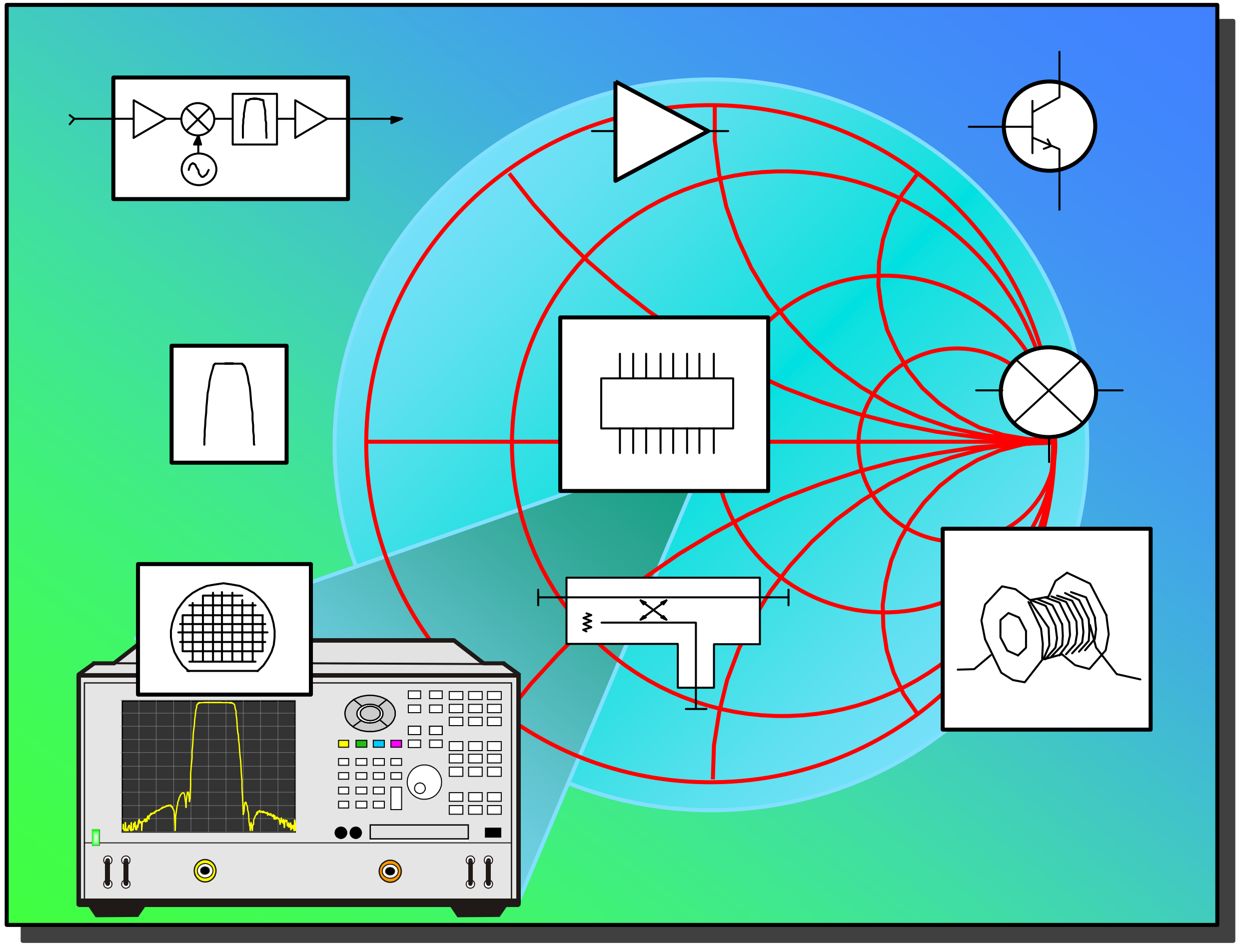
Network Analyzer Basics



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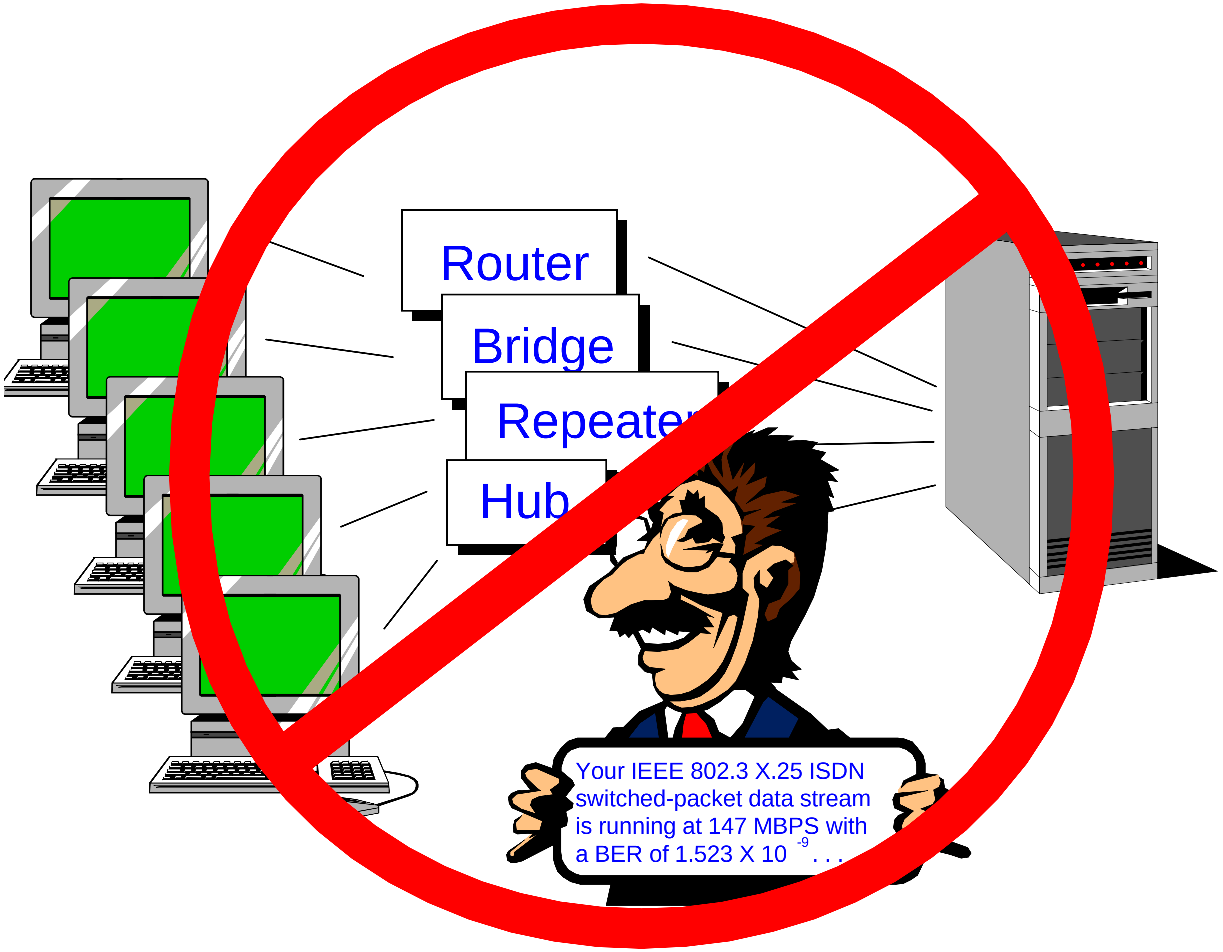
Network Analysis is NOT....



