high bandwidths that are well over 10 Gbps, however APD photodiodes are currently only available up to 10 Gbps.

Other major components in a receiver are the photo current amplifier, noise filter, and decision circuit, see Fig. 10.7.

The receiver converts the optical signal to a conditioned electrical digital signal in the following sequence. First the photodiode converts the fiber optical signal to an electrical current signal. Then the pre-amp amplifies the signal voltage across the load resister  $R_{L}$ . It also incorporates automatic gain control circuitry (AGC) that helps to keep the output signal voltage stable and increases the receiver's dynamic range. Next the low pass noise filter removes unwanted high frequency noise components and improves the signal to noise ratio (SNR). This is because noise is directly dependent on electrical bandwidth. The wider the bandwidth, the more noise power is allowed into the circuit and therefore the lower the SNR. The bandwidth needs to be just wide enough to pass all the signal. The rule of thumb is that the receiver's electrical bandwidth should be approximately 0.7 times the bit rate, see Eq. (10.17). For example, for a 10 Gbps signal the bandwidth should be 7 GHz.

$$\mathsf{BW}_{\mathrm{F}} = 0.7 \times R \tag{10.17}$$

where  $BW_E$  = electrical bandwidth, Hz R = transmission rate, bps Finally the decision circuitry determines the logical meaning of the voltage value in a time slot and reproduces the original signal. If the voltage value is above the decision threshold a logical one is assigned to the time slot and if it is below the decision threshold a logical zero is assigned to the threshold, see Fig. 3.15.

Noise is generated in the front end of the receiver (photodiode to the decision circuitry) that degrades signal performance and decreases the SNR. The two main sources of receiver noise are shot noise and thermal noise. Shot noise occurs in the photodiode and is due to the random distribution of electrons generated by the photo detection process. Thermal noise occurs in any component and is due to random electron motion due to temperature. Thermal noise decreases when the component's temperature is lowered and is nonexistent at absolute zero. The photodiode, load resistor, and pre-amp all contribute to receiver thermal noise. Total noise generated by the receiver is equal to the sum of all receiver noise variances. The noise generated for the two-signal logical level one and zero, is different. Total generated noise for each logic level is shown in Eqs. (10.18) and (10.19).

$$\sigma_0^2 = \sigma_{s0}^2 + \sigma_{t0}^2 \tag{10.18}$$

$$\sigma_1^2 = \sigma_{s1}^2 + \sigma_{t1}^2 \tag{10.19}$$

- where  $\sigma_0$  = total standard deviation (RMS) of photodiode noise current for zero logic level, A
  - σ<sub>1</sub> = total standard deviation (RMS) of photodiode noise current for one logic level, A
  - $\sigma_{s0}$  = standard deviation (RMS) of photodiode shot noise current zero logic level, A
  - $\sigma_{t0}$  = standard deviation (RMS) of thermal noise current zero logic level, A
  - $\sigma_{s1}$  = standard deviation (RMS) of photodiode shot noise current one logic level, A
  - $\sigma_{_{f1}}$  = standard deviation (RMS) of thermal noise current one logic level, A

This decreases the receiver Q-factor see Eq. (3.50) and BER see Eq. (3.63).

$$Q = \frac{\left|I_1 - I_0\right|}{\sigma_1 + \sigma_0}$$

BER 
$$\approx \frac{1}{Q\sqrt{2\pi}} \exp\left(-\frac{Q^2}{2}\right)$$

This detection technique is limited by the shot and thermal noise generated at the receiver. Receiver specifications indicate this limitation as the receiver sensitivity parameter for a specific BER.

The above optical signal detection scheme is referred to as intensity modulation direct detection (IM/DD). It is very common and is used in many types of transceiver equipment such as SONET/SDH and Ethernet. Receiver sensitivity can be improved significantly by employing a technique called coherent detection (CD). This technique involves mixing another local optical carrier  $\omega$ , (unmodulated laser) with the received optical signal  $\omega_c$  before it reaches the photodiode. It is similar to the radio receiver signal detection process using an intermediate frequency (IF) oscillator. The local carrier's optical frequency is selected such that the difference of the two optical frequencies results in an intermediate frequency of approximately 5 GHz (depends on the signal transmission rate),  $\omega_{TE} = \omega_{s} - \omega_{r}$ . Mixing the optical carrier with the optical signal results in the generation of a new intermediate frequency that contains the same information as the original signal. Since the local optical carrier's power is much stronger than the weaker optical signal, the mixing process has the effect of amplifying the weaker signal and thereby improving the SNR. The new intermediate frequency signal is then processed by the receiver circuitry. The disadvantage to this detection method is that the required electronic circuitry is much more complex and costly than the direct detection method. Signal gains are comparable to using EDFA amplifiers in a fiber link. A possible advantage of the coherent detection technique is for DWDM systems. Instead of using a DWDM demultiplexer at the receiver to separate the individual channels, the coherent receiver can separate the channels electronically by selecting different IF frequencies. This provides for a tunable channel selection capability. Also, the IF filters can have much steeper roll off, which can result in tighter channel spacing.

### **10.2.5** Receiver Parameters

The following lists typical receiver parameters and parameter explanations.

1. *Receiver sensitivity at BER:* This is the minimum optical power necessary to be received by the receiver in order to achieve the specified BER. This specification can also provide the minimum OSNR necessary for the signal at this level. This level does not consider any other signal impairments, only signal power loss. A simple method to test receiver sensitivity is to loopback a receiver using a fiber jumper and an optical attenuator. The attenuator is selected such that the looped back receiver power is at the specified receiver sensitivity level. Then a BER test is run for sufficient length of time (see Sec. 3.2) to confirm the specification. Unit is dBm.

- 2. *Maximum receiver power:* This is the maximum signal power the receiver can process and still maintains the specified BER. Unit is dBm.
- 3. *Receiver damage threshold:* At this power level, permanent damage to the receiver may occur. Unit is dBm.
- 4. *Reflectance:* The amount of power the receiver reflects back into the fiber. Unit is dB.
- 5. *OSNR:* This is the minimum OSNR required by the receiver to achieve a BER at or below the specified limit. Unit is dB.

## **10.3 Optical Amplifiers**

An optical amplifier is an electronic device that amplifies an optical signal. Most optical amplifiers are not able to condition the signal in any other way other than increasing signal power. The difference between an optical amplifier and an optical repeater is that the repeater first converts the optical signal to an electrical signal. It then amplifies the electrical signal and likely conditions it to some degree before converting it back to an optical signal. Two common optical amplifier types are the erbiumdoped optical amplifier (EDFA) and the Raman optical amplifier. EDFA type is the most common and cost-effective for most applications. Raman amplifiers are used in situations where additional signal amplification is required without adding significant noise to the link. Semiconductor optical amplifiers (SOA) are also gaining popularity for booster applications because of their small 14-PIN butterfly package. However they suffer from a high noise figure and narrow bandwidth.

### 10.3.1 EDFA Amplifier

The EDFA amplifier is used in applications where the amplification of one or more optical signals (channels) is required in a fiber. The amplifier is unidirectional and therefore for a two-fiber link two amplifiers are required at each amplifier location. EDFA amplifiers are available with excellent signal gain of over 20 dB and sensitivity of less than –27 dBm. Gain of an amplifier is the ratio of output to input optical power, see Eq. (10.20). Equation (10.21) shows gain as decibel.

$$g = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{10.20}$$

$$g_{\rm dB} = 10 \log \left(\frac{P_{\rm out}}{P_{\rm in}}\right) \tag{10.21}$$

where g =amplifier gain

 $g_{dB}^{d}$  = amplifier gain, dB  $P_{out}$  = amplifier output power, mW  $P_{in}$  = amplifier input power, mW



FIGURE 10.8 EDFA amplifier.

The main disadvantage of this amplifier type is that it adds noise to the fiber link. In long fiber links with numerous EDFA amplifiers the noise accumulates and must be managed in order not to degrade the receiver's OSNR below its limit (refer to Chap. 3).

The EDFA amplifier comprises a length of erbium-doped fiber, one or two pump lasers, couplers, and associated electronic circuitry, see Fig. 10.8. The short length of fiber doped with erbium (Er) ions, typically under 50 m, is used as the amplifying medium. One or two pump lasers, co-propagating pump (forward pump) at 980 nm and counter-propagating pump (reverse pump) at 1480 nm, provide the optical energy in the erbium-doped fiber to stimulated the electrons to a higher band. The couplers couple the pump laser power into the erbium-doped fiber. They are typically circulators. The output isolator is used to prevent fiber reflections from entering the erbiumdoped fiber and causing detrimental effects. It is also commonly combined with an ASE filter to reduce output noise. The input isolator prevents any reverse direction amplified spontaneous emission (ASE) noise from entering the fiber.

The EDFA amplification works on the principle of stimulated emissions similar to the laser diode except the stimulating energy comes from a pump laser and not electric current. Photons from the pump laser(s) excite the erbium-doped fiber electrons to higher energy bands. Signal photons propagating through erbium-doped fiber collide with these higher energy electrons causing them to drop back down to the lower band and give off energy as photons. These newly generated photons acquire the same phase, frequency, polarization, and direction as the signal photons (known as coherent radiation), see Fig. 10.9. The result is signal photon multiplication and signal power amplification.

EDFA bandwidth is typically all of C band (1530 to 1565 nm). A few manufacturers also produce EDFAs for L band (1565 to 1625 nm).

EDFA noise is due to spontaneous emissions that are amplified in the EDFA. Thus it is referred to as amplified spontaneous emission



FIGURE 10.9 EDFA electron energy diagram.

(ASE). ASE noise power measured over a given spectral bandwidth  $B_a$  can be written<sup>8</sup> as Eq. (10.22).

$$P_{\rm ASE} = 2n_{\rm sp} h f B_o (g-1) \tag{10.22}$$

where  $P_{ASE}$  = average amplifier ASE noise power, W

- $n_{sp}$  = spontaneous emission (or population inversion) factor
  - h = Planck's constant 6.626069 × 10<sup>-34</sup>, Js
  - *f* = optical signal center frequency, assuming 193.400 THz (1550.12 nm), Hz
  - $B_{a}$  = optical channel bandwidth, Hz

g =amplifier gain

Noise factor is a common parameter listed in specifications that is a measure of the ASE noise characteristic of the amplifier. It can be defined as the ratio of amplifier input signal to noise ratio to output signal to noise ratio, see Eq. (10.23). It can also be related to the spontaneous emission factor with Eq. (10.24). Assuming amplifier gain is high and spontaneous emission factor is approximately 1 then it can be seen from Eq. (10.24) that the quantum noise factor limit is approximately 2 (3 dB).

$$F = \frac{\text{OSNR}_{\text{in}}}{\text{OSNR}_{\text{out}}}$$
(10.23)

$$F = \frac{2n_{\rm sp}(g-1)}{g}$$
(10.24)

where

F = amplifier noise factor

OSNR<sub>in</sub> = amplifier's input optical signal to noise ratio OSNR<sub>out</sub> = amplifier's output optical signal to noise ratio Inserting Eq. (10.24) into Eq. (10.22) EDFA noise can be written as Eq. (10.25).

$$P_{\rm ASE} = FhfB_og \tag{10.25}$$

For example, if an EDFA amplifier has a gain of 20 dB, a noise figure of 6 dB, and is used to amplify a signal that has an OSNR of 50 dB, what is the output OSNR and amount of noise power generated assuming the bandwidth is 0.1 nm (12.48 GHz)? Converting the noise figure to linear units results in 3.98. Converting the signal OSNR to linear units results in 100,000. Noise power is calculated using Eq. (10.25).

$$P_{ASE} = 3.98 \times h \times 193.1 \times 10^{12} \times 12.48 \times 10^{9} \times 100$$
$$P_{ASE} = 0.64 \,\mu W$$
$$P_{ASE} = -32 \,dBm$$

Output signal to noise ratio is calculated using Eq. (10.23).

$$OSNR_{out} = \frac{OSNR_{in}}{F}$$
$$OSNR_{out} = \frac{100,000}{3.98}$$
$$OSNR_{out} = 25,126$$
$$OSNR_{out} = 44 \text{ dB}$$

Keeping OSNR and noise figure in dB, we can use Eq. (10.26) to also calculate OSNR out.

$$OSNR_{out}^{dB} = OSNR_{in}^{dB} - NF_{dB}$$
(10.26)

where  $NF_{dB}$  is the noise figure, dB.

### 10.3.2 Raman Amplifier

The Raman amplifier is typically much more costly and has less gain than an EDFA amplifier. It, therefore, is used only for specialty applications. The main advantage this amplifier has over the EDFA is that it generates very little noise and hence does not degrade span OSNR as much as the EDFA. Its typical application is in EDFA spans where additional gain is required but the OSNR limit has been reached. Adding a Raman amplifier may not significantly affect OSNR, but can provide up to a 20 dB signal gain. Another key attribute is the potential to amplify any fiber band, not just C band as is the case for the EDFA. This allows for Raman amplifiers to boost signals in O, E, and S bands (for CWDM amplification application).

The amplifier works on the principle of stimulated Raman scattering<sup>9</sup> (SRS), which is a nonlinear effect. It consists of a high-power pump laser and fiber coupler (optical circulator). The amplification medium is the span fiber in a distributed type Raman amplifier (DRA). This is a common type of Raman amplifier and is explained here. The lumped or discrete type Raman amplifier internally contains a sufficiently long spool of fiber where the signal amplification occurs. The DRA pump laser is connected to the fiber span in either a counter pump (reverse pump) or a co-pump (forward pump) or configuration, see Fig. 10.10*a* and *b*. The counter pump configuration is



FIGURE 10.10 Raman amplifier configuration.

typically preferred since it does not result in excessively high signal powers at the beginning of the fiber span, which can result in nonlinear distortions, see Fig. 10.10*c*. The advantage of the co-pump configurations is that it produces less noise.

As the pump laser photons propagate in the fiber, they collide and are absorbed by fiber molecules or atoms. This excites the molecules or atoms to higher energy levels. The higher energy levels are not stable states so they quickly decay to lower intermediate energy levels releasing energy as photons in any direction at lower frequencies. This is known as spontaneous Raman scattering or Stokes scattering and contributes to noise in the fiber. Since the molecules decay to an intermediate energy vibration level, the change in energy is less than the initial received energy during molecule excitation. This change in energy from excited level to intermediate level determines the photon frequency since  $\Delta f = \Delta E/h$ . This is referred to as the Stokes frequency shift and determines the Raman gain versus frequency curve shape and location. The remaining energy from the intermediate level to ground level is dissipated as molecular vibrations (phonons) in the fiber. Since there exists a wide range of higher energy levels, the gain curve has a broad spectral width of approximately 30 THz. During stimulated Raman scattering, signal photons co-propagate (in either fiber direction) with a frequency that is within the Raman frequency gain curve spectrum, and acquire energy from the Stokes wave, resulting in signal amplification, see Fig. 10.11.

The Raman gain curve's FWHM width is about 6 THz (48 nm) with a peak at about 13.2 THz below the pump frequency. This is the useful signal amplification spectrum, see Fig. 10.12. Therefore, to amplify a signal in the 1550 nm range the pump laser frequency is required to be 13.2 THz below the signal frequency at about 1452 nm, see Eq. (10.27). Multiple pump lasers with side by side gain curves are used to widen the total Raman gain curve.

$$f_p = f_s + \Delta f_v \tag{10.27}$$

where  $f_p$  = pump frequency, THz  $f_s$  = signal frequency, THz  $\Delta f_n$  = Raman Stokes frequency shift, THz

Raman gain ( $G_R$ ) is the net signal gain distributed over the fiber's effective length. It is a function<sup>10</sup> of pump laser power, fiber effective length, and fiber area, see Eq. (10.28). For fibers with a small effective area, such as in dispersion compensation fiber, Raman gain is higher. Gain is also dependent on the signal separation from the laser pump wavelength, see Fig. 10.12. This is through the fiber's Raman gain coefficient  $g_R$  in Eq. (10.28). Raman signal gain is also specified and field measured as on/off gain. This is defined as the ratio of the output signal power with the pump laser on and off, see Eq. (10.30).



FIGURE 10.11 Raman molecular energy diagram.