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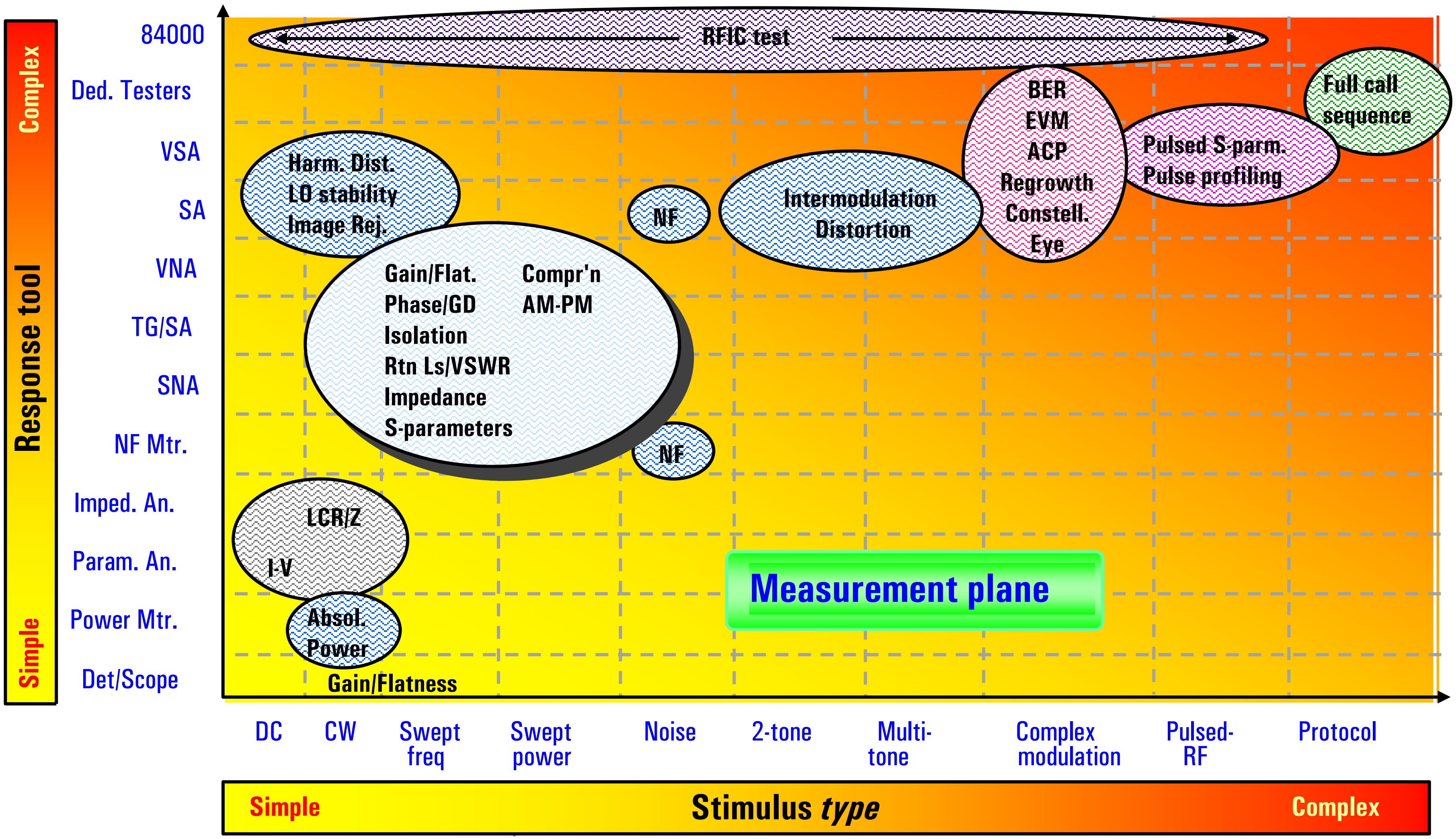
What Types of Devices are Tested?

Device Test Measurement Model



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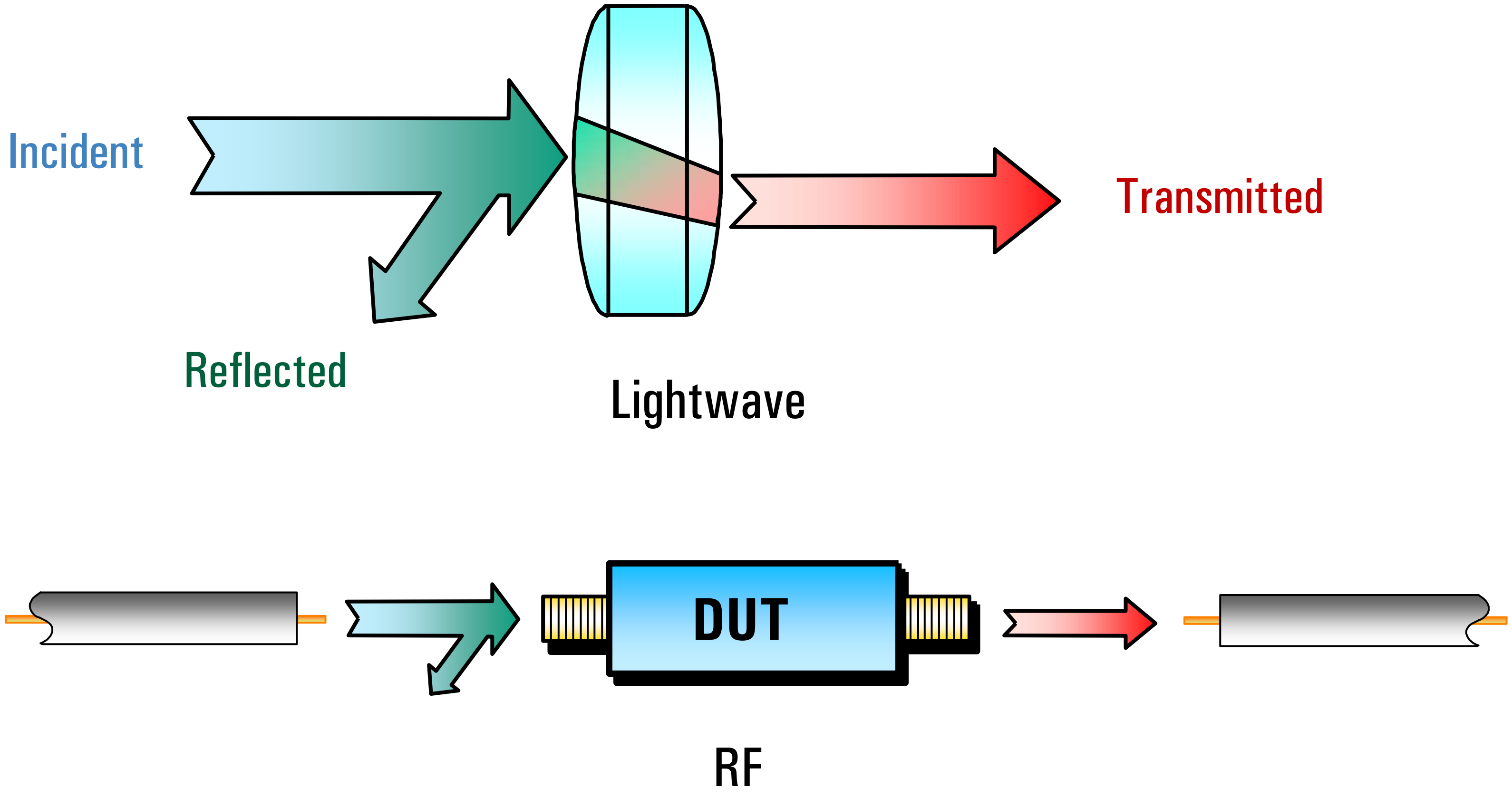
Lightwave Analogy to RF Energy



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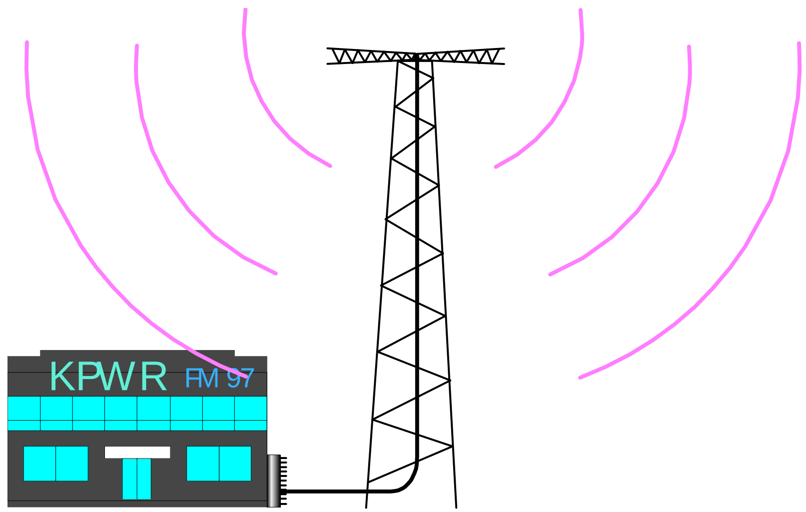
Why Do We Need to Test Components?

- Verify specifications of "building blocks" for more complex RF systems
- Ensure distortionless transmission of communications signals

  - linear: constant amplitude, linear phase / constant group delay
  - nonlinear: harmonics, intermodulation, compression, AM-to-PM conversion
- Ensure good match when absorbing power (e.g., an antenna)



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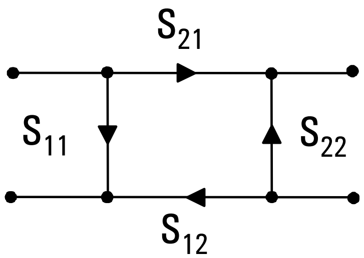
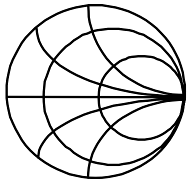
The Need for Both Magnitude and Phase

1. Complete characterization of linear networks

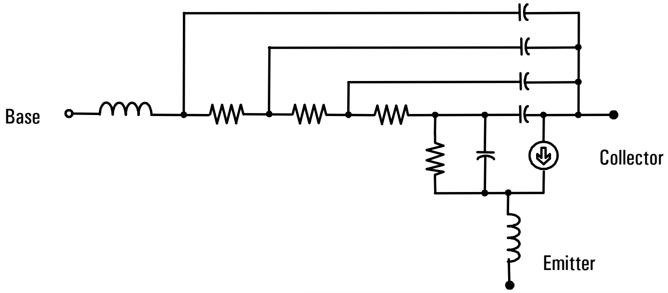


2. Complex impedance needed to design matching circuits

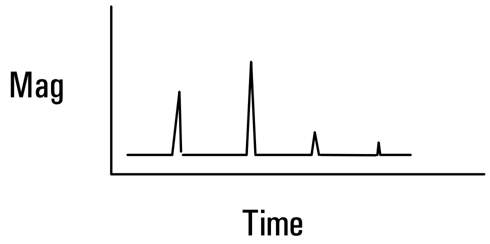


3. Complex values needed for device modeling

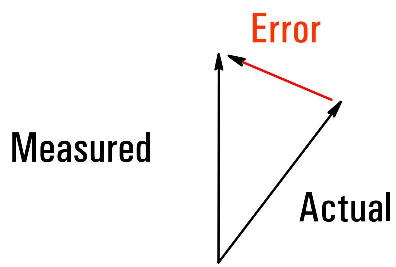
High-frequency transistor model



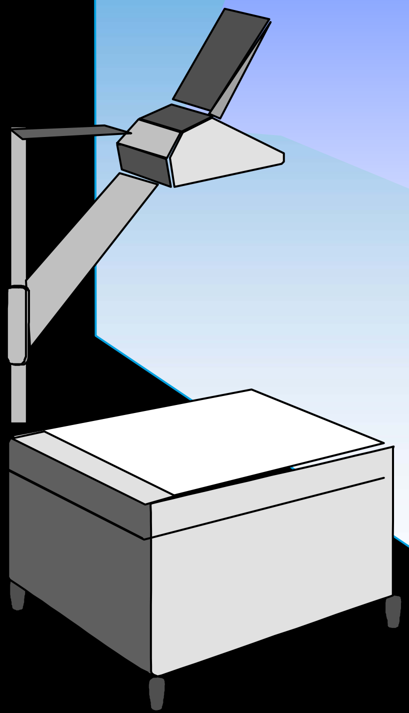
4. Time-domain characterization



5. Vector-error correction

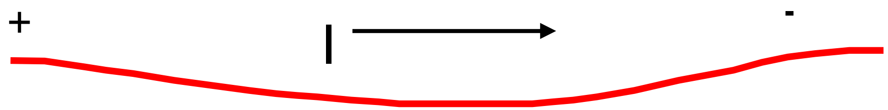


Agenda



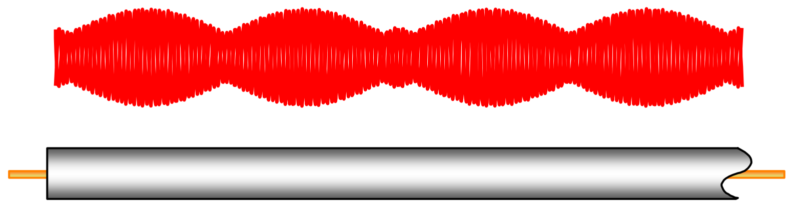
- **What measurements do we make?**
  - Transmission-line basics
  - Reflection and transmission parameters
  - S-parameter definition
- **Network analyzer hardware**
  - Signal separation devices
  - Detection types
  - Dynamic range
  - T/R versus S-parameter test sets
- **Error models and calibration**
  - Types of measurement error
  - One- and two-port models
  - Error-correction choices
  - Basic uncertainty calculations
- **Example measurements**
- **Appendix**

Transmission Line Basics



Low frequencies

- wavelengths > > wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

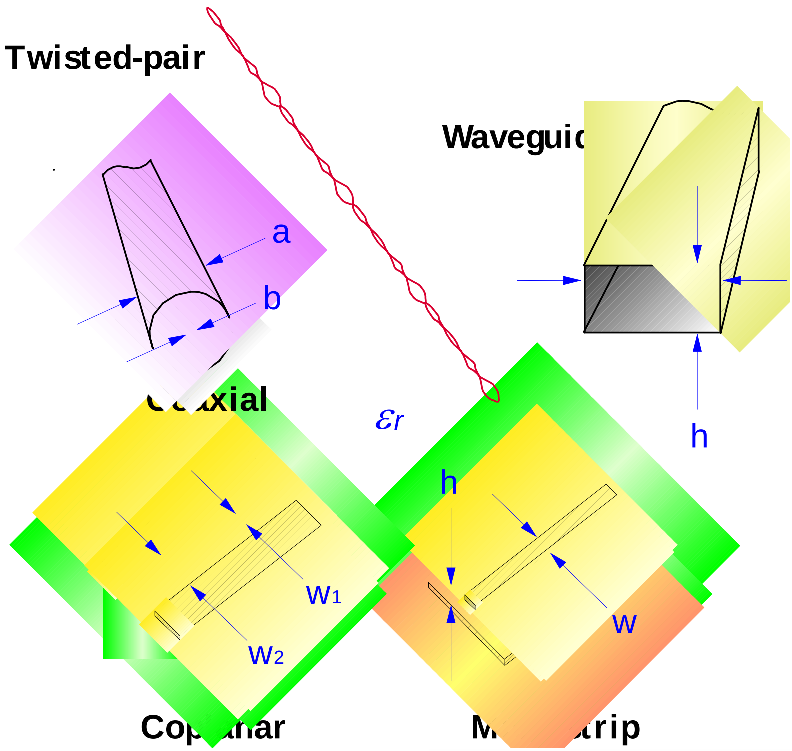


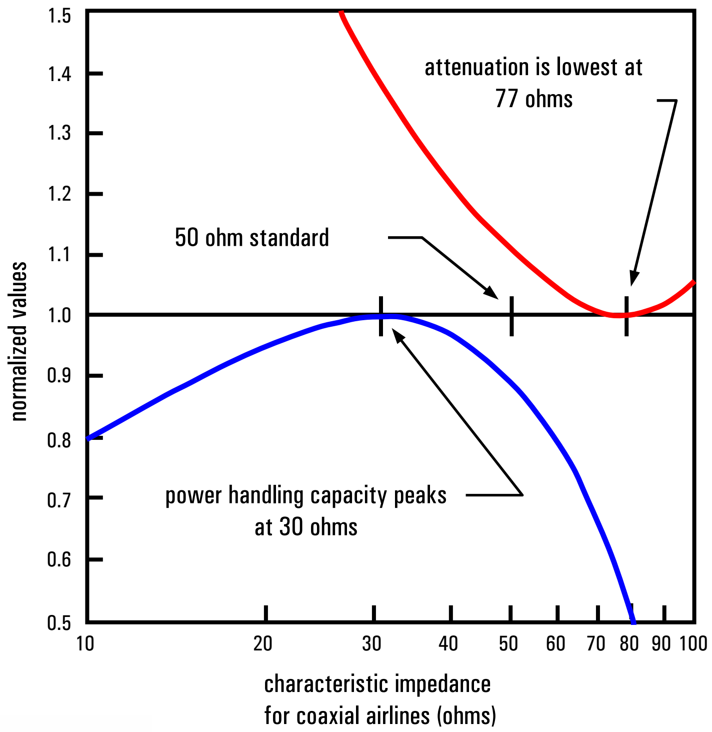
High frequencies

- wavelength ≈ or < < length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Z_o) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