In most cases the Raman ASE noise has little effect on the measured signal value with the pump laser on. However, if there is considerable noise, which can be experienced when the measurement spectral width is large, then the noise power measured with the signal off<sup>11</sup> is subtracted from the pump on signal power to obtain an accurate on/ off gain value, see Eq. (10.29). The Raman on/off gain is often referred to as the Raman gain, see Eq. (10.30).

$$G_{\rm R} = 10 \log \left[ \exp \left( \frac{g_{\rm R} P_{\rm po} L_{\rm eff}}{A_{\rm eff}} \right) \right]$$
(10.28)

$$G_{\text{R.on/off}} = 10 \log \left( \frac{P_s(\text{pump.on,signal.on}) - P_{\text{noise}}(\text{pump.on,signal.off})}{P_s(\text{pump.off,signal.on})} \right)$$
(10.29)



FIGURE 10.12 Raman gain curve.

$$G_{\text{R.on/off}} \approx 10 \log \left[ \frac{P_s(\text{pump.on,signal.on})}{P_s(\text{pump.off,signal.on})} \right]$$
 (10.30)

$$G_{\rm R} = G_{\rm R.on/off} \tag{10.31}$$

The signal power at the end of a fiber length L can be estimated given Raman gain coefficient with Eq. (10.32). The net gain at the end of the fiber link, which includes fiber loss, is given by Eq. (10.33).

$$P_{s} = P_{s0} \exp(-\alpha_{s} L) \exp\left(\frac{g_{\rm R} P_{\rm po} L_{\rm eff}}{A_{\rm eff}}\right)$$
(10.32)

$$G_{\text{net}} = 10 \log \left[ \exp(-\alpha_s L) \exp\left(\frac{g_R P_{\text{po}} L_{\text{eff}}}{A_{\text{eff}}}\right) \right]$$
(10.33)

where  $G_{\rm R} = \text{Raman signal gain distributed over fiber length } L_{\rm eff}$ , dB  $G_{\rm R.on/off} = \text{Raman signal gain at the end of the fiber length } L$ , dB  $G_{\rm net} = \text{Raman net gain at the end of the fiber, dB}$  $P_s = \text{output signal power, W}$ 

 $P_{s0}$  = launch signal power at fiber length L = 0, W

- $P_{\text{noise}}$  = noise power, W
  - $g_{\rm R}$  = fiber's Raman gain coefficient, m/W
  - $P_{po}$  = Raman pump laser launch power, W
  - $A_{\rm eff}^{\rm PO}$  = fiber effective area, m<sup>2</sup>
  - $L_{\text{eff}}$  = pump's fiber effective length, m
  - L =fiber span length, m
  - $\alpha_s$  = fiber attenuation coefficient at the signal's wavelength, m<sup>-1</sup>

For example, if a DRA-configured 500 mW, 1452 nm pump laser is connected to a fiber with a gain coefficient  $g_{\rm R} = 3 \times 10^{-14}$  m/W, effective area of 80 µm<sup>2</sup>, attenuation of 0.21 dB/km and fiber span length of 75 km, the estimated net signal gain at 1550 nm is 16.4 dB. If a 0 dBm signal is launched into the fiber, the amplified signal power output at the end of the 75 km fiber span is 0.6 dBm. If the amplifier is not used, then the signal power is –15.8 dBm only due to fiber attenuation.

Noise created in a DRA span consists of amplified spontaneous emissions (ASE), double Rayleigh scattering (DRS), and pump laser noise. ASE noise is due to photon generation by spontaneous Raman scattering. DRS noise occurs when twice reflected signal power due to Rayleigh scattering is amplified and interferes with the original signal as crosstalk noise, see Fig. 10.13. The strongest reflections occur from connectors and bad splices. Typically DRS noise is less than ASE noise, but for multiple Raman spans it can add up. To reduce this interference, ultra polish connectors (UPC) or angle polish (APC) connectors can be used. Optical isolators can be installed after the laser diodes to reduce reflections into the laser. Also span OTDR traces can help locate high-reflective events for repair. Sheng<sup>12</sup> has shown that counter pump DRA configuration results in better OSNR performance for signal gains of 15 dB and greater.

Pump laser noise is less of a concern because it usually is quite low with RIN of better than 160 dB/Hz. Nonlinear Kerr effects can also contribute to noise due to the high laser pump power. For fibers



FIGURE 10.13 Raman double Rayleigh scattering.

with low DRS noise, the Raman noise figure due to ASE is much better than the EDFA noise figure. Typically the Raman noise figure is -2 to 0 dB, which is about 6 dB better than the EDFA noise figure.

Raman amplifier noise factor is defined as the OSNR at the input of the amplifier to the OSNR at the output of the amplifier, see Eq. (10.34). Noise figure is the dB version of noise factor, see Eq. (10.35).

$$F_{\rm R} = \frac{\rm OSNR_{in}}{\rm OSNR_{out}}$$
(10.34)

$$NF_{R} = 10 \log(F_{R})$$
 (10.35)

The DRA noise and signal gain is distributed over the span fiber's effective length. A convenient configuration used to express Raman distributed noise and gain parameters is as a hypothetical equivalent discrete amplifier that is located at the end of the fiber span. This hypothetical amplifier has the equivalent gain ( $G_{eq}$ ) and noise figure (NF<sub>eq</sub>) as the actual DRA, see Fig. 3.10. Equivalent Raman noise and gain can be shown as Eqs. (10.36) to (10.38). Equivalent parameters are typically listed in manufacturer's specifications see Eq. (10.38).

$$F_{\rm eq} = \frac{F_{\rm R}}{\alpha L} \tag{10.36}$$

$$NF_{eq} = NF_{R} - (\alpha_{dB}L)$$
(10.37)

$$NF_{eq} = NF_R - \Gamma_{span}$$
(10.38)

$$G_{\rm eq} = G_{\rm R} \tag{10.39}$$

where  $F_{eq} = equivalent noise factor$   $F_{R} = distributed Raman amplifier noise factor$   $NF_{eq} = equivalent noise figure, dB$   $NF_{R} = distributed Raman amplifier noise figure, dB$   $\alpha = attenuation coefficient, km^{-1}$   $\alpha_{dB} = attenuation, dB/km$  L = transmission fiber length, km  $G_{eq} = equivalent gain, dB$   $G_{R} = distributed Raman amplifier gain, dB$   $\Gamma_{span} = span loss, dB$   $OSNR_{in} = amplifier's input optical signal to noise ratio$  $<math>OSNR_{out} = amplifier's output optical signal to noise ratio$ 

Counter pump distributed Raman amplifiers are often combined with EDFA pre-amps to extend span distances, see Fig. 10.14. This hybrid configuration can provide 6 dB improvement in the OSNR,



FIGURE 10.14 Hybrid Raman/EDFA configuration.

which can significantly extend span lengths or increase span loss budget. Counter pump DRA can also help reduce nonlinear effects by allowing for channel launch power reduction.

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# CHAPTER **11** Dark Fiber

## 11.1 Leasing or Purchasing Dark Fiber

Leasing dark or dim fiber has become common practice in the telecommunications industry. The term "dark fiber" refers to optical fibers that are not connected to any lightwave equipment and hence they are dark. The term "dim fiber" refers to fiber links that do not originate or terminate optical signals but do offer optical signal regeneration at intermediate sites. A company (carrier) that owns a fiber cable facility (lessor) can lease individual dark or dim fibers to others (lessees) on a monthly or yearly basis. It is up to the lessee to add and maintain all proper lightwave equipment to the entire dark fiber link. For a dim fiber link the lessee generally only needs to add and maintain proper lightwave equipment at the fiber link ends. Generally, and depending on the contract, when a dark fiber is leased the entire fiber spectrum is available to the lessee. This enables the lessee to add WDM equipment to increase the dark fiber capacity. In addition, any data rate and transmission protocol can be placed onto the dark fiber link, limited only by the fiber characteristics. Dim fiber leases can be more restrictive. Intermediate equipment provided by the lessor may not be capable of regenerating WDM channels. Therefore, increasing fiber capacity with WDMs may not be increased possible unless the lessor is willing to install proper WDM intermediate equipment. Also dim fiber intermediate equipment may be further restricted to regenerating only one specific transmission rate and protocol. For both dark and dim fiber leases the lessor is responsible for the maintenance and repair of the fiber cable.

Another revenue-generating method available to carriers is to lease individual WDM channels between locations over a pair of fibers instead of leasing the entire fiber capacity. This is commonly referred to as wavelength leasing or lit fiber leasing. Typically but not always, reference to a fiber wavelength means one wavelength on two fibers, which is a bidirectional channel. In wavelength leasing the lessor provides all necessary lightwave DWDM equipment for signal transmission between the two, or more, end locations. The lessee only needs to interface to the lessor's end location equipment using the most economical method. Often this is done using lower cost 1310 nm transceivers. The lessor's lightwave equipment properly conditions the lessee's signal for fiber link transmission. The conditioning equipment typically consists of transponders, DWDMs, EDFAs, and possibly DCMs. The advantage to the lessor is the ability to lease the entire fiber spectrum capacity to multiple customers and the ability to control transmission rates and protocols. For example, using a simple 40-channel DWDM and transponders, 40 individual channels can be leased to many customers which may result in better revenues than leasing dark fiber. The advantage to the lessees is that they can use lower cost transceivers to interface with lessor's equipment and not need to be concerned with engineering, supplying, and maintaining link lightwave equipment. Leased wavelengths can act as switched circuits where ROADMs are deployed and can be extended through multiple carriers.

A variation of leasing wavelengths is leasing fiber windows. A fiber window can be defined as a range of wavelengths available for transmission in a fiber. Fiber band and window are often used interchangeably; however, window can refer to a segment of a fiber band. Window leasing is more common in metropolitan networks where signal regeneration is not necessary. WDMs are deployed at the fiber ends to break out specific fiber windows by the lessor. The WDMs can be simple 1310/1550 nm cross bands, CWDMs, or even DWDMs. However, only a passive interface is provided to the lessee and in essence it is a dark window. The lessee is required to provide proper transceivers for signal transmission in the fiber window. For example, if a CWDM window is leased, then the lessee provides proper CWDM transceivers that can reach the entire transmission length. Fiber link loss and chromatic dispersion typically need to be considered for dark window transmission.

Dark or dim fiber assets can also be transferred under an indefeasible rights of use (IRU) agreement. Under this agreement the buyer holds an exclusive and irrevocable right to use the fiber and other agreed to equipment or facilities over the period of the IRU, typically 10 or more years. The seller still maintains ownership and maintenance of the fiber cable over the time period. This can be a preferable method to acquire fibers, since under the IRU the buyer may be able to treat the investment as a capital cost instead of an expense.<sup>1</sup>

It should be noted that all of the above points are dependent on contract text and interpretation. Table 11.1 summarizes this information.

### **11.2 Dark Fiber Considerations**

When negotiating any kind of fiber lease or purchase, the following points should be considered.

**Fiber Access Location** It is important to clearly identify the exact locations where the lessee can access the fiber cable ends, including

	Dark Fiber	Dim Fiber	Leased Wavelengths	Leased Window
Lessee WDM	yes	possibly	no	possibly
Transmission rate limiting	no	possibly	possibly	no
Any protocol	yes	possibly	no	yes
Lightwave transmission equipment	lessee	lessee at fiber ends	lessor	lessee
Lightwave equipment maintenance	lessee	lessee at fiber ends	lessor	lessee
Cable maintenance	lessor	lessor	lessor	lessor

TABLE 11.1	Fiber Leasing Gene	eral Information
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building address, rack position, fiber distribution panel position, and fiber assignment. Fiber access, space, and power agreements may need to be negotiated with the lessor or property owner.

**Fiber Termination** Common outside plant (OSP) fiber cable terminations are with SC or FC connectors but others may also be used. Unterminated cable can also be present, which will then require a splicing crew to install the required terminations and distribution panel before lightwave equipment can be connected.

**Fiber Count** The number of fibers and their assignments should be clearly identified throughout the cable(s) route.

**Fiber Cable Route** A map of the fiber cable route is very useful to the lessee, although this information may be difficult to obtain from the lessor. The route plan can identify aerial and buried cable sections, as well as cable type in each section. If the leased fiber cable route is known, diverse cable routes can be planned for protection routes and potentially problematic sections identified.

**Fiber Specifications** Fiber specifications for all fibers used throughout the route should be obtained and stored for current and future link planning.

**Fiber Link Characterization** Fiber parameters such as loss, length, chromatic dispersion, PMD, and so on can be measured and recorded to establish a benchmark at the time of the fiber lease or purchase. This record can be compared to future measurements to ensure agreement

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limits are not exceeded at the time of purchase and during the life of the operation. Fiber parameters can change over time due to cable repairs, cable reroutes, or other environmental conditions. These measurements can also be used during network planning and upgrades.

**Restoration Time** The lessor can specify the maximum time for fiber restoration in the event of a fiber cable cut or other fiber outage. Restoration time can vary greatly and depends on many factors such as lessor's commitment, availability of repair personnel and equipment, environment, and travel time.

**Contact and Escalation List** Contact numbers, keys, and/or entry codes can be identified for all lessee interfaces and equipment.

**Maintenance Notice and Schedule** The lessor can provide detailed schedules for routine maintenance work and minimum notice time for emergency maintenance work that may or will cause link outages during the agreement term. Lessee may ask for guaranteed minimum fiber link availability to ensure link disruptions do not affect lessee operation.

## Reference

1. Interconnection arrangements between and among the domestic and international record carriers, 89 F.C.C. 2d 194, 211 n. 27, 1982.

## CHAPTER **12** Fiber Network Planning

### **12.1 Guidelines**

Listed below are a few general guidelines to help plan Ethernet, SONET/SDH, and other fiber optic networks. They are organized in a rough sequence of events for typical systems.

- 1. First, establish a fiber link between end locations. This fiber link can be leased from the carrier as explained in Chap. 11, or a new fiber cable build. Numerous options are explained in Chap. 11 for leasing existing fibers. Pay careful attention to not only the fiber cable type but also fiber type. The most common fiber type used in cable builds is standard ITU G.652 fiber also known as non-dispersion shifted fiber (NDSF). Non-zero dispersion shifted fiber (NZ-DSF) ITU G.655 type is also popular in long-haul applications because it has a lower dispersion coefficient than standard fiber. Do not use dispersion shift fiber ITU G.653 unless there is a very good reason to use it. This fiber type has a zero dispersion value at 1550 nm, which can cause nonlinear distortion effects, refer to Chap. 7. For long cable runs where link loss or dispersion values exceed receiver budgets, identify intermediate sites that can accommodate signal regeneration or amplification equipment.
- 2. Consider an alternate, physically diverse, fiber cable protection route between end locations to help increase link reliability in the event the primary cable is damaged.
- 3. Complete fiber characterization of all newly acquired fibers. Measured fiber parameters help in proper link budget planning and establish a beginning of life record for future network expansion or reference in the event of link degradation.

- 4. Identify the total number of current and future circuit requirements and transmission rates.
- 5. For SONET/SDH systems, identify the proper SONET/SDH equipment type and configuration. For Ethernet circuits, identify proper switches and routers. Pay attention to multiplexing methods. Can circuits be time division multiplexed into a large aggregate circuit or should circuits be kept separate and multiplexed optically using WDMs?
- 6. Complete the detailed fiber link design. This includes calculating optical power, dispersion and OSNR budgets, as well as nonlinear effects. If you use WDMs or plan to use WDMs, consider their link budget effects. For typical links only certain parameter budgets need to be considered, as described below:
  - Optical power budgets are considered for all links.
  - Chromatic dispersion is considered for links with transmission rates of 1 Gbps or greater.
  - Polarization mode dispersion is considered for links with transmission rates of 10 Gbps or greater.
  - OSNR is considered for links with optical amplifiers.
  - Nonlinear distortion is considered for links with optical amplifiers or DWDMs with 40 or more channels.

For simple links (no amplifiers, no DWDM) that are within the transceiver's power budget and distance limit, only the optical power budget needs to be considered.

- Select the transmission equipment manufacturer. The manufacturer or manufacturer representative can typically provide a detailed quote for the cost of the required equipment and installation. Tender packages can be issued to receive bids from a number of suppliers.
- 8. Review the equipment and select the best response. The equipment should meet current transmission requirements and be expandable to accommodate future growth. Often companies go overboard on transmission equipment purchases believing that the most expensive and high-end equipment will automatically be the best choice for their network. Many smaller manufacturers provide high-quality equipment at a fraction of the cost of the high-end models. Careful selection is important. For example, a single-span multicircuit link that is equipped with simple basic DWDMs or CWDM as described in Chap. 6 may be able to fulfill current and future expansion requirements. Such units are economical, reliable, and simple to install and maintain.
- 9. Schedule and install equipment as per engineering design and documentation.

- 10. Perform final acceptance testing on all circuits. Typically a BER and/or RFC 2544 test is completed, as described in Chap. 9.
- 11. Address any outstanding issues before traffic is placed onto the transmission system.
- 12. Often overlooked in many telecom projects is accurate network documentation. Maintaining detailed equipment and fiber documentation is important. This documentation can include all equipment specifications, fiber and cable specification, fiber characterization measurements, test results, system connection drawings, floor plans and rack layouts.