Transmission line Zo

- Zo determines relationship between voltage and current waves
- Zo is a function of physical dimensions and ε_r
- Zo is usually a real impedance (e.g. 50 or 75 ohms)





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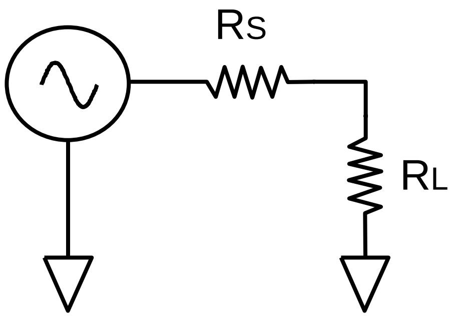
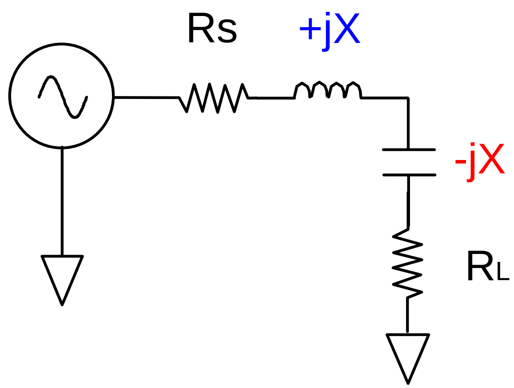
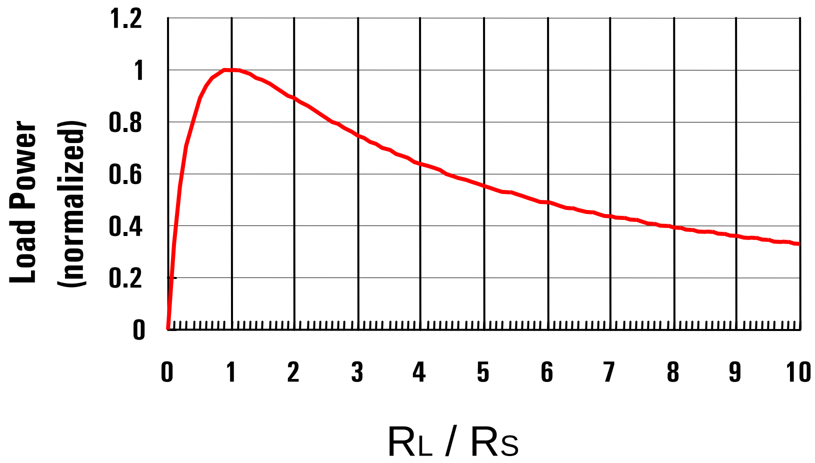
Power Transfer Efficiency



For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)





Maximum power is transferred when $R_L = R_S$

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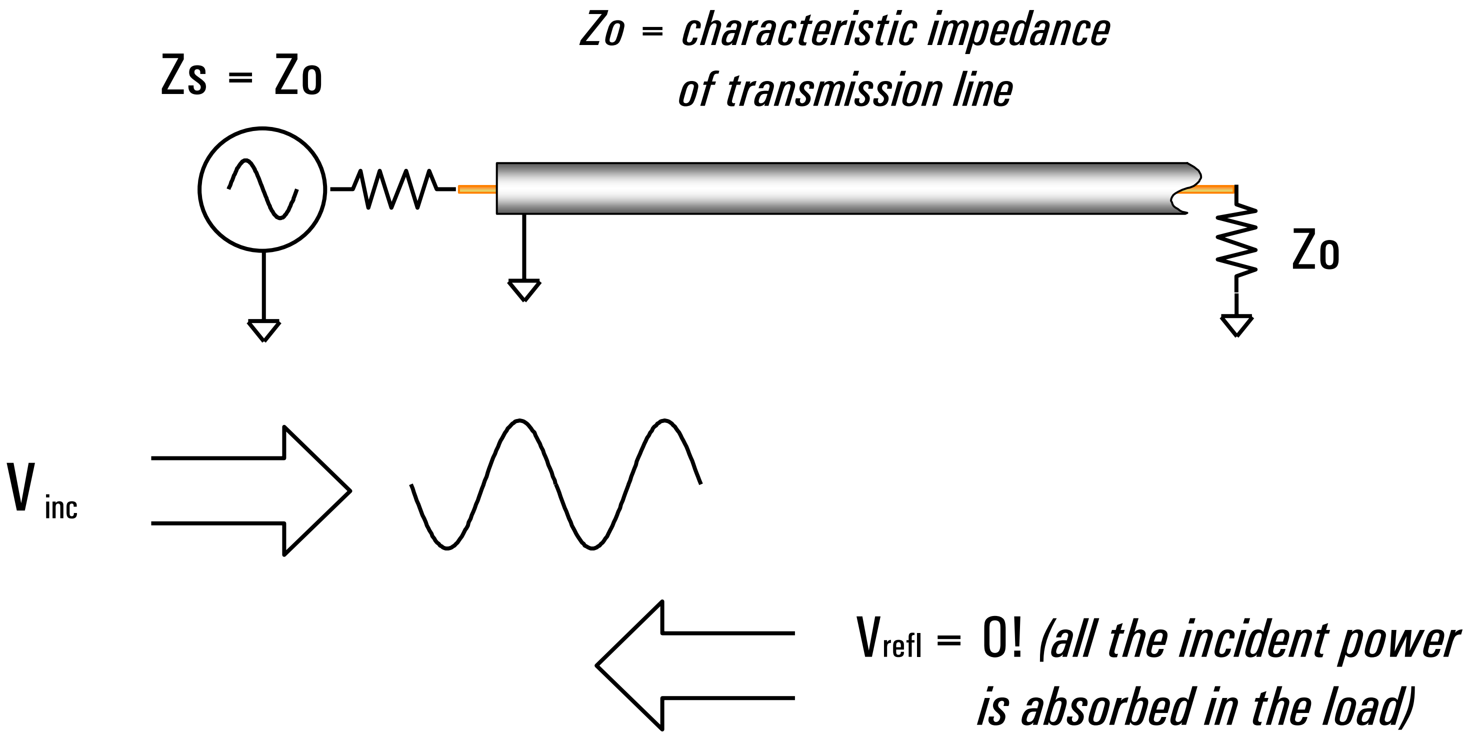
Transmission Line Terminated with Zo