## **12.2** Metropolitan Ethernet Network

Company owned metropolitan Ethernet network can be an attractive alternative to leasing circuits from a carrier. Typically the dark fiber connecting company sites will be the most costly part of the link. Since the distances in metropolitan environments are relatively short, long reach fiber transceivers are generally all that is required to establish a simple high-speed fiber link. These transceivers are currently available as pluggables that can be inserted into many Ethernet switch and router models. They are available for 10/100 Mbps, GigE, and 10 GigE fiber transmission. WDM transceivers are also available that can be used with simple CWDM or DWDM multiplexers (see Chap. 6). Simple DWDMs are available with 4 to 44 channels using 100 GHz spaced channels and up to 87 channels using 50 GHz spaced channels (in C band). If 10 GigE transceivers are deployed, the fiber capacity over two fibers can reach 870 Gbps.

Ethernet physical layer fiber link configuration is a point-to-point. For each fiber link, a second diversely routed fiber link can be added to be used as a protection path and/or for load sharing. Traffic switching can be accomplished by the Ethernet switch or by an external optical fiber switch. For long fiber spans where optical budgets are exceeded, optical amplifiers can be added to compensate for power loss. In this case, proper dispersion, PMD and OSNR management is required.

### 12.3 SONET/SDH Network

Synchronous optical network (SONET) is an American National Standards Institute<sup>1</sup> (ANSI) standard for communications over optical fiber. It is defined by standards ANSI T1.105 and Telcordia<sup>2</sup> GR-253-CORE. Since its introduction in 1984, it has been deployed by every major carrier in North America. An equivalent transmission standard approved by International Telecommunication Union<sup>3</sup> (ITU, formerly CCITT) is called synchronous digital hierarchy (SDH). It has been accepted and used worldwide outside of North America.

The SONET terminal is a type of add/drop time division multiplexer (ADM) that can multiplex many digital electrical signals into a single optical channel. This is accomplished by a byte-interleaved multiplexing scheme. Typical signal inputs are DS3, T1, and Ethernet. These signals are converted (mapped) in the SONET equipment to synchronous transport module signals (STS). One DS3 is mapped to one STS-1 signal. One T1 is mapped to one virtual tributary signal (VT1.5). Twenty-eight VT1.5 signals can be combined into one STS-1 signal. Higher-level STS signals are formed by multiplexing together integer multiples of STS-1s. Once the highest-level aggregate is formed, the aggregate is converted to an optic signal (optical carrier—OC-x) of the same level and transmitted into the span fiber. Therefore, if a STS-3 is built for output then the output signal is an OC-3. SONET and SDH levels and transmission rates are shown in App. G.

One primary benefit in deploying SONET/SDH equipment is the ability of the system to recognize and reroute traffic in the event of a fiber cut, equipment failure, or significant signal degradation. This survivability is available for SONET/SDH linear or ring configurations is referred to as automatic protection switching APS. Both configurations have their applications, advantages, and disadvantages.

The linear configuration is made up of two end terminals and a number of regenerators in between if required. Traffic flows from one terminal to another, without any means of adding or dropping traffic at intermediate sites, see Fig. 12.1. APS operation in a linear systems is available as 1+1, 1:1 or 1:n configuration. In 1+1 APS two redundant fiber links carry the same traffic. The receiver determines and switches to the best link. 1:1 APS is similar to 1+1 APS where two redundant links are required. However, the link that is not being used is idle or can carry other lower priority traffic. In the event of a protection switch, the lower priority traffic is lost. 1:n APS provides one back up link for up to 14 primary links. All primary links must have the same beginning and end points. The back up link can carry low



FIGURE 12.1 SONET/SDH linear system.

priority traffic that will be lost in the event of a protection switch. This method is more efficient since only one back up link provides protection for up to 14 primary links.

The linear configuration requires four fibers to connect two end terminals. Two fibers are designated work or primary fibers. Work fibers are the fibers that carry the traffic under normal operating conditions. The other two fibers are designated as protect, secondary or backup fibers. In the event of a fiber cut of any one of the work fibers, the SONET/SDH terminals recognize the APS event and switches all the traffic onto the protect fibers. Switching occurs in 50 ms or less, so disruption to traffic is minimal. Once the work fibers are restored, the traffic is then switched back onto the work fibers. This configuration also guards against laser transmitter or receiver failures. If a transmitter fibers just like a fiber failure. Once the card is replaced, the system can restore the traffic onto the work fibers.

If a fiber or an optical card fails on the protect fibers, then of course the system does not switch traffic but instead sends an alarm to the network manager identifying the problem so that it can be quickly repaired. The system always carries traffic on the designated work fibers unless there is a degradation, fiber cut, or card failure of the work fibers.

For a linear system, all four fibers can be connected in to one fiber optic cable. However, if the cable is cut, then there would be a complete loss in traffic. Alternatively, the system can be deployed in a physically diverse route, see Fig. 12.2. Two separate and physically



FIGURE 12.2 SONET/SDH linear system with cable diversity.

diverse fiber cables can be used for the work and protect fibers. Since the two cables are physically diverse, a cable cut would not affect the alternate cable path and therefore not result in loss of traffic. Only a 50 ms traffic switch would occur from the bad cable to the good cable.

This physically diverse fiber routing configuration for a linear SONET/SDH system provides the best protection of traffic between two linear terminals. The main disadvantage of this configuration is that traffic cannot drop off at intermediate sites. All traffic must flow between the two end terminals.

A SONET/SDH ring configuration is made up of two or more SONET/SDH add/drop multiplexers (ADMs) that are connected in a two- or four-fiber ring. Regenerators can be used at sites where traffic is to only pass through and not drop off. Note that regenerators do not have traffic switching capability. Unlike a linear system, the SONET/SDH ring system can have up to 16 ADMs (has been increased by manufacturers) in the ring with a capability of adding or dropping traffic at any of the ADM locations, see Fig. 12.3.

The SONET/SDH ring can be configured into different APS types, bidirectional line switched ring (BLSR) or unidirectional path switch ring (UPSR). The SDH equivalents are called multiplexed section shared protection ring (MS-SPRING) or subnetwork connection protection (SNCP). BLSR can be further configured using two- or fourring fibers.



FIGURE 12.3 SONET/SDH ring.



FIGURE 12.4 SONET two-fiber BLSR.

**Two-Fiber BLSR Ring** The two-fiber BLSR ring configuration uses two fibers for communication around the ring. Each ADM has a total of four fiber connections, two fibers (transmit and receive) in one direction and two fibers in the other direction, see Fig. 12.4.

The capacity in any one direction out of an ADM is only half of its OC-*n* capacity. This is because half of the ring capacity is used for traffic, while the other half is reserved for protection in case of a fiber failure. If traffic needs to flow between NE1 and NE2, a connection is established using span 1 fibers. If other traffic needs to be routed between NE1 and NE3, a connection can be established using spans 3 and 4, and NE4. If there is a failure in a span, then all traffic through that span is switched and rerouted around the ring using the protection half of the OC-*n* capacity. For example, in an OC-48 two-fiber BLSR ring, a maximum of 24 STS-1s can be routed in each direction out of an ADM, around the ring, see Fig. 12.5. The total capacity is 48 STS-1s out of any ADM. The other 24 STS-1 channels around the ring are reserved for protection traffic only.

In the event of a fiber cable cut or terminal transceiver failure in one of the spans, traffic will be rerouted around the other ring direction on the protection channels. For example, if a failure occurs in span 1, NEs 1 and 2 will switch the traffic that was on span 1 onto


FIGURE 12.5 Two-fiber BLSR capacity.



FIGURE **12.6** Two-fiber BLSR switch.







FIGURE **12.8** Four-fiber BLSR traffic.



FIGURE 12.9 Four-fiber BLSR with span failure.

protection channels of spans 2, 3, and 4, see Fig. 12.6. After the failed span is restored, the traffic will be switched back onto span 1 fibers. During this failure, traffic between NEs 1 and 3 using spans 3 and 4 is unaffected.

**Four-Fiber BLSR Ring** In a four-fiber BLSR ring configuration, each ADM communicates through four fibers, in each direction, around the ring. This is a total of eight fiber connections for each ADM, see Fig. 12.7. Two fibers carry all traffic, while the other two fibers act as protection fibers and remain ready in case of a failure.

For example, an OC-48 four-fiber BLSR ring can carry 48 working STS-1s around the ring. At an ADM, 48 STS-1s can enter from both fiber directions for a possible maximum of 96 STS-1s at the one ADM (dependent on equipment), see Fig. 12.8.

The four-fiber BLSR ring protects against failure in two ways span switching and line switching. A span switch would occur in a span if there were a failure with the work fibers or work transmit/ receive cards. The traffic in the span work fibers would be switched to the same span protect fibers. Traffic would remain in the span, but just on different fibers. Other parts of the ring would not be affected, see Fig. 12.9. The ring can even survive multiple span failures without losing traffic, see Fig. 12.10.

Often, the four fibers in a span are in the same cable. Therefore, if the cable gets cut, the ring will perform a line switch. All traffic



**FIGURE 12.10** Four-fiber BLSR traffic with multiple span failures.

through the failed span is rerouted around the ring, onto the protect fibers, see Fig. 12.11.

Both two- and four-fiber BLSR rings are commonly deployed. Advantages and disadvantages for these two configurations are below.

Two-Fiber BLSR	
Advantages	Disadvantage
Less expensive due to fewer required optical cards than four- fiber BLSR	Can only carry half the OC- <i>n</i> capacity for traffic in either direction out of an ADM because the other half is reserved for protection
Only two fibers are required	
Can reuse STS channels if unoccupied in other sections of the ring	



FIGURE 12.11 Four-fiber BLSR traffic with cable failure.

Four-Fiber BLSR	
Advantages	Disadvantages
Can carry the full OC- <i>n</i> traffic around the ring	Initially more expensive
Provides line and span switching	Twice as many fibers are required
Can handle multiple span failures	More complex
Can reuse STS bandwidth anywhere in the ring	

**UPSR Ring** The SONET UPSR configuration is a two-fiber ring. All STS traffic flows in one direction (counterclockwise) around the ring using only the one work ring fiber. For example as shown in Fig. 12.12*a*, STS #3 traffic is transmitted out of NE1 on the work ring fiber counter-clockwise around the ring. It is received by NE3 which transmits traffic onto the same work ring fiber counterclockwise





through NE4 back to NE1. The other ring fiber is reserved as the protect fiber. Also at the transmit end, STS #3 traffic is bridged onto the protect fiber and propagates in the clockwise direction around the ring. However, the receiver is not connected to this fiber's traffic in normal operating conditions. In the event of a cable fault, the receiver switches from receiving the work fiber traffic to the protect fiber traffic. For example, if a cable fault, should occur between NE2 and NE3, then the receivers at NE1 and NE3 switched from receiving work fiber traffic to protect fiber traffic, see Fig. 12.12*b*. This STS traffic switching is completed only at the receive end since the transmit end traffic is already bridged onto the protect fiber. Therefore, during normal operation all STS channels travel around the entire ring. Whereas in BLSR configuration STS traffic travels only between the NE ADMs.

The advantages and disadvantages of the UPSR configuration are shown below.

UPSR	
Advantage	Disadvantages
Easy to administer	All STS channels propagate around the entire ring
Receiving node makes all switching decisions. A communication channel to transmitting node is not required.	Cannot reuse STS channels anywhere in the ring

### References

- 1. American National Standards Institute, 1819 L Street, NW, 6th floor, Washington, DC.
- 2. Telcordia, One Telcordia Drive, Piscataway, NJ.
- International Telecommunication Union, Place de Nations, 1211 Geneva 20, Switzerland.

# APPENDIX A Symbols, Abbreviations, and Glossary of Terms

### A.1 Symbols and Abbreviations Used Frequently in This Text

#### **Greek Symbols**

 $\langle \cdots \rangle$  = average value of the group of values inside the brackets,

$$\langle x \rangle = \overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

 $\alpha$  = optical fiber attenuation coefficient, km<sup>-1</sup> or m<sup>-1</sup>

Note: 
$$\alpha = \frac{\alpha_{dB}}{10 \log e}$$

 $\alpha_{dB}$  = optical fiber attenuation coefficient, dB/km

 $\alpha_c = \text{laser chirp alpha parameter, } \alpha_c \approx -C_0$ 

 $\beta$  = phase propagation parameter, rad/m

- $\beta_0$  = wavelength-independent phase shift during signal propagation, rad/m
- $\beta_1$  = inverse of speed of signal propagating in fiber,  $\beta_1 = 1/v_o$ , ps/km
- $\beta_2$  = defines signal pulse broadening, also known as the GVD parameter, related to dispersion chromatic dispersion CD =  $-2\pi c \beta_2/\lambda^2$ , ps<sup>2</sup>/km

$$\beta_3 =$$
 slope GVD, or second-order GVD, when  $\beta_2 \approx 0$ 

$$\Gamma$$
 = optical power loss, dB, where  $\Gamma$  = -10 log  $\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)$ 

- $\Pi$  = fiber's power density, dBm/ $\mu$ m<sup>2</sup>
- $\Delta f$  = optical spectral width, GHz
- $\Delta f_{\rm rms}$  = RMS spectral width of a signal, GHz
- $\Delta f_{-20dB}$  = spectral width measured down 20 dB from signal peak of the transmission signal during modulation, GHz
  - $\Delta \lambda$  = optical signal spectral width, nm
  - $\Delta \tau_{\rm DG} = \rm DGD, \, ps$
  - $\Delta \tau_{CD}$  = change in chromatic dispersion group delay at wavelength  $\lambda$ , ps
    - $\Delta \omega$  = change in angular frequency or spectral width ( $\Delta \omega$  =  $(-2\pi c/\lambda^2)\Delta\lambda$ ), rad/s
    - $\pm\delta\lambda$  = half optical signal spectral width, where  $\Delta\lambda = \Delta\lambda/2$ , nm
    - $\pm \delta f$  = half optical signal spectral width, where  $\Delta f = \Delta f/2$ , GHz
    - $\pm \delta f =$  half optical spectral width, where  $\Delta f = \Delta f / 2$ , GHz
      - $\epsilon$  = epsilon value = 0.3 for 1 dB power penalty and 0.48 for 2 dB power penalty at BER 10<sup>-12</sup>

$$\varepsilon_0$$
 = permitivity of vacuum constant, 8.854 × 10<sup>-12</sup> farads/m

 $<\Delta \tau_{DG} > =$  average DGD in a fiber or optical component, ps

- $\lambda$  = Greek letter lambda that represents an optical wavelength, nm
- $\lambda_0$  = zero dispersion wavelength, nm
- $\lambda_c$  = center wavelength. It is often used to identify the center wavelength of an optical source or WDM channel, nm
- $\mu_0$  = permeability of vacuum,  $4\pi \times 10^{-7}$  H/m
- $\sigma$  = standard deviation or RMS value of a waveform in the time domain or frequency domain
- $\sigma^2 = variance$
- $τ_{CDλ}$  = chromatic dispersion relative group delay at a wavelength λ, ps
  - $\omega$  = angular frequency, also known as circular frequency ( $\omega = 2\pi c/\lambda$  or  $\omega = 2\pi f$ ), rad/s

#### **Roman Symbols**

- $A_{\rm eff}$  = fiber effective area
  - A = ampere
- $B_m$  = noise equivalent bandwidth NEB, nm
- $B_r$  = resolution bandwidth RBW, nm
- $B_{o}$  = optical filter channel passband, Hz or nm
- $B_s = ITU$  channel spacing, GHz or nm
- BER = bit error ratio

BW = Optical spectral width, nm or GHz BW<sub>cb</sub> = DWDM or CWDM channel optical spectral width, GHz c = speed of light in a vacuum, defined as 299,792,458 m/s C = coulombs $C_0 =$  laser chirp parameter CD = chromatic dispersion, ps/nm $CD_{c}$  = chromatic dispersion coefficient, ps/(nm km) CD<sub>DCM</sub> = chromatic dispersion due to the dispersion compensation module (DCM), ps/nm  $CD_f$  = chromatic dispersion due only to the fiber, ps/nm CD<sub>tot</sub> = total link chromatic dispersion, ps/nm  $D_{\text{material}} = \text{fiber material dispersion at wavelength } \lambda$ , ps/nm  $D_{\text{waveguide}}$  = fiber waveguide dispersion at wavelength  $\lambda$ , ps/nm DGD<sub>max</sub> = maximum DGD in a fiber or optical component for a specific wavelength range, ps DSCR = dispersion slope compensation, % F =noise factor,  $F = 10^{NF/10}$ f = frequency, GHz  $f_c$  = center frequency, GHz  $f_{\rm mod}$  = modulation frequency, Hz fps = frames per second g = gain, linear  $g_{\rm R}$  = Raman gain coefficient G = gain, dBGVD = group-velocity dispersion parameter, same as  $\beta_{\gamma}$  $h = \text{Planck's constant } 6.626069 \times 10^{-34}$ , Js H = Henry IL = insertion loss, dBL =length of a fiber, m  $L_{\rm eff}$  = fiber effective length, m  $L_{\rm eff} = \frac{1 - \exp(-aL)}{\alpha}$  $L_{\rm CD}$  = fiber link length limit due to chromatic dispersion, km Loss = fiber link optical power loss, dB  $Loss_{\tau}$  = total fiber link optical power loss, dB M = positive or negative integer including zero m = meter $m_{\rm s}$  = pulse shape parameter