For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

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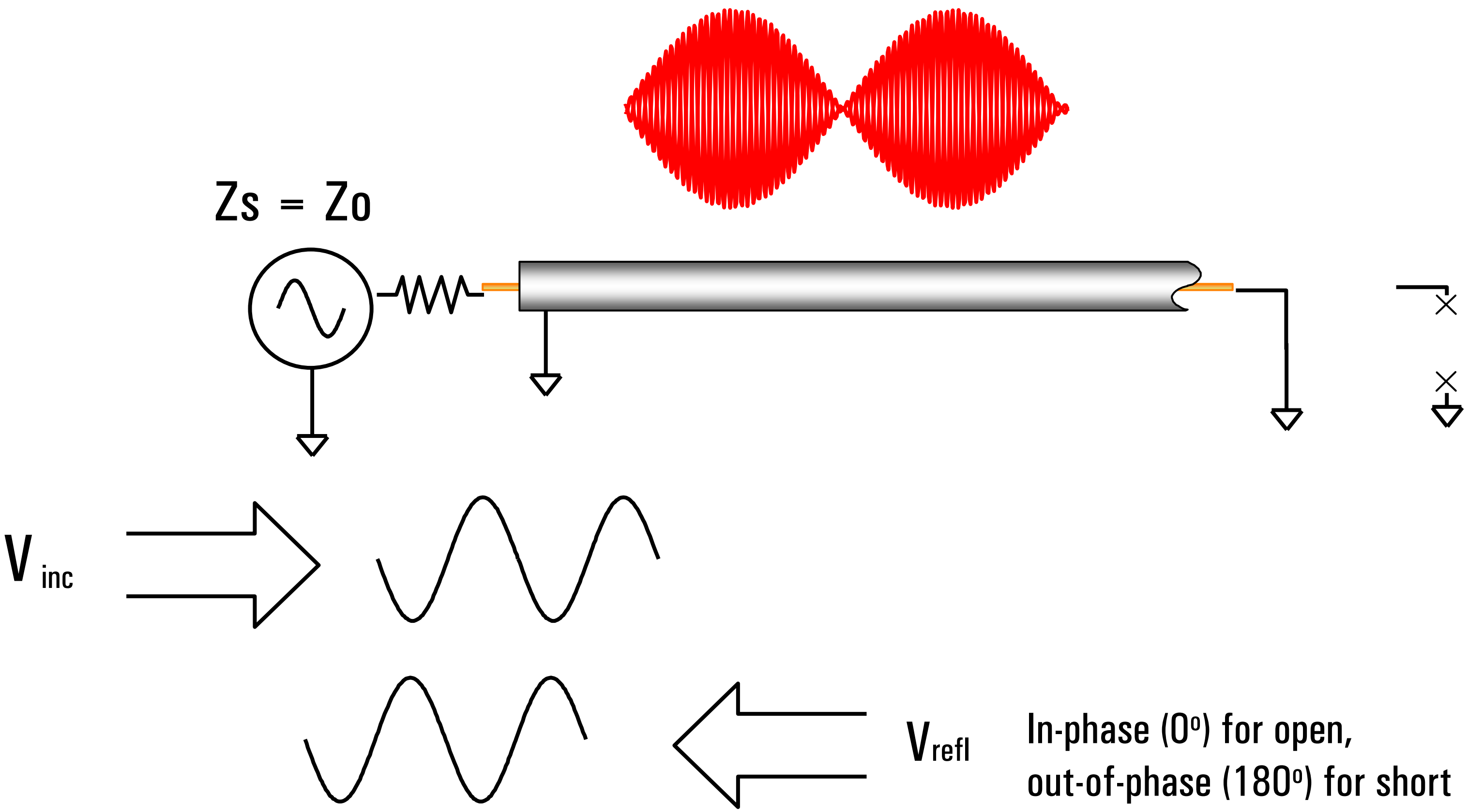
Transmission Line Terminated with Short, Open



In-phase (0°) for open,
out-of-phase (180°) for short

For reflection, a transmission line terminated in a short or open reflects all power back to source

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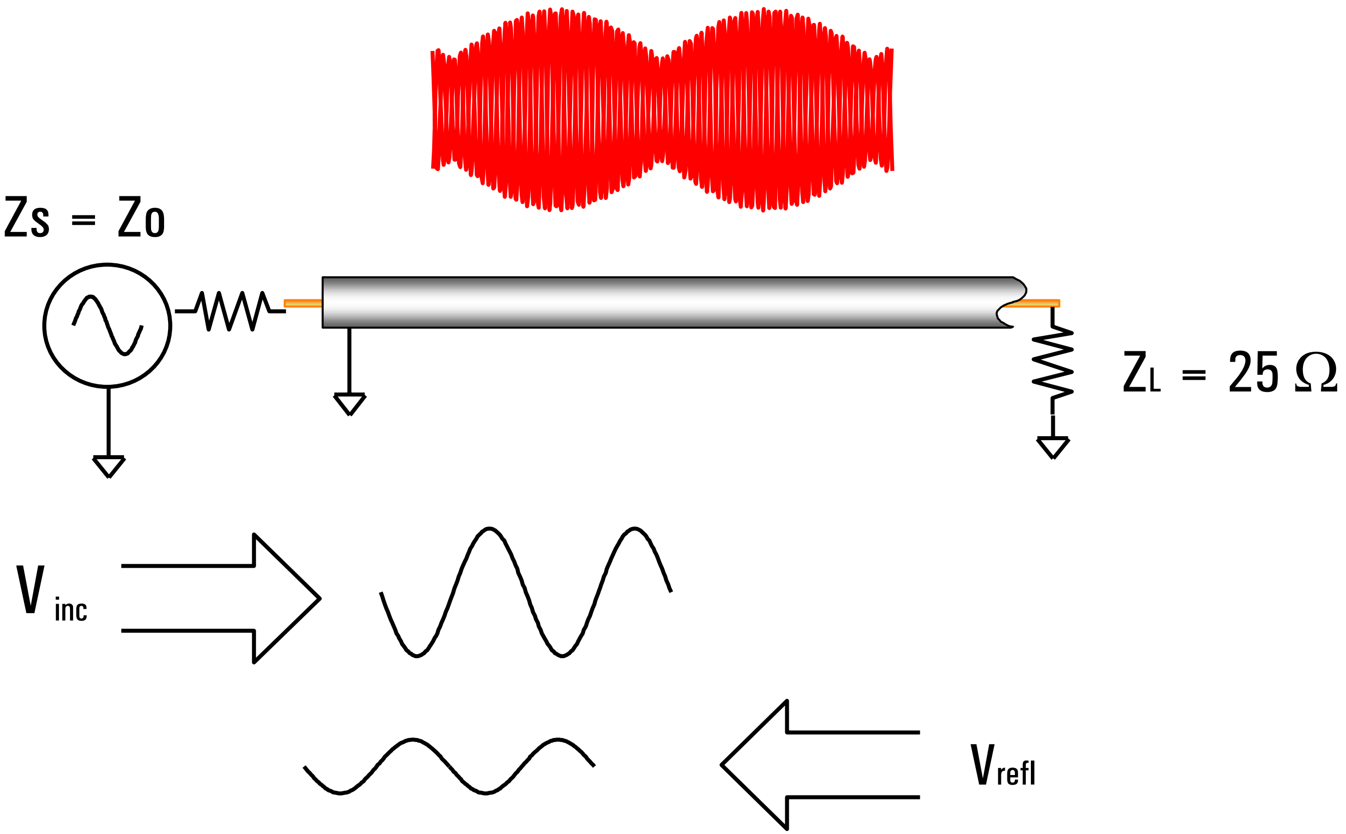
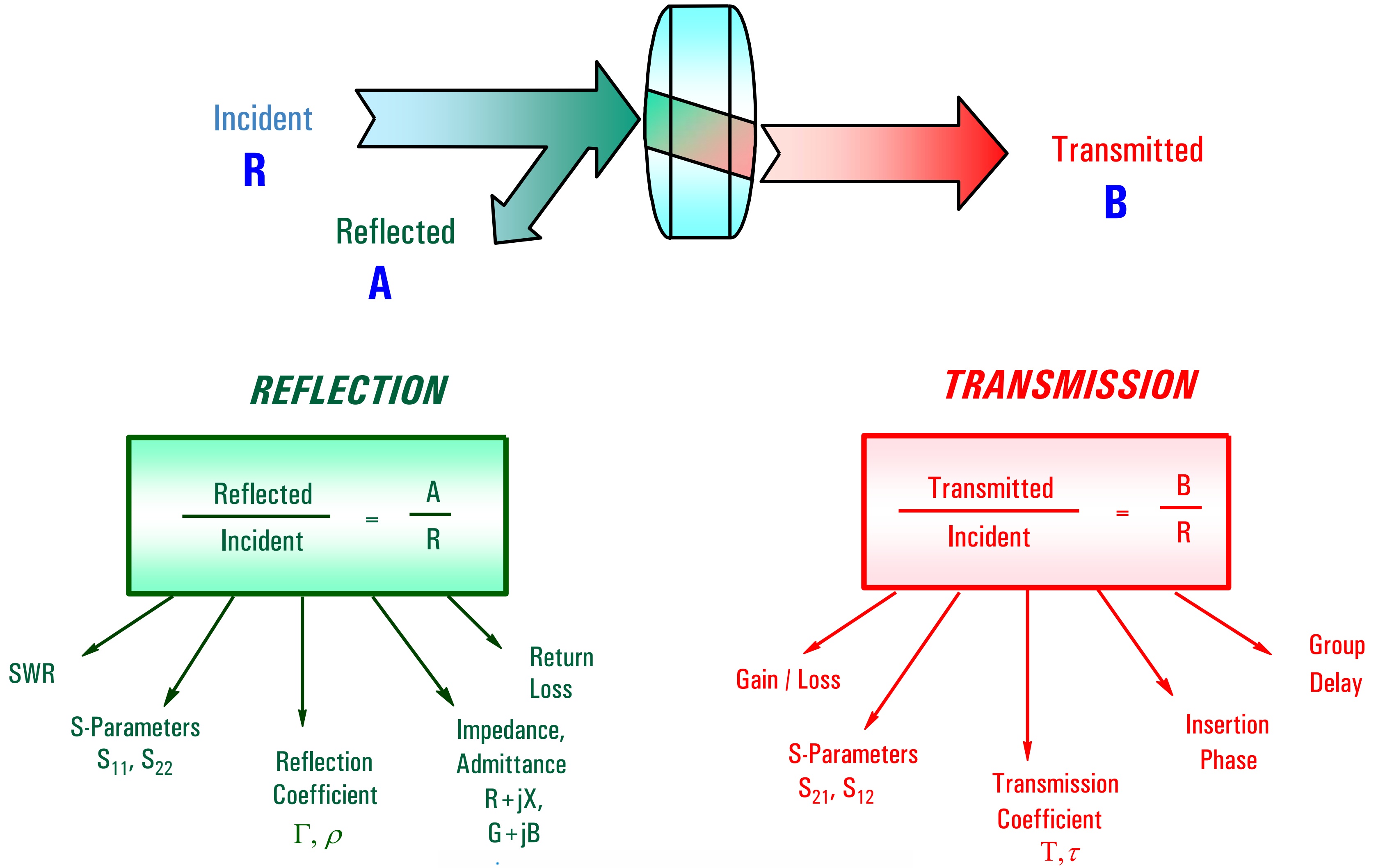
Transmission Line Terminated with 25 Ω