 $m^2 = square meter$ 

- N = positive or negative integer including zero
- NF = noise figure, NF =  $10 \log(F)$ , dB
  - n = refractive index of a material
- $n_{\rm eff}$  = fiber's effective refractive index
- $n_q$  = fiber's effective group refractive index
- $n_2$  = nonlinear-index coefficient (or the Kerr coefficient), varies  $2.2 \times 10^{-20}$  to  $3.4 \times 10^{-20}$  (typical is  $3.0 \times 10^{-20}$  m<sup>2</sup>/W), m<sup>2</sup>/W
- $n_{\rm sp}$  = electron population emission (or inversion) factor
- OSNR = optical signal to noise ratio, the ratio of optical signal power to noise power over a spectral resolution bandwidth (RBW), dB
  - P = optical power, dBm or mW or W
  - $P_{ASE} = EDFA ASE$  noise power, W
    - $P_e =$  power penalty, dB
  - $P_{out}$  = optical output power, mw or dBm
    - $P_{in}$  = optical input power, mw or dBm
  - $P_{sig}$  = optical signal power, dBm or mW
  - $P_{\text{noise}} = \text{noise power, dBm or mW}$ 
    - $p_r = \text{probability}$
    - $P_{T}$  = total optical power, dBm
  - PDL = polarization-dependent loss, dB

 $PDL_{tot} = total link PDL, dB$ 

- PMD2 = second-order polarization mode dispersion is the DGD dependency on wavelength that causes the PSP pulses to broaden or shrink, ps/nm
- PMD2<sub>c</sub> = proportionality coefficient when multiplied by the fiber length equals the fiber second-order PMD, ps/(nm · km)
  - $PMD_c = polarization mode dispersion coefficient, ps/<math>\sqrt{km}$
  - $PMD_f = PMD$  due to fiber, ps
- $PMD_{maxc}$  = maximum PMD coefficient for a fiber link, ps/ $\sqrt{km}$ 
  - $PMD_{mi} = measured PMD, ps$
  - PMD<sub>tot</sub> = total link PMD including PMD contributions of all link fiber and optical components, ps
  - $PMD_{totc}$  = total link PMD coefficient including PMD contributions of all link fiber and optical components, ps/ $\sqrt{km}$ 
    - PMD<sub>Q</sub> = statistical upper bound value specified for an imaginary reference link consisting of at least M equal

length sections (typically M = 20) of concatenated, randomly selected, fiber cables with a probability of less than Q (typically Q = 0.01% for 99.99 percentile) that the actual link PMD coefficient will exceed the PMD<sub>Q</sub> value. It is also known as link design value (LDV). It is measured in units ps/ $\sqrt{km}$ .

- R = transmission bit rate, bps
- $R_{out}$  = single-fiber mean outage rate, outages per year

RDS, = fiber relative dispersion slope at 1550 nm, nm<sup>-1</sup>

- $R_p$  = photodiode responsivity, A/W
  - S = information spectral density, bps/Hz

 $S_{\text{NRZ}}$  = power spectral density, W/Hz

- $S_f$  = fiber chromatic dispersion slope at 1550 nm, ps/nm<sup>2</sup>
- $S_{fc}$  = fiber chromatic dispersion slope at 1550 nm, ps/(nm<sup>2</sup>km)
- $S_{\text{DCF}}$  = DCF chromatic dispersion slope at 1550 nm, ps/nm<sup>2</sup>
  - $SF = safety factor, the ration of DGD_{max}$  to average DGD or  $PMD_{tot}$  over a wavelength range
    - $t_{\lambda}$  = elapsed time of reflected pulse for both directions at wavelength, s
    - T = bit time slot period, s

 $T_{\text{HWEM}}$  = half width at 1/e amplitude point pulse width, s

- $T_{\text{FWHM}}$  = full width at half maximum amplitude point pulse width (-3 dB), s
  - $T_r = \text{transmittance}$
  - U = circuit unavailability measure, s or min
  - v = phase velocity of light
  - $v_g =$  group velocity of light
  - V = voltage, volt
  - W = optical power, Watt
  - Year = 365.242199 days

#### A.2 Abbreviations

1000Base-LX = IEEE 802.3z standard that operates on single-mode fiber up to distance of 10 km
1000Base-SX = IEEE 802.3z standard that operates on multimode fiber up to distance of 550 m
1000Base-ZX = IEEE 802.3z standard that operates on single-mode fiber up to distance of 70 km
ADM = add/drop multiplexer

ADSS = all dialectic self-supporting cable

ANSI = American National Standards Institute

- APD = avalanche photodiode
- APS = automatic protection switching
- ASE = amplified spontaneous emissions, generation of random photons due to electron or molecule decay to a lower energy state. These photons are considered as noise in an optical amplifier.
- ATM = asynchronous transfer mode
- AWG = array-waveguide grating
  - BER = *see* bit error ratio
- BERT = bit error rate test
- BLSR = bilateral line switched ring
- CAD = computer-aided design
- CAM = computer-aided manufacturing
- CATV = common antenna (cable) television
- CCITT (now ITU-T) = Consultative Committee on International Telephone & Telegraph. An international committee that develops and recommends standards for telecommunications.
  - CCTV = closed-circuit television
  - CCW = counterclockwise
  - CDDI = copper distributed data interface. A protocol standard similar to FDDI but using an unshielded twisted pair or shielded twisted pair to provide 100-Mbps data.
    - CIR = see committed information rate
    - CO = central office
    - CRC = see cyclic redundancy check
    - CSA = Canadian Standards Association
  - CSMA = carrier sense multiple access with collision detection
    - CSU = channel service unit
    - CW = clockwise or continuous wave
  - CWDM = *see* course wavelength division multiplexing *or* course wavelength division multiplexer
    - dB = see decibel

dBm = decibel power measurement relative to 1 mW

$$P_{\rm dBm} = 10 \log \left(\frac{P}{1_{\rm mW}}\right)$$

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DCE = data communication equipment DCF = chromatic dispersion compensating fiber DCM = dispersion compensation module can consist of dispersion compensating fiber (DCF) or other technology to compensate chromatic dispersion across a wavelength range DCU = dispersion compensation unit, also known as DCM DF = diffraction grating DFB = see distributed feedback laser DGD = *see* differential group delay DM-DFB = directly modulated distributed feedback laser DMD = differential mode delay effect DML = directly modulated laser DNA = digital network architecture DRA = distributed Raman amplifier DRS = double Rayleigh scattering DS0 = digital signal level 0, that is 64 kbps. 24 DS0s make a DS1 DS1 = digital signal level 1, that is 1.544 Mbps, T1 rate DS2 = digital signal level 2, that is 6.312 Mbps, T2 rate DS3 = digital signal level 3, that is 44.736 Mbps, consists of 28 DS1s DSCR = dispersion slope compensation ratio DSF = dispersion shifted fiber DSU = digital service unit DTE = data terminal equipment DTMF = dual tone multiple frequency DUT = device under test DWDM = see dense wavelength division multiplexing or dense wavelength division multiplexer EAM = electro-absorption modulator EDC = electronic dispersion compensation EDFA = erbium doped fiber amplifier, an optical amplifier that uses erbium doped fiber technology to amplify optical signals in C

EFEC = enhanced forward error correction

and L bands

EIA = Electronic Industries Association

EIR = see excess information rate EMI = electromagnetic interference EM-DFB = externally modulated distributed feedback laser FBG = fiber Bragg grating FDDI = fiber distributed data interface FEC = forward error correction FOT = fiber optic terminal FT1 = fractional T1, a fraction of the full 24 channels in a T1 FTTC = fiber to the curb FTTH = fiber to the home FWHM = see full width at half maximum amplitude (-3 dB) point FWM = four-wave mixing, interchannel GBIC = *see* gigabit interface converter Gbps or Gb/s = giga (10<sup>9</sup>) bits per second, transmission rate GBps or  $GB/s = giga (10^{\circ})$  bytes per second, transmission rate (1 byte = 8 bits)GFEC = generic forward error correction GUI = graphical user interface GVD = group-velocity dispersion, also known as chromatic dispersion HDTV = high-definition television HWEM = half width at 1/e maximum amplitude point ICEA = Insulated Cable Engineers Association, Inc. IEEE = Institute of Electrical and Electronics Engineers IFWM = intrachannel four-wave mixing IRU = indefeasible rights of use ISI = intersymbol interference ISO = International Organization for Standards ITU-T = International Telecommunications Union Telecommunication Standardization Sector, www.itu.int IXPM = intrachannel cross-phase modulation LAN = local area network LED = light emitting diode LTE = light terminating equipment M13 = multiplexer DS1 to DS3

MAC = see media access and control layer MAN = metropolitan area network Mbps or Mb/s = mega (10<sup>6</sup>) bits per second, transmission rate MC = main cross connectMFD = see mode field diameter MLM = see multi-longitudinal mode laser MOD = mean outage duration of a circuit MPI = *see* multipath interference MPN = see mode partition noise MSDS = material safety data sheet MTBO = mean time between circuit outages mW = milliwatt, one thousandth of a watt  $(10^{-3})$ MZI = Mach-Zehnder modulator NDSF = non-dispersion shifted fiber, also known as SSMF NEB = see noise equivalent bandwidth NEBW = see noise equivalent bandwidth NEC = national electrical code NLSE = nonlinear Schrödinger equation NRZ = non-return-to-zero transmission pulse format, used for SONET/SDH transmission NZ-DSF = non-zero dispersion shifted fiber OADM = optical add/drop module OAM&P = operations, administration, maintenance, and provisioning OCWR = optical continuous wave reflectometer OMA = optical modulation amplitude OOK = on-off keying digital modulation OPGW = optical ground wire OSA = optical spectrum analyzer OSC = optical supervisory channel OSI = open system interconnetion OSNR = optical signal to noise ratio OSP = outside plant OTDR = optical time domain reflectometer OTN = optical transport network PBX = private branch exchange PCM = see pulse-code modulation PDG = see polarization-dependent gain

PDL = see polarization-dependent los
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- PIC = photonic integrated circuit
- PIN = positive intrinsic negative photodiode
- PLC = see planar lightwave circuit
- PMD = see polarization mode dispersion
- PMF = *see* polarization maintaining fiber
- PM fiber = see polarization maintaining fiber
  - POTS = plain old telephone system
    - PSD = power spectral density
    - PSP = principal states of polarization, two orthogonal polarization axes in a fiber or optical component
  - RBW = see resolution bandwidth
  - RDS = ratio of the chromatic dispersion slope to the chromatic dispersion at the 1550 nm wavelength
  - RFI = radio frequency interference
  - RGD = see relative group delay
    - RIN = see relative intensity noise
  - RMS = root mean square
  - ROPA = remote optically pumped amplifier
    - Rx = receive. For fiber systems refers to equipment optical receiver fiber input connection. Also designated as "In" port.
  - RxDTV = receiver decision threshold voltage
    - RZ = return-to-zero transmission pulse format
    - SBS = stimulated Brillouin scattering
    - SDH = synchronous digital hierachy
      - SFP = *see* small form-factor pluggable, transmission rate under 3 Gbps
    - SFP+ = see small form-factor pluggable, transmission rate 10 Gbps
    - SLA = see service level agreement
    - SLM = see single longitudinal mode laser
    - SMSR = side mode suppression ratio
      - SNA = systems network architecture. IBM's sevenlayer data communication layer
      - SNR = signal to noise ratio (electrical)
- SONET = synchronous optical network
  - SPM = self-phase modulation
  - SRS = stimulated Raman scattering

SSE = *see* source spontaneous emissions

- SSMF = standard single-mode fiber, also known as NDSF
  - STP = shielded twisted pair
- STS-1 = synchronous transport signal level
  - TFF = thin-film filter
    - Tx = transmit. For fiber systems refers to equipment laser or LED signal output connection. Also designated as "Out" port.
    - UI = see unit interval
  - UTP = unshielded twisted pair
- VCSEL = vertical cavity surface emitting laser
  - VECP = *see* vertical eye closure penalty
- VLAN = virtual LAN
  - VOA = variable optical attenuator
  - VoIP = voice over IP
  - WAN = wide area network
- WDM = *see* wavelength division multiplexing or wavelength division multiplexer
- XENPAK = see Xenpak
  - XFP = *see* 10 Gbps small form factor pluggable
  - XPM = cross-phase modulation
  - ZWPF = zero water peak fiber

#### A.3 Glossary of Terms

**1+1 APS** An automatic protection switching configuration where two redundant fiber links carry the same traffic. The receiver determines and switches to the best link.

**1:1 APS** An automatic protection switching configuration similar to 1+1 APS where two redundant links are required. However, the link that is not being used is idle or can carry other lower priority traffic. In the event of a protection switch, the lower priority traffic is lost.

**1:n APS** An automatic protection switching configuration similar to 1:1 that provides one back up link for up to 14 primary links. All primary links must have the same beginning and end points. The back up link can carry low priority traffic that will be lost in the event of a protection switch. This method is more efficient since only one back up link provides protection for up to 14 primary links.

**10 Gbps small form factor pluggable (XFP)** A compact optical transceiver that adheres to XFP multi-source agreement (MSA) specification standard.

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XFPs are available in four categories: 1310 nm optics, 1550 nm optics, DWDM, or CWDM optics. XFP data rate is 10 Gbps.

**802.3** A local area network protocol that uses CSMA/CD for medium access control and a bus topology defined in layers 1 and 2 of the OSI protocol stack.

**802.4** A local area network protocol known as token bus uses a tokenpassing access method and a bus topology. Originated by General Motors and targeted for the manufacturing environment. It is defined in layers 1 and 2 of the OSI protocol stack.

**802.5** A local area network protocol known as token ring uses a tokenpassing with priority and reservation access method and a star wired ring topology. Originated by IBM. It is defined in layers 1 and 2 of the OSI protocol stack.

**3R regeneration** The retiming, re-amplifying, and reshaping of a digital signal.

**Absorption** The loss of optical power in fiber, resulting from the conversion of light to heat. Caused by impurities, OH migration, defects, or absorption bands.

**Acceptance angle** The angle at which all incident light is totally and internally reflected by the optical fiber core. Acceptance angle = sin NA. Also known as maximum coupling angle.

**Adapter** A mechanical device used to align and join two fiber optic connectors. It is often referred to as a coupling, bulkhead, or interconnecting sleeve.

**Amplified spontaneous emissions (ASE)** The generation of random photons due to electron or molecule decay to a lower energy state. These photons are considered as noise in an optical amplifier.

**Analog** A waveform format that is continuous and smooth and is used to indicate infinite levels of signal amplitude. *Also see* digital.

**Angstrom** Unit of length equal to  $10^{-10}$  meter or 0.1 nanometer.

**Aramid yarn** A light material, usually yellow or orange, that provides strength and support to fiber bundles in a cable. Kevlar is a particular type of aramid yarn that has very high strength.

**Armor** Additional protection between cable jacket layers usually made of corrugated steel.

**Asynchronous** A signal that is not synchronized to a network clock.

**Attenuation** The loss of optical power per 1 km unit length of fiber as a signal propagates in a fiber span. It is measured in dB/km units.

**Backbone cabling** The portion of telecommunication cabling that connects telecommunication closets, equipment rooms, buildings, or

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cities. It is a transmission medium (usually fiber optics) that provides a high-speed connection to numerous distributed facilities.

**Bare fiber adapter** An optical fiber connector designed to temporarily connect an unterminated optical fiber to a connector. This allows for quick testing of unterminated fibers.

**Baseband signal** A signal that is not shifted up to a higher frequency by modulating a carrier frequency. The signal bandwidth starts at 0 Hz and extends to some upper frequency. Example is Ethernet signal and T1 signal.

**Baud rate or symbol rate or transmission rate** For a physical layer protocol it is the maximum possible number of times a signal can change states from a logical 1 to logical 0 or logical 0 to logical 1 per second. The state is usually voltage, optical intensity, frequency, or phase. It can also be described as the number of symbols that can be transmitted in 1 second. The relationship between baud rate and bit rate is as follows.

Bit rate = baud rate × number of bits per baud

The number of bits per baud is determined by the modulation scheme. In this text, we assume that the number of bits per baud is one and therefore the baud rate is the same as the bit rate.

**Bidirectional coupler** An optical coupler that allows optical transmissions in a fiber in both directions.

**Binary** *n*-zero suppression A line coding system for digitally transmitted signals. The *n* represents the number of zeros that are replaced with a special code to maintain pulse density required for synchronization. Typically n is 3, 6, or 8.

**Birefringence** The splitting of light into two components due to anisotropic composition of a fiber or optical component.

Bit One binary digit.

**Bit error ratio (bit error rate)** A measure of the quality of a data circuit. It is the ratio of the number of data bits received incorrectly divided by the total number of data bits received. Most telecommunication systems require a maximum channel BER of  $10^{-12}$  or  $10^{-10}$ .

**Bit rate** The number of bits that are transmitted in one second. Unit is bps.

**Bridge** Connects two or more similar LANs in layer 2 of the OSI protocol stack.

**Broadband signal** A signal that consists of a carrier wave modulated with a baseband signal. Its bandwidth begins at some non-zero frequency and extends to a higher non-zero frequency. Example is a radio signal and a TV signal.

**Brouter** A vendor device that acts both as a bridge and router.

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**Buffer** A protective cover of plastic or other material, usually color coded, covering the optical fiber. A buffer can either be tight, as in a tight-buffered cable and adhered directly to the optical fiber coating, or it can be loose, as in a loose-tube cable, where one or more fibers lie loosely in the buffer tube. The buffer must be stripped off for cleaving and splicing.

Byte Eight adjacent binary digits (bits).

**Channel** A signal communications path, typically full duplex, but can be half duplex or simplex, that extends within one system. It is defined by a center wavelength or frequency and a passband. See Appendix for ITU-T standard WDM channels. A full duplex fiber communication channel requires two fibers. Signal transmission in each fiber is in opposite directions, which allows for the full duplex communication. In certain WDM technology, one fiber can be used for full duplex communications; however, both (transmit and receive) transmission signals must be at different wavelengths. Also, using bidirectional coupler technology at both ends of the fiber link, full duplex communications can be accomplished, with some restrictions, in one fiber at the same wavelength.

**Chirp (aka frequency chirp)** The incidental spectral frequency modulation of a pulse, or part of a pulse as it is launched into the fiber. Common in directly modulated DFB lasers.

**Chromatic dispersion** A property of optical fiber or optical component that causes different wavelengths of light to travel at different velocities.

**Circuit** A signal communications path, typically full duplex (Tx and Rx) but can be half duplex or simplex, that can extend further than one system and can extend throughout a network.

**Circulator** A passive nonreciprocal device with three or more (fiber) connection ports. When a signal enters one port, it is directed to the adjacent port, and the other ports remain isolated. Signal entering port 1 is directed to port 2, signal entering port 2 is directed to port 3, etc., in cyclic order. Typical use for a circulator is in a bidirectional coupler or band splitter.

**Cladding** A low index of refraction layer of glass or other material that surrounds the fiber core, causing the light to stay captive in the core.

**Cleaver** An instrument used to cut optical fibers in such a way that the ends can be connected with low loss.

**CO** Central office. A local telephone company office that contains a switch terminating subscribers.

**Coating** A thin layer of plastic, or other material, usually 250 or 500  $\mu$ m in diameter and color coded, covering the cladding of a fiber. Most fibers have a coating. It must be stripped for cleaving and splicing.

**Codec** A device that converts analog signals to digital signals. It also converts digital signals to analog signals.

**Committed information rate (CIR)** The average data rate that is supported in packet network such as Ethernet.

**Concentrator** An electronic device used in LANs that allows a number of stations to be connected to a single data trunk.

**Conductor** A material allowing the flow of an electric current.

**Connector (fiber optic)** A device that joins two optical fibers together in a repeatable, low-optical-loss manner.

**Cord** A short length of flexible cable used for connecting equipment.

**Core** The inner portion of the fiber that carries light. Light stays in the core due to the difference in refractive index between the core and cladding.

**Coupler (fiber optic)** A device that joins three or more optical fiber ends together so that an optical signal can be split, or transmitted, from one fiber to two or more fibers.

**Critical angle** The smallest angle at which a meridianal light ray can be totally reflected in a fiber core.

**Cut off wavelength, fiber** The wavelength that a single mode fiber will no longer support and propagate one mode of light. Specified by fiber cable manufacturers as a maximum value, typically ~1260 nm.

**Cyclic redundancy check (CRC)** This is an error checking algorithm used in protocols such as Ethernet to help detect errors in blocks or frames of data. The transmitter adds an extra byte(s) to a frame called frame check sequence (FCS) that contains redundant information about the data frame. The receiver compares the received data against the FCS to help identify transmission errors. However, this method does not catch all errors.

**Dark current** The current that flows in a photo detector when there is no light on the detector.

**Dark fiber** Optical fiber(s) that are not connected to any lightwave equipment and hence they are dark.

**Data bandwidth** The maximum data rate that can be accommodated by a channel.

**Data rate** The amount of bits of information that can be transmitted per second. Expressed as Gbps, Mbps, kbps, or bps.

**Decibel (dB)** A base 10 logarithmic unit of measurement defining a ratio of power where *P* is the actual value being measured and  $P_{ref}$  is the value it is being compared to, as  $P_{dB} = 10 \log(P/P_{ref})$ . In fiber optics *P* is typically output power in mW and  $P_{ref}$  is input optical power in mW.

**Dense wavelength division multiplexing (DWDM)** A WDM technology where wavelength spacing is 1000 GHz or less (typically 200 GHz and less) as per ITU-T standard.<sup>2</sup>

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**Dielectric** A material that will not conduct electricity under normal operating conditions (insulator).

**Differential group delay (DGD)** The amount of pulse spreading in time between the two orthogonal polarization modes (pulses) in a fiber or optical component. It is measured in units of ps.

**Digital** A data waveform format that has only two physical levels corresponding to 0s and 1s. *Also see* analog.

**Dim fiber** Optical fiber(s) that do not originate optical signals but do offer optical signal regeneration at intermediate sites.

**Dispersion** Distortion of light signals in a fiber caused by fiber propagation characteristics.

**Distributed feedback laser** A laser diode that has a Bragg reflection grating in order to suppress multiple longitudinal nodes.

**Double window fiber** A fiber designed to operate at two different wavelengths.

**Erbium-doped fiber amplifier (EDFA)** An optical amplifier that can amplify an optical signal without converting it into an electrical signal.

**Ethernet** An 802.3 LAN technology that uses the CSMA/CD access method and a bus topology.

**Excess information rate (EIR)** The data rate available in excess of the committed information rate (CIR). Typically allowed for short bursts.

**Fabry-Perot filter** A filter formed by a cavity that has two plane and parallel reflective ends.

**Ferrule** The rigid center portion of a fiber optic connector, usually steel or ceramic.

**Fiber bandwidth** The transmission frequency or wavelength range where signal magnitude decreases to half of its optical power (–3 dB).

**Fiber count** The number of optical fibers between any two locations. It can also refer to the number of optical fibers in a single cable.

**Fiber effective area** The average cross sectional area of the fiber that transmits optical power. It is similar to but not calculated the same as MFD.<sup>3</sup> It is measured in units of  $\mu$ m<sup>2</sup>.

**Fiber jumper (single or dual)** A flexible short length of a single fiber cable with connectors at both ends used to connect equipment to other equipment or to fiber distribution panels. The fiber jumper has a 3 or 2 mm diameter jacket that is yellow for single-mode fiber and orange for multimode fiber. Lengths vary greatly, are usually custom made at the factory, and are typically between 1 and 30 m in length. A dual fiber jumper is a jumper with two fibers within one common jacket.

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**Fiber optics** The transmission of light through optical fibers for communication and signaling.

**Flame test rating (Ft 1, 4, 6)** A Canadian flame test rating for cables as per CSA C22.2 No. 0.3-M1985.

**Frequency** The number of times a periodic action occurs in 1 second. Unit is cycles or hertz per second (Hz).

**Fresnel reflection** Reflections at end of fibers (at connectors, mechanical splices) caused by the difference of the index of refractive between glass and air.

**Full duplex** A communication channel that can receive and transmit information at the same time. Most fiber communications is full duplex. Full duplex fiber communication uses two fibers, but can use one fiber if bidirectional couplers or WDMs are deployed.

**Full width at half maximum** The spectral width of a signal or filter at 3 dB down from peak (half power). It is measured in units of nm.

**Gain** The increase of optical power from input to output in a fiber or optical component. It is measured in dB units.  $G = -10 \log(P_{out}/P_{in})$ , where  $P_{out} \ge P_{in}$ .

**Gainer (splice)** An OTDR trace event that occurs at a fiber splice. It is shown by the OTDR as a rise in the trace instead of a drop at the splice. This occurs because of the increase in Rayleigh backscatter of the second fiber, caused by splicing two different fibers. An accurate splice reading can be made at this event by OTDR testing the event from both ends of the fiber, and then averaging the result.

**Giga** A prefix meaning one billion  $(10^9)$ .

**Gigabit interface converter (GBIC)** A compact optical transceiver that adheres to standard defined in SFF Committee document SFF-8053. It is used for gigabit Ethernet and fiber channel transmission. GBICs are available in four categories: 1310 nm optics, 1550 nm optics, DWDM, or CWDM optics. GBIC data rate is 1 Gbps.

**Graded index fiber** An optical fiber in which the index of refraction of the core gradually decreases toward the cladding.

**Ground** A common electrical current return point to the earth usually through a ground rod.

**Ground loop currents** Undesirable ground currents that cause interference. Usually created when grounds are connected at more than one point.

**Group delay** The propagation delay of a pulse traveling in a fiber or optical component. It is measured in units of ps.

**Group velocity, light** The velocity of a modulated envelope of light propagating in a medium such as a fiber. It can be thought of as the

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velocity of an optical pulse propagating in a fiber. It is measured in units of m/s.

**Half duplex** A communication channel that can receive and transmit information but not at the same time.

Hertz (Hz) One cycle per second.

**Hub** A communication device that uses a star wiring pattern topology common in LANs.

**Hybrid fiber/coax (HFC)** A cable that contains both optical fiber and coax cable.

**Impedance** The total opposition an electric circuit offers to an alternating current flow that includes both resistance and reactance.

**In-band noise** Noise within the signal's spectral bandwidth or noise within the signal's channel.

**Index matching fluid** A liquid or gel with a refractive index that matches the core of the fiber.

**Index of refraction** The ratio of the speed of light in a vacuum to the speed of light in a material. Air n = 1.003; glass n = 1.4 to 1.6. The n also varies slightly for different wavelengths.

**Information spectral density** The amount of spectrum 1 bit per second of information occupies. It is defined as the signal bit rate divided by the signal channel width in hertz, unit bits/s/Hz.

Information spectral efficiency See information spectral density.

**Insertion loss (IL)** The optical loss through a device in a fiber link, units dB. The loss may vary with wavelength.

Insulator A material that does not conduct electricity.

**Intensity, optical** The optical power per unit area, unit  $W/m^2$ .

Inter-building cabling Cabling between buildings.

**Interferometric noise** Signal amplitude variations due to interference caused by multiple reflections in the fiber of the same signal.

**Intra-building cabling** Cabling within a building.

**Intranet** A company's private electronic communications network that uses internet protocols, devices, and applications to share information amongst its employees but is securely separated from the internet. It is often referred to as a private internet.

**Jacket** The outer coating of a wire or cable.

**Kilo** A prefix meaning one thousand (1000).

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**LiNbO**<sub>3</sub> modulator Lithium niobate external modulator used for modulating DFB lasers at high rates.

**Laser** An acronym standing for "light amplification by stimulated emission of radiation." A device that produces light, by the stimulated emission method, with a narrow range of wavelengths and emitted in a directional coherent beam. Fiber optic lasers are solid-state devices.

Laser spectral bandwidth The optical bandwidth occupied by a laser.

**Light, fiber optic** The spectrum of light at 850, 1300, and 1500 nm wavelengths. These wavelengths are not visible to the human eye.

**Lightwave equipment** Any electronic communication equipment that is used for optical fiber transmission. It is also known as optical terminating equipment or optical modem.

**Linear effects** Effects that are not dependent on the optical signal power. *See also* nonlinear effects.

**Link, fiber** A continuous optical communications path between two transceivers. It includes optical amplifiers as part of the path. It typically consists of two fibers or two different wavelengths in one fiber for full duplex communications. See Fig. A.1.

**Loss** The diminishment of optical power from input to output in a fiber or optical component. It is measured in dB units.  $\Gamma = -10 \log(P_{out} / P_{in})$ , where  $P_{out} \le P_{in}$ .

**Maximum coupling angle** The angle by which all incident light is totally and internally reflected by the optical fiber core. Maximum coupling angle = sin NA.

**Media access and control layer** The data link layer of the OSI model that moves data packets to and from network interface cards (NIC).

**Mega** A prefix meaning one million  $(10^6)$ .

**Micro** A prefix meaning one millionth  $(10^{-6})$ .



FIGURE A.1 Fiber cable span and link lengths.

**Microbending loss** Loss in a fiber, caused by sharp curves of the core with displacements of a few micrometers. Such bends may be caused by the buffer, jacket, packaging, installation, and so on. Losses can be significant over a distance.

**Milli** A prefix meaning one thousandth  $(10^{-3})$ .

**Minimum bend radius** The minimum radius of a curve that a fiber optic cable or optical fiber can be bent without any adverse effects to the cable or optical fiber characteristics.

**Mode** A single electromagnetic light wave that satisfies Maxwell's equations and the boundary conditions given by the fiber. It can simply be considered as a light ray path in a fiber.

**Mode field diameter** The optical power distribution diameter (spot size) across the fiber core and cladding.<sup>1</sup> MFD varies with wavelength. It is measured in units of  $\mu$ m.

**Mode partition noise (MPN)** This noise occurs because of random variations of individual laser modes even though the total laser output power remains constant. The noise is generated in fibers where the signal dispersion wavelength is not zero. The fluctuating modes travel at different group velocities due to chromatic dispersion, which results in mode desynchronization and added receiver noise. MPN occurs in MLM lasers but can also occur in SLM lasers that have large side nodes.

**Mode scrambler** A device that causes modes to mix in a fiber.

**Modem** An electronic device that converts one form of signal to another form using a modulation technique. An optical modem converts the electrical signal to an optical signal and vice versa.

**Modulation** The process of encoding signal information onto a carrier by changing the carrier's amplitude *A*, frequency  $\omega_{\alpha'}$  or  $\phi$ .

**Modulation rate** The rate a carrier is modulated. Also known as the transmission rate.

**Multi-longitudinal mode laser** A laser diode that radiates more than one longitudinal mode.

Multimode fiber A fiber that propagates more than one mode of light.

**Multipath interference** The ratio between the secondary path and main path of an interfering optical signal. It can cause problems in fiber links where Raman amplifiers are deployed. It is measured in units of dB.

**Multiplexer** An electronic unit that combines two or more communication channels onto one aggregate channel.

**Nano** A prefix meaning one billionth  $(10^{-9})$ .

**Narrow-band WDM** A WDM (wavelength division multiplexer—see under W) that couples different wavelengths in the 1550 nm band onto a fiber.

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Noise Undesirable signal interference. It can be random or deterministic.

**Noise equivalent bandwidth** The width of a filter with a rectangle passband, that would pass the same noise power as the actual OSA RBW filter, with area equal to the area of the actual RBW filter and with the same height as the actual RBW filter at the center wavelength. It is measured in nm.

**Nonlinear effects** Effects that are dependent on the optical signal power. See also linear effects.

**Non-return to zero (NRZ)** A digital code where the signal level is too high for a 1 bit, too low for a 0 bit, and does not return too low for successive 1 bits.

**Numerical aperture** The sine of the angle measured between an incident light ray and the boundary axis, in which an optical fiber can accept and propagate light rays. It is a measure of the light-accepting property of the optical fiber.

**Octet** A series of 8 bits. Same as byte.

**Ohm** The electrical unit of resistance.

**Optical add/drop module (OADM)** A unit used to add or drop selected wavelengths in a fiber.

**Optical dynamic range** The receiver optical dynamic range is the light-level window in dBm at which a receiver can accept optical power.

**Optical fiber** A single optical transmission element that comprises a core, cladding, and coating. Commonly made of silica glass but can also be made from plastic.