Standing wave pattern does not go to zero as with short or open

High-Frequency Device Characterization



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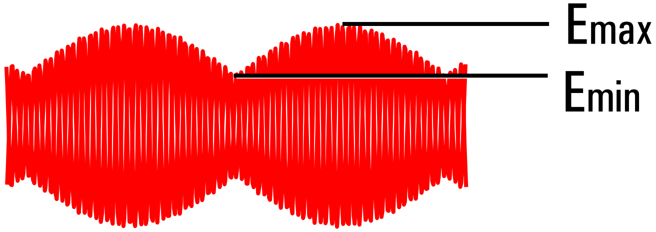
Reflection Parameters

Reflection Coefficient $\Gamma = \dfrac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \dfrac{Z_L - Z_0}{Z_L + Z_0}$

Return loss = $-20 \log(\rho)$, $\rho = |\Gamma|$



Voltage Standing Wave Ratio

VSWR $= \dfrac{E_{max}}{E_{min}} = \dfrac{1+\rho}{1-\rho}$

No reflection (ZL = Zo)		*Full reflection (ZL = open, short)*
0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

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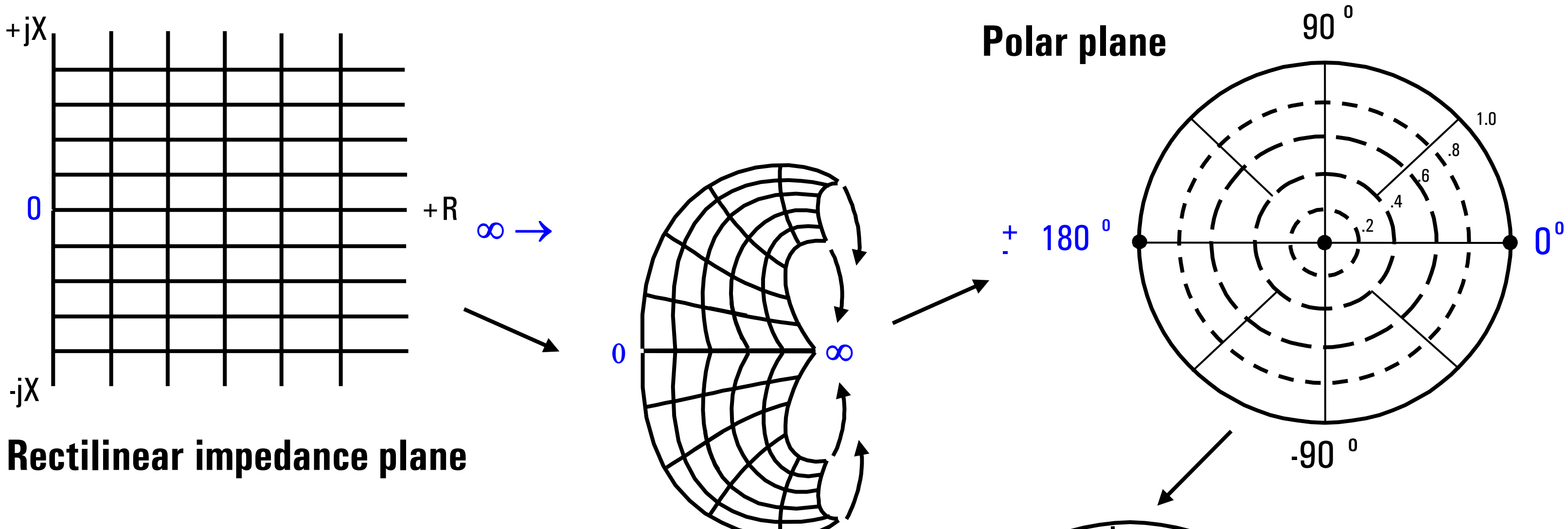
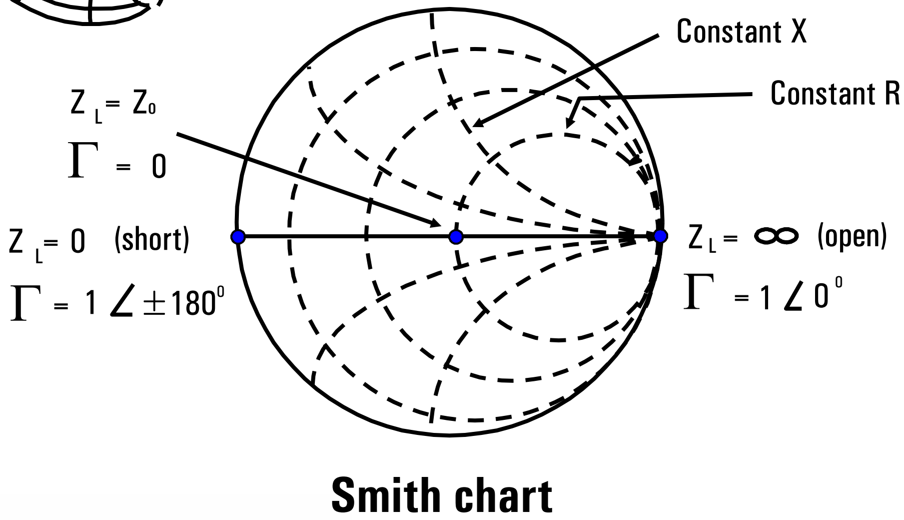
Smith Chart Review



Smith Chart maps rectilinear impedance plane onto polar plane



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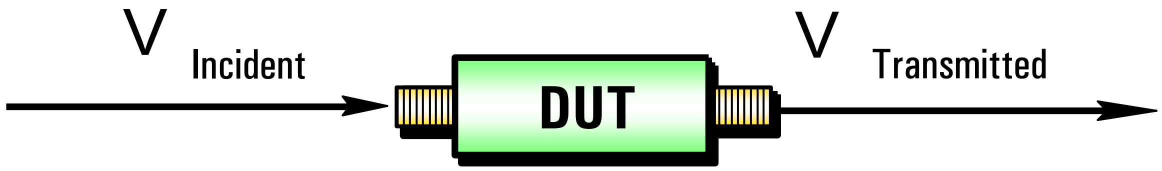
Transmission Parameters



$$\text{Transmission Coefficient} = T = \frac{V_{\text{Transmitted}}}{V_{\text{Incident}}} = \tau\angle\phi$$

$$\text{Insertion Loss (dB)} = -20\,\text{Log}\left|\frac{V_{\text{Trans}}}{V_{\text{Inc}}}\right| = -20\log\tau$$

$$\text{Gain (dB)} = 20\,\text{Log}\left|\frac{V_{\text{Trans}}}{V_{\text{Inc}}}\right| = 20\log\tau$$