**Optical loss** The reduction of fiber optic power caused by a substance.

**Optical margin** The value in dB of the difference between the total optical link loss and the manufacturer's equipment optical sensitivity.

**Optical return loss (ORL)** The total optical power reflected back to the input end of a fiber and represented in dB.

**Optical signal-to-noise ratio (OSNR)** The ratio of optical signal power to noise power, represented in dB.

**Optical time domain reflectometer (OTDR)** A test instrument that sends short light pulses down an optical fiber to determine the fiber's characteristics, attenuation, and length.

**Optical transport network (OTN)** An ITU-T standard protocol defined in G.709, G.805, G.872 and G.874.1 that combines and is transparent to optical protocols such as SONET, SDH, and Ethernet. It also adds OAM&P and FEC capability.

**Packet** A grouping of data with an address header and control information.

Pad (optical) A fixed optical attenuator.

**Patch cord (jumper), optical** A short length of buffered optical fiber, 3 mm in diameter, with connectors at both ends. It can be used to connect equipment to patch panels or jumper patch panels.

Patch panel A fiber cable termination panel.

**Phase velocity, light** The velocity of the phase of any one frequency of light propagating in a medium such as in a fiber or optical component. It is measured in units of m/s.

Phonon A quantum of acoustic or vibration energy.

**Photodetector** A device that converts light energy into electrical energy. A silicon photo diode is commonly used in fiber optics.

**Photon** A quantum of light radiation.

**Pico** A prefix meaning  $10^{-12}$ .

**Pigtail** A short length of buffered optical fiber with a connector at one end. It is used to terminate fibers.

**Planar lightwave circuit (PLC)** This technology monolithically integrates multiple optical devices such as DWDMs, optical switches, lasers, and amplifiers into a single planar (flat) chip. PLC circuits are fabricated on a silica or silicon substrate. It offers an integrated solution similar to the semiconductor industry.

**Polarization-dependent gain (PDG)** EDFA gain varies slightly with signal polarizations.

**Polarization-dependent loss (PDL)** The ratio of the maximum to the minimum optical power for all possible input polarization states of an optical system or component. It is measured in units of dB.

**Polarization maintaining fiber** An optical fiber that maintains polarization state constant along the length of the fiber. There is very little cross coupling of power between axes.

**Polarization mode dispersion (PMD)** The time or wavelength region linear average of instantaneous differential group delay (DGD) values in a fiber or optical component. It is measured in units of ps.

**Polarization mode dispersion coefficient** A proportionality coefficient when multiplied by the square root of the fiber length equals the fiber PMD. It is measured in units  $ps/\sqrt{km}$ .

**Polyethylene** A thermoplastic material often used for cable jackets.

**Polyvinyl chloride** A thermoplastic material often used for cable jackets.

**Pop** Point of presence. A physical location where a carrier provides services to a customer.

**Power penalty** The necessary increase in signal power, to compensate for signal loss due to an impairment, in order to maintain the same BER, dB.

**Power spectral density** Signal integrated power per unit (typically 1 nm or Hz) slice of the spectrum, units dBm/nm or dBm/Hz.

**Protocol** A set of rules that govern the transmission and reception of information.

**Pulse-code modulation (PCM)** A method of converting an analog signal into a digital signal. Small, uniform, and equal time interval samples of the analog signal's amplitude are represented by data words.

**Rayleigh scattering** The scattering of light in all directions in a fiber due to small inhomogeneities.

**Receiver, optical** An electronic unit that converts light signals to electrical signals.

**Reflectance** The reflected optical power from a single event in a fiber, measured in dB.

**Relative group delay** The time difference between optical pulses of different wavelengths and the  $\lambda_0$  wavelength pulse.

**Relative intensity noise** The ratio of electrical noise power, normalized to a 1 Hz bandwidth, to the average power of photo current in the photo receiver. Typically used when discussing noise emitted by a laser.

**Repeater, optical 3R** Fiber optic equipment that reconditions and retransmits an optical signal by re-amplifying, retiming, and reshaping the signal (3R).

**Resolution bandwidth** The OSA's filter spectral bandwidth. It regulates the amount of light spectrum that passes to the photo detector. The photo detector measures the average optical power in the resolution bandwidth. Therefore, the ability of an OSA to display two signals closely spaced as two distinct signals is determined by the resolution bandwidth setting. Typical OSA resolution bandwidth range is less than 10 nm with common settings of 1.0, 0.5, 0.1, and 0.05 nm. Resolution bandwidth is measured 3 dB down (FWHM) from filter peak.

**Return to zero (RZ)** A digital code where the signal level is high for a 1 bit for the first half of the bit interval and then goes to low for the second half of the bit interval. The level stays low for a 0 bit complete interval.

**Root mean square (RMS)** Statistical standard deviation of discrete values from their mean is

$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n} (x_i - \langle x \rangle)^2\right]^{1/2} \quad \text{Mean (average) value is } \langle x \rangle = \frac{1}{n}\sum_{i=1}^{n} x_i$$

If the population mean is zero, then RMS (root mean square) is the same as standard deviation  $\sigma_{\rm rms}^2 = \sigma^2 + \langle x \rangle^2$  In electronics, standard

deviation only measures the AC value of a signal. If there is no DC component to an AC signal then the standard deviation is the same as the RMS value.

For a continuous temporal function the RMS value<sup>1</sup> is as follows:

$$\sigma_{\rm rms} = \left[ \langle t^2 \rangle - \langle t \rangle^2 \right]^{1/2}$$
Mean (average) value is  $\langle t \rangle = \frac{\int_{-\infty}^{\infty} t \left| A(z,t) \right|^2 dt}{\int_{-\infty}^{\infty} \left| A(z,t) \right|^2 dt}$ .
$$\sigma_{\rm rms}(z) = \left[ \frac{\int_{-\infty}^{+\infty} t^2 \left| A(z,t) \right|^2 dt}{\int_{-\infty}^{+\infty} \left| A(z,t) \right|^2 dt} - \left[ \frac{\int_{-\infty}^{+\infty} t \left| A(z,t) \right|^2 dt}{\int_{-\infty}^{+\infty} \left| A(z,t) \right|^2 dt} \right]^2 \right]^{1/2}$$

**Router** A LAN device that operates at the OSI protocol stack network layer and is used to connect dissimilar LANs or networks.

**Section, fiber cable** An original length of fiber cable that has not been spliced in the field.

**Self-steepening, fiber pulse** The nonlinear effect where the peak of a pulse propagates slower in the fiber than the edges of the pulse. It occurs because of the intensity dependence of GVD. The effect typically considered in soliton transmission.

**Sensitivity** The minimum amount of optical power needed to be received by the lightwave equipment to achieve a specific BER.

**Service level agreement (SLA)** An agreement between parties where the service is formally defined.

**Signal-spontaneous beat noise** Mixed emissions of signal power and spontaneous emission because of the nonlinear characteristic of a photo detector. These emissions are limited by the electrical bandwidth of the photo detector.

**Simplex** A communication channel that transmits information in only one direction. Example, FM radio station.

**Single longitudinal mode laser** A laser diode that radiates a single dominant longitudinal mode. Side modes are typically suppressed by >25 dB. Example, DFB laser.

**Single-mode fiber** A fiber that carries only one mode of light. Only one light path is propagated.

**Small form-factor pluggable (SFP)** A compact optical or copper transceiver that adheres to multisource agreement (MSA) specification standard. Available in six categories: copper, 850 nm optics, 1310 nm optics, 1550 nm optics, DWDM, or CWDM optics. SFP transmission rates are less than 3 Gbps. SFP+ transmission rate is 10 Gbps.

**Source spontaneous emissions (SSE)** Random emission of photons in an optical source such as a laser. It contributes to signal noise degradation.

**Span, fiber** The OSP fiber cable length between electronic equipment, typically transceivers or optical amplifiers. A fiber span can be made up of one or more concatenated fiber cables that are spliced together or joined together by connectors. Span length is less than or equal to the link length. See Fig. A.1

**Spectral bandwidth** A group of optical wavelengths (or frequencies) occupied by or reserved for optical sources. Not to be confused with data bandwidth.

**Speed of light**  $2.998 \times 10^8$  m/s in a complete vacuum. It is less in any other material.

**Splice, fiber** The joining of two optical fibers to provide for a low loss optical path (< 0.5 dB) by method of fusion splicing or mechanical splicing methods.

**Spontaneous emission** Random emission of photons that occurs when electrons that are in excited energy states decay to lower energy states.

**Spontaneous-spontaneous beat noise** Noise generated in the photo detector because the spontaneous emission mixes with itself because of the nonlinear characteristic of a photo detector. These emissions are limited by the electrical bandwidth of the photo detector.

**Standard deviation of mean** Statistical standard deviation of discrete x values from their mean is defined as

$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n} (x_i - \langle x \rangle)^2\right]^{1/2}.$$
 Mean (average) value is defined as  $\langle x \rangle = \frac{1}{n}\sum_{i=1}^{n} x_i.$ 

For continuous function f(x) it is defined as

$$\sigma = \left[\int (x_i - \langle x \rangle)^2 f(x) dx\right]^{1/2}$$
. Mean (average) value is defined as  $\langle x \rangle = \int x f(x) dx$ .

**Step index fiber** An optical fiber in which the core has a constant index of refraction.

**Stimulated emission** The emission of a photon that occurs when an electron in an excited energy state is stimulated to a lower energy state by another incoming photon. The newly generated photon takes on the same phase, frequency, polarization, and direction as the incoming

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photon, which is known as coherent radiation. The resulting effect is the power of the incoming light is amplified.

Stratum A primary reference clock used for network synchronization.

**Synchronous signal** A signal that is synchronized to a network clock.

**Synchronous transmission** Data communication protocol where the data is sent continuously.

**System, telecommunication** A group of interrelated equipment elements (typically from one manufacturer) that interact to form a signal communication path or paths.

**Telecommunications network** A group of telecommunications systems that are connected together in such a way as to allow passage of signals between them.

**Transceiver, optical** A device that can both transmit and receive optical signals and convert these signals to the proper electrical format. A transceiver consists of a laser or LED diode for the transmitter and a photodiode or APD for the receiver. Optical transceivers for many types of equipment are available as small-form factor pluggables (SFPs).

**Transmission rate** *See* baud rate.

**Transmitter, optical** An electronic unit that converts electrical signals to light signals.

**Transponder, optical** A device that converts an optical transmission of any wavelength and spectral width to a standard wavelength and spectral width such as to a standard ITU DWDM wavelength. Commonly used in DWDM systems.

**Transmittance, optical (T**,) The ratio of optical output power to input power for a fiber or component at a specific wavelength. It is the same as the optical power loss ratio,  $T_r = \frac{P_{out}}{P_{in}} = 10^{-\Gamma/10}$ .

**Ultra-dense wavelength division multiplexing (ultra-DWDM)** A DWDM technology where wavelength spacing is 25 GHz and less.

**Unit interval (UI)** One symbol length of the transmission rate. Also known as the period. UI = 1/R

**Vertical eye closure penalty** The vertical dimension of the eye pattern opening  $(A_0)$  as a ratio with OMA.

$$\text{VECP} = 10 \log \left(\frac{\text{OMA}}{A_0}\right)$$

**Wavelength, laser** Laser light with specific center frequency and spectral width. Center frequencies are ITU-T standard and can be seen in App. C.

**Wavelength division multiplexer (WDM)** A unit that can couple and decouple more than one optical wavelength ( $\lambda$ ) onto one optical fiber.

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**Wavelength division multiplexing (WDM)** A technology where two or more optical signals with different wavelengths are combined into one fiber and where two or more optical signals with different wavelengths are separated from one fiber into individual fibers.

**Wide-band WDM** A WDM that couples 1310 and 1550 nm wavelengths onto a fiber.

**Window, fiber** A range of wavelengths available for transmission in a fiber. Same as fiber band (O, E, S, C, or L band) or segment of a band.

**Xenpak** A compact optical transceiver that is a product of a multivendor consortium, which has defined the Xenpak multisource agreement (MSA) standard. They are available in five categories: 850 nm optics, 1310 nm optics, 1550 nm optics, DWDM, or CWDM optics. Xenpak data rate is 10 Gbps.

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## APPENDIX **B** Spreadsheet Format for OSNR Calculation

#### **B.1 EDFA OSNR Calculation**

The below three tables (Tables B.1, B.2, and B.3) use Eqs. (3.24) and (3.29) to determine final OSNR for one, two, or three EDFA links (if EDFAs and laser are the only noise sources in the link). If fiber links contain more than three EDFAs, follow the established format in Table B.3 and add the next EDFA stage (Table B.1) to the bottom of this table using the output OSNR of the previous EDFA calculation as input to the next EDFA OSNR.

Copy this table into a computer spreadsheet application. Then insert the formula from the equation column into the calculation column. Replace the variable names in the formula with the proper cell reference. To confirm the table works properly, use the input data shown, for example, in Sec. 3.1.

For the **Input OSNR** dB row, enter the laser source OSNR in the **Input Data** column if this is the first EDFA in the fiber link. Laser source OSNR due to SSE is available from the transceiver manufacturer. For a DFB laser, typical values range from 35 to 57 dB. If this EDFA follows a previous EDFA, then this cell should contain the output of the previous calculated EDFA's output OSNR.

For the **Input signal power** dB row, enter the signal power seen at the EDFA input in dBm units.

For the Noise figure, enter the EDFA's noise figure in dB units.

For **Channel bandwidth**, enter the RBW specified by the equipment manufacturer in the receiver specifications in Hz units. If it is 0.1 nm, then enter input data  $1.25 \times 10^{10}$  Hz or if it is 0.5 nm then enter input data  $6.239 \times 10^{10}$  Hz.

For the frequency of light, enter the frequency of the laser source in Hz units. Use  $1.25 \times 10^{10}$  Hz for a 1550.12 nm laser.
Description	Name	Equation	Input Data	Calculation	Unit
First EDFA					
Input OSNR	OSNRindB		57.00		
Input OSNR	OSNRin	= 10^(OSNRindB /10)		5.01187E+5	dB
Input signal power	PindB		-12.00		dBm
Input signal power	Pin	= 10^(PindB/10) /1000		6.30957E-5	watt
Noise figure	NF		5.00		dB
Noise factor	F	= 10^(NFdB/10)		3.16228E+00	
Channel bandwidth	Br		1.25000E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	$= F \times h \times f \times Br$		5.06550E-9	watt
Output OSNR	OSNRout	= 1/(1/OSNRin + FhfBr/Pin)		1.21539E+4	
Output OSNR	OSNRoutdB	= 10log (OSNRout)		40.85	dB

 TABLE B.1
 Single EDFA OSNR Calculation Table

The output OSNR calculation provides the OSNR at the output of the EDFA for the link. If the EDFA is the last EDFA (and last noise source) in the link, this is the final OSNR seen by the receiver.

Table B.1 can be used to calculate final OSNR if a single EDFA is in the optical link.

Table B.2 can be used to calculate final OSNR if two EDFAs are in the optical link.

Table B.3 can be used to calculate final OSNR if three EDFAs are in the optical link.

Description	Name	Equation	Input Data	Calculation	Unit
First EDFA					
Input OSNR	OSNRindB		57.00		dB
Input OSNR	OSNRin	= 10^(OSNRindB/10)		5.01187E+5	
Input signal power	PindB		-21.00		dBm
Input signal power	Pin	= 10^(PindB/10)/1000		7.94328E-6	watt
Noise figure	NFdB		5.00		dB
Noise factor	F	= 10^(NFdB/10)		3.16228E+00	
Channel bandwidth	Br		6.23900E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	$= F \times h \times f \times Br$		2.52829E-8	watt
Output OSNR	OSNRout	= 1/(1/OSNRin+FhfBr/Pin)		3.13979+2	
Output OSNR	OSNRoutdB	= 10 log(OSNRout)		24.97	dB

 TABLE B.2
 Two EDFA OSNR Calculation Table (Continued)

Description	Name	Equation	Input Data	Calculation	Unit
Second EDFA					
Input OSNR	OSNRindB		24.97		dB
Input OSNR	OSNRin	$= 10^{(OSNRindB/10)}$		3.13979E+2	
Input signal power	PindB		-21.00		dBm
Input signal power	Pin	$= 10^{(PindB/10)}/1000$		7.94328E-6	watt
Noise figure	NFdB		5.00		dB
Noise factor	F	= 10^(NFdB/10)		3.16228E+00	
Channel bandwidth	Br		6.23900E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	$= F \times h \times f \times Br$		2.52829E-8	watt
Output OSNR	OSNRout	= 1/(1/OSNRin+FhfBr/Pin)		1.57039E+2	
Output OSNR	OSNRoutdB	= 10 log(OSNRout)		21.96	dB

 TABLE B.2
 Two EDFA OSNR Calculation Table (Continued)

Description	Name	Equation	Input Data	Calculation	Unit
First EDFA					
Input OSNR	OSNRindB		57.00		dB
Input OSNR	OSNRin	$= 10^{OSNRindB/10}$		5.01187E+5	
Input signal power	PindB		-22.00		dBm
Input signal power	Pin	= 10^(PindB/10)/1000		6.30957E-6	watt
Noise figure	NFdB		5.00		dB
Noise factor	F	= 10^(NFdB/10)		3.16228E+00	
Channel bandwidth	Br		1.25000E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	$= F \times h \times f \times Br$		5.06550E-9	watt
Output OSNR	OSNRout	= 1/(1/OSNRin+FhfBr/Pin)		1.24251E+3	
Output OSNR	OSNRoutdB	= 10 log(OSNRout)		30.94	dB

 TABLE B.3
 Three EDFA OSNR Calculation Table (Continued)

Description	Name	Equation	Input Data	Calculation	Unit
Second EDFA					
Input OSNR	OSNRindB		30.94		dB
Input OSNR	OSNRin	= 10^(0SNRindB/10)		1.24251E+3	
Input signal power	PindB		-25.00		dBm
Input signal power	Pin	= 10^(PindB/10)/1000		3.16228E-6	watt
Noise figure	NFdB		5.00		dB
Noise factor	F	= 10^(NFdB/10)		3.16228E+00	
Channel bandwidth	Br		1.25000E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	$= F \times h \times f \times Br$		5.06550E-9	watt
Output OSNR	OSNRout	= 1/(1/OSNRin+FhfBr/Pin)		4.15511E+2	
Output OSNR	OSNRoutdB	= 10 log(OSNRout)		26.19	dB

Third EDFA					
Input OSNR	OSNRindB		26.19		dB
Input OSNR	OSNRin	$= 10^{(OSNRindB/10)}$		4.15511E+2	
Input signal power	PindB		-25.00		dBm
Input signal power	Pin	$= 10^{(PindB/10)}/1000$		3.16228E-6	Watt
Noise figure	NFdB		5.00		dB
Noise factor	F	$= 10^{(NFdB/10)}$		3.16228E+00	
Channel bandwidth	Br		1.25000E+10		Hz
Frequency of light	f		1.93400E+14		Hz
Planck's constant	h		6.62607E-34		Js
Pase/G	FhfBr	= F × h × f × Br		5.06550E-9	Watt
Output OSNR	OSNRout	= 1/(1/OSNRin+FhfBr/Pin)		2.49468E+2	
Output OSNR	OSNRoutdB	= 10 log(OSNRout)		23.97	dB

 TABLE B.3
 Three EDFA OSNR Calculation Table (Continued)

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# APPENDIX **C** WDM Channel Assignments

# C.1 Fiber Bands

Fiber spectrum is divided into six bands as shown in Table C.1.

Band	Description	Wavelength Range (nm)
850	Multimode window	800 to 910
0	Original	1260 to 1360
E	Extended	1360 to 1460
S	Short wavelengths	1460 to 1530
С	Conventional (EDFA window)	1530 to 1565
L	Long wavelengths (extended EDFA window)	1565 to 1625
U	Ultra long wavelengths	1625 to 1675

 TABLE C.1
 ITU-T Fiber Bands<sup>1</sup> (Windows)

## C.1.1 Band Descriptions

850 band "Multimode window"	This band is used only for multimode fiber transmission.
O band "Original"	This is the first band used for single- mode fiber communications. It is cur- rently popular because of the lower cost of optics for this band. It has higher attenuation than C-Band and therefore is only used for short span.

E band "Extended"	This band is affected by higher attenu- ation due to water (OH) molecule absorption peak at 1383 nm. This prob- lem is overcome by newer "full spec- trum" fiber that meets standard ITU-T G.652.c/d. It is used when 16-channel CWDM systems are deployed. If non "full spectrum" fiber use, fiber link loss should be measured at each CWDM channel to ensure total link loss does not exceed equipment optical budget.
S band "Short wavelength"	This band extends C-band DWDM chan- nel assignments for large channel count systems. Also, it is used by many sys- tems for the optical supervisory channel (OSC).
C band "Conventional"	This band is used for most DWDM communications and all standard 1550 transceivers. EDFAs are designed to amplify all channels in this band. Selected EDFA can extend amplification into S and L bands.
L band "Long wavelength"	This band extends C-band DWDM chan- nel assignments for large channel count systems.
U band "Ultra long wavelength"	This band extends L band; however, it may not be usable for traffic in some fibers.

# C.2 WDM Channel Assignments

The below table was constructed from ITU-T WDM channel assignments.<sup>2,3</sup> Note, channels are defined in frequency units. Channel center wavelengths are calculated for free space propagation using  $\lambda = c/f$ , where the speed of light c = 299,792,458 m/s. Frequencies and wavelengths shown in these charts are nominal channel center frequencies and wavelengths.

ITU-T 100 and 200 GHz DWDM Grid								Industry Assign	Typical ments <sup>‡</sup>		
	Ba	ind	Chan. No.†	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	8- chan.	16- chan.	32- chan.	44- chan.
	s		73	197.30	1519.48	x	x				
			72	197.20	1520.25	x					
			71	197.10	1521.02	x	x				
			70	197.00	1521.79	x					
			69	196.90	1522.56	x	x				
			68	196.80	1523.34	x					
			67	196.70	1524.11	x	x				
			66	196.60	1524.89	x					
			65	196.50	1525.66	x	x				
			64	196.40	1526.44	x					
			63	196.30	1527.22	x	x				
			62	196.20	1527.99	x					
			61	196.10	1528.77	x	x				
			60	196.00	1529.55	x					
			59	195.90	1530.33	x	x				x
			58	195.80	1531.12	x				x	x
			57	195.70	1531.90	x	x		x	x	x
			56	195.60	1532.68	x				x	x
			55	195.50	1533.47	x	x		x	x	x
			54	195.40	1534.25	x				x	x
		e*	53	195.30	1535.04	x	x		x	x	x
e B			52	195.20	1535.82	x				x	x
Rang	~	B	51	195.10	1536.61	x	x		x	x	x
DFA			50	195.00	1537.40	x				x	x
			49	194.90	1538.19	x	x		x	x	x
			48	194.80	1538.98	x				x	x
			47	194.70	1539.77	x	x		x	x	x
			46	194.60	1540.56	x				x	x
			45	194.50	1541.35	x	x		x	x	x
			44	194.40	1542.14	x				x	x
			43	194.30	1542.94	x	x		x	x	x
			42	194.20	1543.73	x					x

ITU-T 100 and 200 GHz DWDM Grid								Industry Assign	Typical ments <sup>‡</sup>	l	
	Ba	and	Chan. No.†	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	8- chan.	16- chan.	32- chan.	44- chan.
			41	194.10	1544.53	x	x				x
			40	194.00	1545.32	x					x
			39	193.90	1546.12	x	x				x
			38	193.80	1546.92	x					x
			37	193.70	1547.72	x	x	x	x	x	x
			36	193.60	1548.51	x				x	x
			35	193.50	1549.32	x	x	x	x	x	x
			34	193.40	1550.12	x				x	x
			33	193.30	1550.92	x	x	x	x	x	x
			32	193.20	1551.72	x				x	x
			31	193.10	1552.52	x	x	x	x	x	x
ge		*	30	193.00	1553.33	x				x	x
Ran	C	Red	29	192.90	1554.13	x	x	x	x	x	x
DFA			28	192.80	1554.94	x				x	x
			27	192.70	1555.75	x	x	x	x	x	x
			26	192.60	1556.55	x				x	x
			25	192.50	1557.36	x	x	x	x	x	x
			24	192.40	1558.17	x				x	x
			23	192.30	1558.98	x	x	x	x	x	x
			22	192.20	1559.79	x				x	x
			21	192.10	1560.61	x	x				x
			20	192.00	1561.42	x					x
			19	191.90	1562.23	x	x				x
			18	191.80	1563.05	x					x
			17	191.70	1563.86	x	x				x
			16	191.60	1564.68	x					x
			15	191.50	1565.50	x	x				
			14	191.40	1566.31	x					
			13	191.30	1567.13	x	x				
			12	191.20	1567.95	x					
			11	191.10	1568.77	x	x				

 TABLE C.2
 ITU-T 100 and 200 GHz DWDM Grid (Continued)

		10	191.00	1569.59	x			
		9	190.90	1570.42	x	x		
		8	190.80	1571.24	x			
		7	190.70	1572.06	x	x		
		6	190.60	1572.89	x			
		5	190.50	1573.71	x	x		
		4	190.40	1574.54	x			
		3	190.30	1575.37	x	x		
		2	190.20	1576.20	x			
		1	190.10	1577.03	x	x		
		0	190.00	1577.86	x			
			189.90	1578.69	x	x		
			189.80	1579.52	x			
			189.70	1580.35	x	x		
ge			189.60	1581.18	x			
Ran			189.50	1582.02	x	x		
DFA			189.40	1582.85	x			
nd E			189.30	1583.69	x	x		
L-Ba			189.20	1584.53	x			
ded			189.10	1585.36	x	x		
(ten			189.00	1586.20	x			
ш			188.90	1587.04	x	x		
			188.80	1587.88	x			
			188.70	1588.73	x	x		
			188.60	1589.57	x			
			188.50	1590.41	x	x		
			188.40	1591.26	x			
			188.30	1592.10	х	x		
			188.20	1592.95	x			
			188.10	1593.79	x	x		
			188.00	1594.64	x			
			187.90	1595.49	x	x		
			187.80	1596.34	x			
			187.70	1597.19	x	x		
			187.60	1598.04	x			

	I	TU-T 10	0 and 200		Industry Assign	<sup>7</sup> Typical ments <sup>‡</sup>				
Ba	nd	Chan. No.†	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	8- chan.	16- chan.	32- chan.	44- chan.
			187.50	1598.89	x	x				
			187.40	1599.75	x					
			187.30	1600.60	x	x				
			187.20	1601.46	x					
			187.10	1602.31	x	x				
			187.00	1603.17	x					
			186.90	1604.03	x	x				

\*Red (upstream traffic) and Blue (downstream traffic) bands are not standardized and limits can vary.

<sup>†</sup>Channel numbering is not standardized and can vary among manufacturers. <sup>‡</sup>Not ITU-T assignments.

TABLE C.2 ITU-T 100 and 200 GHz DWDM Grid (Continued)

	ITU-T 5	60 GHz Channel Spacin	ng Grid	
Band	Chan. No.*	Center Freq. (THz)	Center Wave. (nm)	
С	59.0	195.90	1530.33	
	58.5	195.85	1530.72	
	58.0 195.80		1531.12	
	57.5	195.75	1531.51	
	57.0 195.70		1531.90	
	56.5	195.65	1532.29	
	56.0	195.60	1532.68	
	55.5	195.55	1533.07	
	55.0	195.50	1533.47	
	54.5	195.45	1533.86	
	54.0	195.40	1534.25	
	53.5	195.35	1534.64	
	53.0	195.30	1535.04	

	52.5	195.25	1535.43	
	52.0	195.20	1535.82	
	51.5	195.15	1536.22	
	51.0	195.10	1536.61	
	50.5	195.05	1537.00	
	50.0	195.00	1537.40	
	49.5	194.95	1537.79	
	49.0	194.90	1538.19	
	48.5	194.85	1538.58	
	48.0	194.80	1538.98	
	47.5	194.75	1539.37	
	47.0	194.70	1539.77	
С	46.5	194.65	1540.16	
	46.0	194.60	1540.56	
	45.5	194.55	1540.95	
	45.0	194.50	1541.35	
	44.5	194.45	1541.75	
	44.0	194.40	1542.14	
	43.5	194.35	1542.54	
	43.0	194.30	1542.94	
	42.5	194.25	1543.33	
	42.0	194.20	1543.73	
	41.5	194.15	1544.13	
	41.0	194.10	1544.53	
	40.5	194.05	1544.92	
	40.0	194.00	1545.32	
	39.5	193.95	1545.72	
	39.0	193.90	1546.12	
	38.5	193.85	1546.52	
	38.0	193.80	1546.92	
	37.5	193.75	1547.32	
	37.0	193.70	1547.72	
	36.5	193.65	1548.11	

TABLE C.3
 (Continued)

	ITU-T 5	0 GHz Channel Spacin	g Grid		
Band	Chan. No.*	Center Freq. (THz)	Center Wave. (nm)		
	36.0	193.60	1548.51		
	35.5	193.55	1548.91		
	35.0	193.50	1549.32		
	34.5	193.45	1549.72		
	34.0	193.40	1550.12		
	33.5	193.35	1550.52		
	33.0	193.30	1550.92		
	32.5	193.25	1551.32		
	32.0	193.20	1551.72		
	31.5	193.15	1552.12		
	31.0	193.10	1552.52		
	30.5	193.05	1552.93		
С	30.0	193.00	1553.33		
	29.5	192.95	1553.73		
	29.0	192.90	1554.13		
	28.5	192.85	1554.54		
	28.0	192.80	1554.94		
	27.5	192.75	1555.34		
	27.0	192.70	1555.75		
	26.5	192.65	1556.15		
	26.0	192.60	1556.55		
	25.5	192.55	1556.96		
	25.0	192.50	1557.36		
	24.5	192.45	1557.77		
	24.0	192.40	1558.17		
	23.5	192.35	1558.58		
	23.0	192.30	1558.98		
	22.5	192.25	1559.39		
	22.0	192.20	1559.79		
	21.5	192.15	1560.20		
	21.0	192.10	1560.61		

TABLE C.3
 ITU-T 50 GHz DWDM Grid (Continued)

	20.5	192.05	1561.01
	20.0	192.00	1561.42
	19.5	191.95	1561.83
	19.0	191.90	1562.23
	18.5	191.85	1562.64
	18.0	191.80	1563.05
	17.5	191.75	1563.45
	17.0	191.70	1563.86
	16.5	191.65	1564.27
	16.0	191.60	1564.68
L	15.5	191.55	1565.09
	15.0	191.50	1565.50
	14.5	191.45	1565.90
	14.0	191.40	1566.31
	13.5	191.35	1566.72
	13.0	191.30	1567.13
	12.5	191.25	1567.54
	12.0	191.20	1567.95
	11.5	191.15	1568.36
	11.0	191.10	1568.77
	10.5	191.05	1569.18
	10.0	191.00	1569.59
	9.5	190.95	1570.01
	9.0	190.90	1570.42
	8.5	190.85	1570.83
	8.0	190.80	1571.24
	7.5	190.75	1571.65
	7.0	190.70	1572.06
	6.5	190.65	1572.48
	6.0	190.60	1572.89
	5.5	190.55	1573.30
	5.0	190.50	1573.71
	4.5	190.45	1574.13

 TABLE C.3
 (Continued)

	ITU-T 50 GHz Channel Spacing Grid										
Band	Chan. No.*	Center Freq. (THz)	Center Wave. (nm)								
	4.0	190.40	1574.54								
	3.5	190.35	1574.95								
	3.0	190.30	1575.37								
	2.5	190.25	1575.78								
	2.0	190.20	1576.20								
	1.5	190.15	1576.61								
	1.0	190.10	1577.03								
	0.5	190.05	1577.44								
	0.0	190.00	1577.86								

\*Channel numbering is not standardized and can vary among manufacturers.

TABLE C.3 ITU-T 50 GHz DWDM Grid (Continued	)
---	---

CWDM Channel Spacing Grid									
Chan. No.†	Nominal Center Wavelength	4- Chan.	8- Chan.	16- Chan.	18- Chan.	Note			
27	1271				x	May not be usable due to single-mode cutoff wavelength, or have high loss.			
29	1291				х				
31	1311			x	x				
33	1331			x	x				
35	1351			x	x	This channel may suffer from higher loss due to water peak.*			
37	1371			x	x	This channel may suffer from higher loss due to water peak.*			
39	1391			x	x	This channel may suffer from higher loss due to water peak.*			
41	1411			x	x	This channel may suffer from higher loss due to water peak.*			
43	1431			x	x	This channel may suffer from higher loss due to water peak.*			

 TABLE C.4
 CWDM Channels (Continued)

	CWDM Channel Spacing Grid									
Chan. No.†	Nominal Center Wavelength	4- Chan.	8- Chan.	16- Chan.	18- Chan.	Note				
45	1451			x	x	This channel may suffer from higher loss due to water peak.*				
47	1471		x	x	x	Typical eight wavelengths used in 8-channel CWDM systems.				
49	1491		x	х	х					
51	1511		x	x	x					
53	1531		x	x	х					
55	1551	х	x	х	x					
57	1571	х	x	х	x					
59	1591	х	х	х	x					
61	1611	x	x	x	x					

\*CWDM channels 1351 to 1451 may suffer from higher fiber attenuation due to water peak at approximately 1383 nm. Full-spectrum fiber, ITU-T G.652. c/d, does not suffer from this effect.