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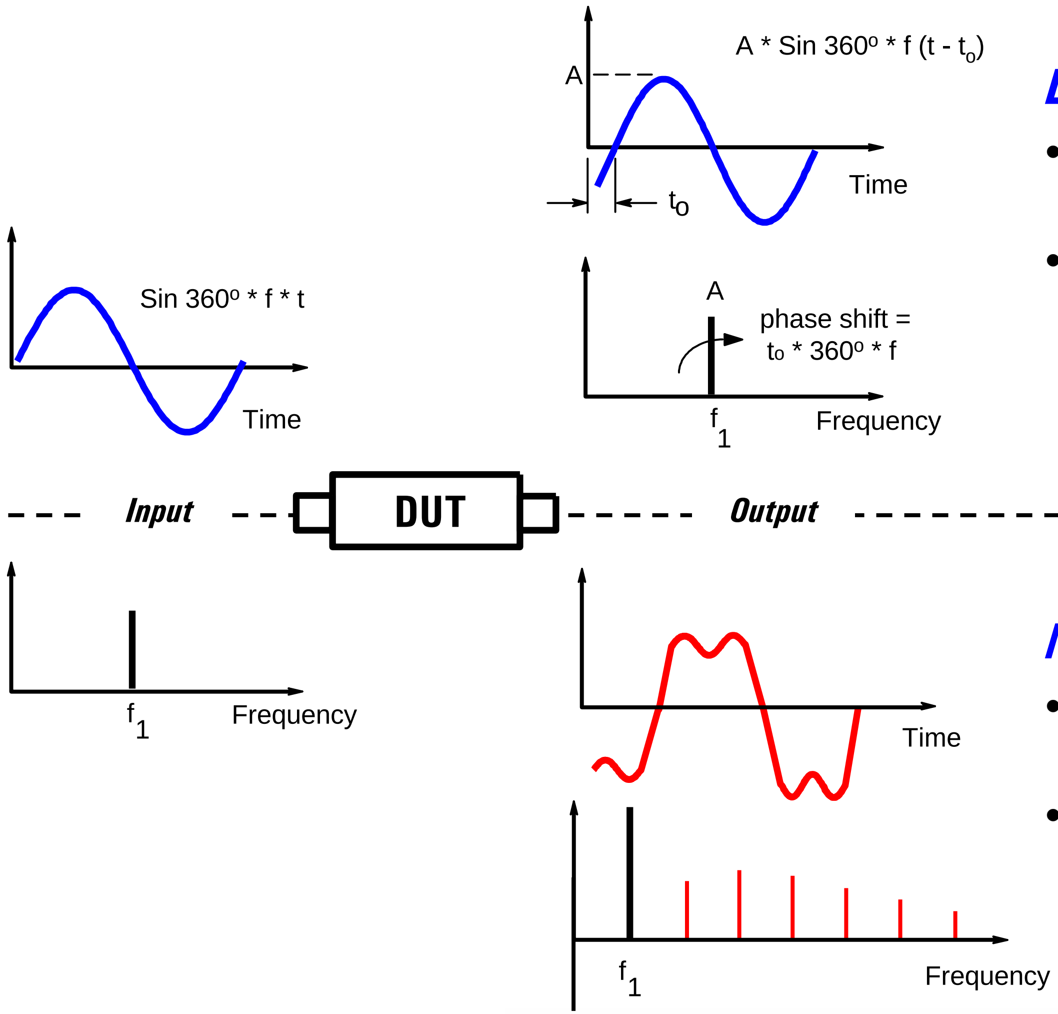
Linear Versus Nonlinear Behavior



Linear behavior:

- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

Nonlinear behavior:

- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)

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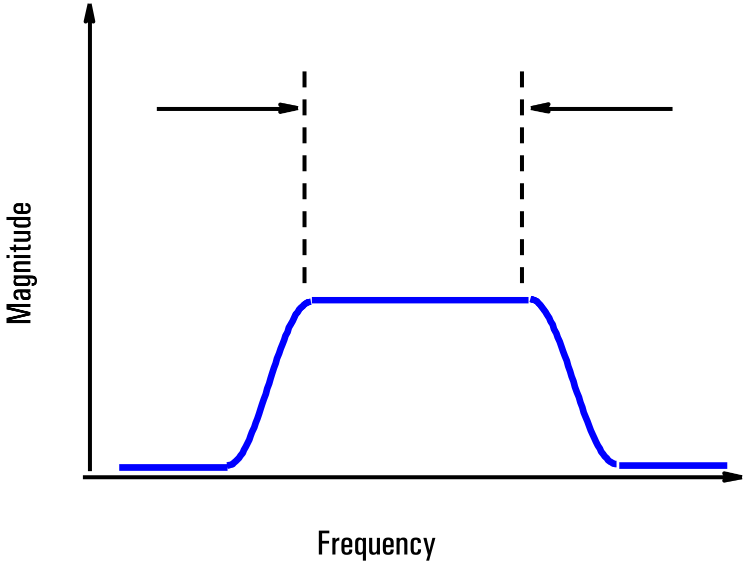
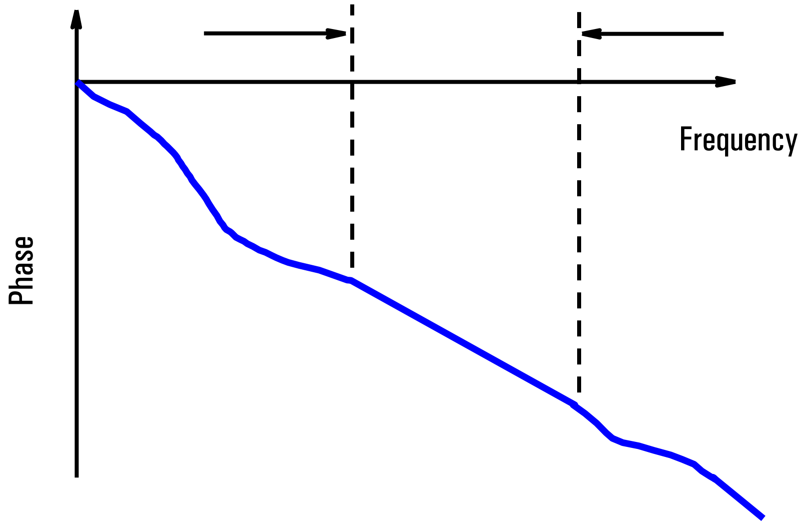
Criteria for Distortionless Transmission