<sup>+</sup>Channel numbering is not standardized and can vary among manufacturers.

### TABLE C.4 CWDM Channels

			TU-T 10	00 and 200 GH	z DWDM Grid			CWDM
EDFA	Bar	nd	Chan. No.*	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	Passband ±6.5 nm Channel
			73	197.30	1519.48	x	x	
			72	197.20	1520.25	x		
			71	197.10	1521.02	x	x	
			70	197.00	1521.79	x		
			69	196.90	1522.56	x	x	
			68	196.80	1523.34	x		
	c		67	196.70	1524.11	x	x	
	3		66	196.60	1524.89	x		1531
			65	196.50	1525.66	x	x	1531
			64	196.40	1526.44	x		1531
			63	196.30	1527.22	x	x	1531
			62	196.20	1527.99	x		1531
			61	196.10	1528.77	x	x	1531
			60	196.00	1529.55	x		1531
			59	195.90	1530.33	x	x	1531
			58	195.80	1531.12	x		1531
			57	195.70	1531.90	x	x	1531
			56	195.60	1532.68	x		1531
			55	195.50	1533.47	x	x	1531
nge			54	195.40	1534.25	x		1531
A Ra			53	195.30	1535.04	x	x	1531
EDF/	0	å	52	195.20	1535.82	x		1531
cal E	C	Blu	51	195.10	1536.61	x	x	1531
Typic			50	195.00	1537.40	x		
			49	194.90	1538.19	x	x	
			48	194.80	1538.98	x		
			47	194.70	1539.77	x	x	
			46	194.60	1540.56	x		
			45	194.50	1541.35	x	x	
			44	194.40	1542.14	x		

TABLE C.5 CWDM Passband on DWDM Grid

		I	TU-T 10	00 and 200 GH	z DWDM Grid			CWDM
EDFA	Band		Chan. No.*	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	Passband ±6.5 nm Channel
			43	194.30	1542.94	x	x	
			42	194.20	1543.73	x		
			41	194.10	1544.53	x	x	
			40	194.00	1545.32	x		1551
			39	193.90	1546.12	x	x	1551
			38	193.80	1546.92	x		1551
			37	193.70	1547.72	x	x	1551
			36	193.60	1548.51	x		1551
			35	193.50	1549.32	x	x	1551
			34	193.40	1550.12	x		1551
			33	193.30	1550.92	x	x	1551
			32	193.20	1551.72	x		1551
			31	193.10	1552.52	x	x	1551
		~	30	193.00	1553.33	x		1551
		Sed	29	192.90	1554.13	x	x	1551
			28	192.80	1554.94	x		1551
			27	192.70	1555.75	x	x	1551
			26	192.60	1556.55	x		1551
			25	192.50	1557.36	x	x	1551
			24	192.40	1558.17	x		
			23	192.30	1558.98	x	x	
			22	192.20	1559.79	x		
			21	192.10	1560.61	x	x	
			20	192.00	1561.42	x		
			19	191.90	1562.23	x	x	
			18	191.80	1563.05	x		
			17	191.70	1563.86	x	x	
			16	191.60	1564.68	x		1571
			15	191.50	1565.50	x	x	1571
			14	191.40	1566.31	x		1571

 TABLE C.5
 CWDM Passband on DWDM Grid (Continued)

							1
		13	191.30	1567.13	x	x	1571
		12	191.20	1567.95	x		1571
		11	191.10	1568.77	x	x	1571
		10	191.00	1569.59	x		1571
		9	190.90	1570.42	x	x	1571
		8	190.80	1571.24	x		1571
		7	190.70	1572.06	x	x	1571
		6	190.60	1572.89	x		1571
		5	190.50	1573.71	x	x	1571
		4	190.40	1574.54	x		1571
		3	190.30	1575.37	x	x	1571
		2	190.20	1576.20	x		1571
Ð		1	190.10	1577.03	x	x	1571
ang		0	190.00	1577.86	x		
A R			189.90	1578.69	x	x	
EDF			189.80	1579.52	x		
bne	L		189.70	1580.35	x	x	
L-Ba			189.60	1581.18	x		
led			189.50	1582.02	x	x	
tenc			189.40	1582.85	x		
EXt			189.30	1583.69	x	x	
			189.20	1584.53	x		
			189.10	1585.36	x	x	1591
			189.00	1586.20	x		1591
			188.90	1587.04	x	x	1591
			188.80	1587.88	x		1591
			188.70	1588.73	x	x	1591
			188.60	1589.57	x		1591
			188.50	1590.41	x	x	1591
			188.40	1591.26	x		1591
			188.30	1592.10	x	x	1591
			188.20	1592.95	x		1591
			188.10	1593.79	x	x	1591
			188.00	1594.64	x		1591

TABLE C.5 (Continued)

ITU-T 100 and 200 GHz DWDM Grid					CWDM		
EDFA Band No.*		Chan. No.*	Center Freq. (THz)	Center Wave. (nm)	100 GHz	200 GHz	Passband ±6.5 nm Channel
			187.90	1595.49	x	x	1591
			187.80	1596.34	x		1591
			187.70	1597.19	x	x	1591
			187.60	1598.04	x		
			187.50	1598.89	x	x	
			187.40	1599.75	x		
			187.30	1600.60	x	x	
			187.20	1601.46	x		
			187.10	1602.31	x	x	
			187.00	1603.17	x		
			186.90	1604.03	x	x	

\*Red (upstream  $\lambda)$  and Blue (downstream  $\lambda)$  bands are not standardized and limits can vary.

TABLE C.5 CWDM Passband on DWDM Grid (Continued)

## References

- 1. ITU-T Series G Supplement 39, "Optical system design and engineering considerations," International Telecommunications Union, Jan. 2006.
- ITU-T G.692, "Optical interfaces for multichannel systems with optical amplifiers," International Telecommunications Union, Annex A, Oct. 1998.
- ITU-T G.694.1, "Spectral grids for WDM applications: DWDM frequency grid," International Telecommunications Union, Annex A, Jun. 2002.

# APPENDIX **D** Useful Formulae

# D.1 Spectral Width Conversion between Wavelength and Frequency Units

Given spectral bandwidth in frequency units (GHz), the below equations can be used to convert to wavelength units (nm), see Fig. D.1.

$$\lambda_c = \frac{c}{f_c} \tag{D.1}$$

$$\Delta \lambda = c \times \left(\frac{1}{f_1} - \frac{1}{f_2}\right) \tag{D.2}$$

$$\Delta \lambda = c \times \left( \frac{1}{f_c - \delta f} - \frac{1}{f_c + \delta f} \right)$$
(D.3)

$$\Delta \lambda = 2c \times \left(\frac{1}{2f_c - \Delta f} - \frac{1}{2f_c + \Delta f}\right) \tag{D.4}$$

Given spectral bandwidth in wavelength units (nm), the below equations can be used to convert to frequency units (GHz), see Fig. D.1.

$$\Delta f = c \times \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \tag{D.5}$$

$$\Delta f = 2c \times \left(\frac{1}{2\lambda_c - \Delta\lambda} - \frac{1}{2\lambda_c + \Delta\lambda}\right)$$
(D.6)

An approximation for the above relationship can be used as shown in Eq. (D.8) by expanding the equation  $\lambda = c/f$  in a Taylor series.

$$\lambda_1 - \lambda_2 = \Delta \lambda \approx \frac{\lambda_c^2 (f_1 - f_2)}{c}$$
(D.7)

$$\Delta \lambda \approx \frac{\lambda_c^2}{c} \Delta f \tag{D.8}$$

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where c = speed of light in a vacuum, m/s

- $\lambda_c$  = center wavelength of the spectral width, nm
- $\delta\lambda$  = half optical signal spectral width, where  $\delta\lambda = \Delta\lambda/2$ , nm
- $\Delta \lambda$  = optical signal spectral width, nm
  - $f_c$  = center frequency of the spectral width, GHz
- $\delta f$  = half optical signal spectral width, where  $\delta f = \Delta f/2$ , GHz
- $\Delta f$  = optical signal spectral width, GHz

Table D.1 shows common wavelength to frequency conversions.

Spectral Width or Optical Bandwidth $(\Delta\lambda \text{ or } B_o)$ Centered at 1550 nm			
nm (pm)	GHz		
0.01 (10)	1.25		
0.02 (20)	2.5		
0.05 (50)	6.24		
0.1 (100)	12.5		
0.2 (200)	25.0		
0.4 (400)	50		
0.5 (500)	62.4		
0.8 (800)	100		
1.0 (1000)	125		
1.6 (1600)	200		
2.0 (2000)	250		
3.2 (3200)	400		



## D.2 Summation of Channel Optical Power in a WDM

To determine aggregate optical power of a WDM, two methods can be used. If the WDM input power of each channel is the same, then the output power will double (add 3 dB) every time the channel count doubles. For example, if an 8-channel DWDM has four active input channels and each channel's input power is 0 dBm, then the WDM aggregate output power would be +6 dBm less the WDM insertion loss. If the channel insertion loss is 2 dB then the output would be +4 dBm, see Table D.2.

If the WDM input channel powers are not identical, then the input powers need to be converted to milliwatts, summed, and then converted back to dBm units. To convert from dBm units to milliwatts use Eq. (D.9). Sum all channel powers using Eq. (D.10).

$$W = 10^{P/10}$$
 (D.9)

$$W_{\text{total}} = W_1 + W_2 + W_3 \cdots$$
 (D.10)

To convert optical power in mW back to dBm units use Eq. (D.11).

$$P = 10 \log W \tag{D.11}$$

where W = optical power, mW P = is optical power, dBm

Finally, subtract the WDM insertion loss to determine the WDM aggregate output power output, see the example in Table D.3.

Number of Channels	Channel Input Power (dBm)	Insertion Loss (dB)	Aggregate Output (dBm)
1	0	2	-2
2	0	2	+1
4	0	2	+4
8	0	2	+7
16	0	2	+10
32	0	2	+13

 
 TABLE D.2
 WDM Aggregate Output Power with Equal Channel Inputs Example

Channel Number	Channel Input Power (dBm)	Channel Input Power (mW)	Insertion Loss (dB)	Cumulative Aggregate Output (dBm)
1	0	1.0	2	-2.0
2	-2	0.631	2	0.12
3	+3	2.0	2	3.60
4	-1	0.794	2	4.46
5	-4	0.398	2	4.83
6	+4	2.512	2	6.65

 TABLE D.3
 WDM Aggregate Output Power with Unequal Channel Inputs Example

## **D.3** Chromatic Dispersion Coefficient Calculation

Given zero dispersion slope, zero dispersion wavelength, and operating wavelength, the chromatic dispersion coefficient can be estimated using Eq. (D.12) for G.652 fiber.<sup>1</sup>

$$CD_{c} \approx \frac{S_{0}}{4} \left[ \lambda - \frac{\lambda_{0}^{4}}{\lambda^{3}} \right]$$
(D.12)

where  $CD_c$  = chromatic dispersion, ps/(nm · km)

 $S_0 = \text{zero dispersion slope, } ps/(nm^2 \cdot km)$ 

 $\lambda_0$  = zero dispersion wavelength, nm

 $\lambda$  = operating wavelength, where 1200 nm  $\leq \lambda \leq$  1600 nm, nm

## Reference

1. ITU-T G.652, "Characteristics of single-mode optical fiber and cable," International Telecommunications Union, June 2005.

# APPENDIX **E** Gaussian Pulse Characteristics

## E.1 Gaussian Pulse

A Gaussian pulse distribution can be defined by Eq. (E.1), see Fig E.1.

$$E(t) = \sqrt{P_o} \exp\left(-\frac{1}{2} \left(\frac{t}{T_{\rm HWEM}}\right)^2\right)$$
(E.1)

$$P(t) = P_0 \exp\left(-\left(\frac{t}{T_{\text{HWEM}}}\right)^2\right)$$
(E.2)

$$\sigma = \frac{1}{\sqrt{2}} T_{\rm HWEM} \tag{E.3}$$

$$\sigma = \frac{1}{2\sqrt{2\ln 2}} T_{\rm FWHM} \tag{E.4}$$

$$T_{\rm FWHM} = (2\sqrt{\ln 2})T_{\rm HWEM} \tag{E.5}$$

where E(t) = pulse's electric field amplitude (voltage), V/m  $P_o = \text{pulse's optical peak power, W}$  t = time, s  $\sigma = \text{RMS width of the pulse's optical power, s}$   $T_{\text{HWEM}} = \text{half pulse width at 1/e optical power point, s}$   $T_{\text{FWHM}} = \text{full pulse width at half maximum optical power point}$ (-3 dB), s



FIGURE E.1 Gaussian pulse.

# 

# **Relevant Standards**

GR-253-CORE Synchronous optical network (SONET) transport system

GR-761-CORE Generic criteria for chromatic dispersion test sets

GR-2854-CORE Generic requirements for fiber optic dispersion compensators

IEC 60793-1-1 Optical fibers—part 1–1: Generic specification—general

IEC 60793-1-42 Optical fibers—part 1–42: Measurement methods and test procedures—chromatic dispersion

IEC 61280-4 Fiber optic communication subsystem test procedures—Part 4–1: Cable plant and links

IEC 61281-1 Fiber optic communication subsystems—Part 1: Generic specification

IEC 61744 Calibration of fiber optic chromatic dispersion test sets ITU-T G.650 Definition and test methods for the relevant parameters of single-mode fibers

ITU-T G.652 Characteristics of a single-mode optical fiber cable

ITU-T G.653 Characteristics of a dispersion-shifted single-mode optical fiber cable

ITU-T G.655 Characteristics of a non-zero dispersion-shifted single-mode optical fiber cable

TIA/EIA FOTP-168 Chromatic dispersion measurement of multimode graded-index and single-mode optical fibers by spectral group delay measurement in the time domain

TIA/EIA FOTP-169 Chromatic dispersion measurement of singlemode optical fibers by the phase-shift method

TIA/EIA FOTP-175 Chromatic dispersion measurement of singlemode optical fibers by the differential phase-shift method This page intentionally left blank

# APPENDIX **G** Common Units, Powers, Constants, and Transmission Rates

# G.1 Units

Unit	Symbol	Measurement
meter	m	length
gram	g	mass
volt	V	voltage
ohm	Ω	resistance
ampere	А	current
coulomb	С	charge
watt	W	power
joule	J	energy
farad	F	capacitance
second	S	time
Celsius	С	temperature
kelvin	K	temperature
bit	b	pulse
byte	byte	8 bits

# G.2 Powers of 10 Symbols

Factor	Symbol	Name
10-18	а	atto
10-15	f	femto
10-12	р	pico
10-10	Å	angstrom
10-9	n	nano
10-6	μ	micro
10-3	m	milli
10-2	С	centi
10-1	d	deci
10+1	da	deca
10+2	h	hecto
10+3	k	kilo
10+6	М	mega
10+9	G	giga
10+12	Т	tera
10+15	Р	peta
10+18	E	exa

# G.3 Physical Constants

Speed of light in a vacuum	<i>c</i> = 299792458 m/s
Planck's constant	$h = 6.626069 \times 10^{-34} \text{ J} \cdot \text{s} (\text{J/Hz})$
Boltzmann's constant	$k = 1.38 \times 10^{-23} \text{ J/K}$
Electron charge	$e = -1.6 \times 10^{-19} \text{ C}$

# G.4 Digital Transmission Rates

Designation	Data Rate	Voice Channels (64 kbps)
DS0	64 kbps	1
FT1	(1 to 24) $ imes$ 64 kbps	1 to 24
T1-DS1	1.544 Mbps	24
T2-DS2	6.312 Mbps	96
T3-DS3	44.736 Mbps	672
T4-DS4	274.175 Mbps	4032

## G.5 SONET/SDH Transmission Rates

SONET Optical Carrier Level	SONET Frame Format	SDH Frame Format	Payload Bandwidth (Mbps)	Transmission Rate (Mbps)
n/a	VT1.5	n/a	1.544	1.728
0C-1	STS-1	STM-0	48.96	51.84
0C-3	STS-3	STM-1	150.336	155.52
0C-12	STS-12	STM-4	601.344	622.08
0C-48	STS-48	STM-16	2405.376	2488.32
0C-192	STS-192	STM-64	9621.504	9953.28
0C-768	STS-768	STM-256	38486.016	39813.12

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