Linear Networks

Constant amplitude over bandwidth of interest



Linear phase over bandwidth of interest



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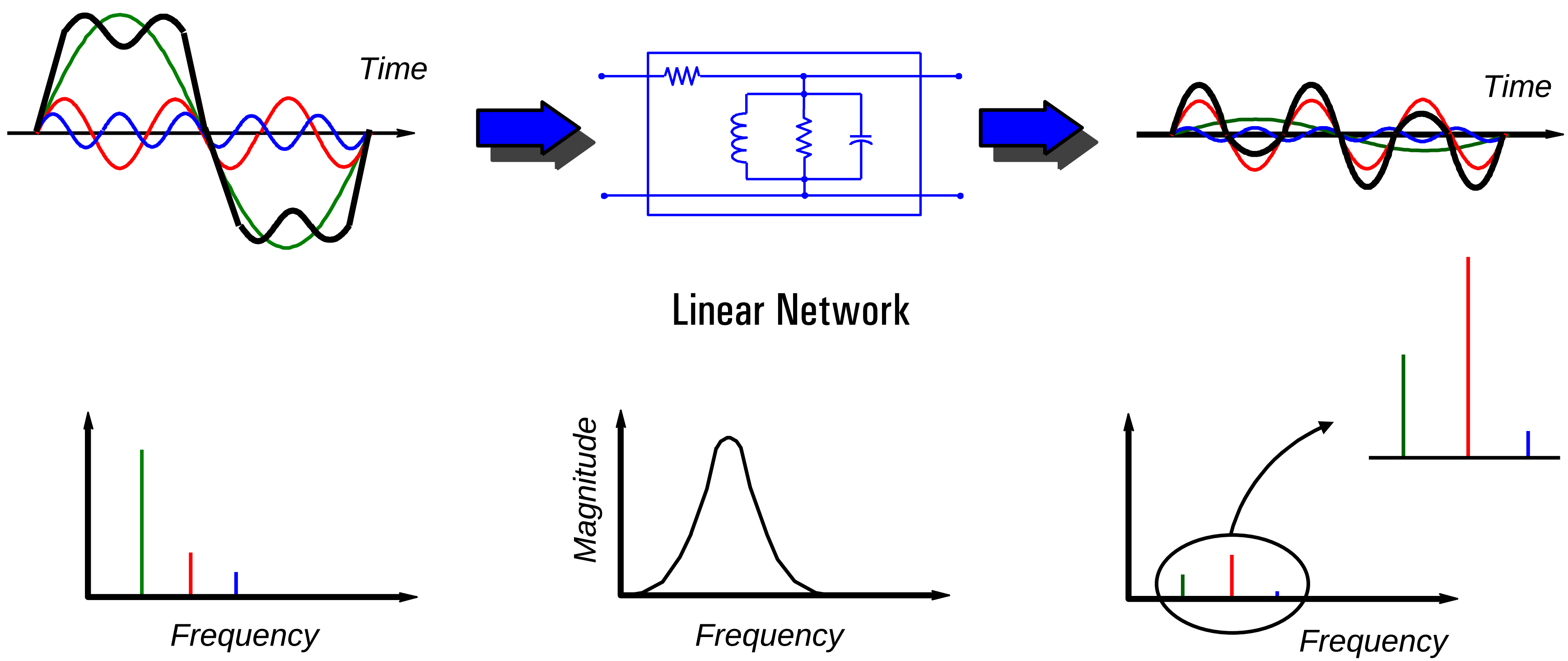
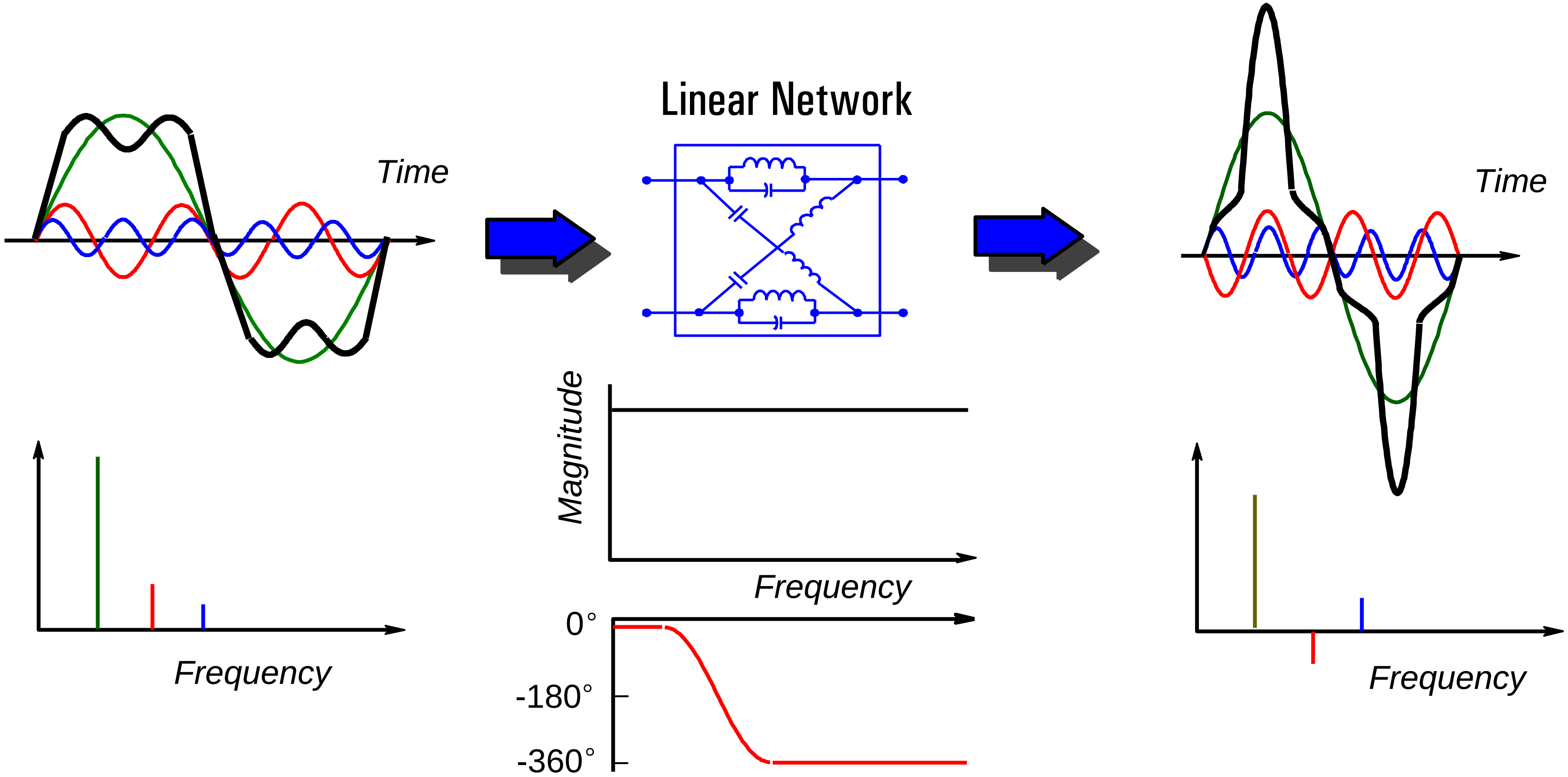
Magnitude Variation with Frequency

$F(t) = \sin wt + 1/3 \sin 3wt + 1/5 \sin 5wt$



Phase Variation with Frequency

F(t) = sin wt + 1 /3 sin 3wt + 1 /5 sin 5wt



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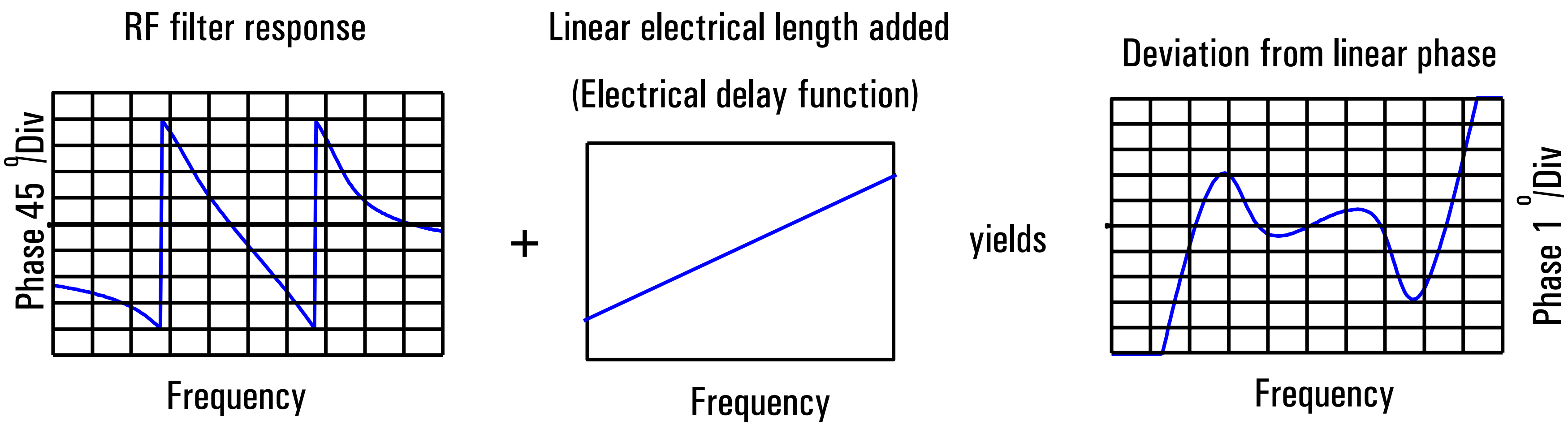
Deviation from Linear Phase

Use electrical delay to remove linear portion of phase response



Low resolution

High resolution

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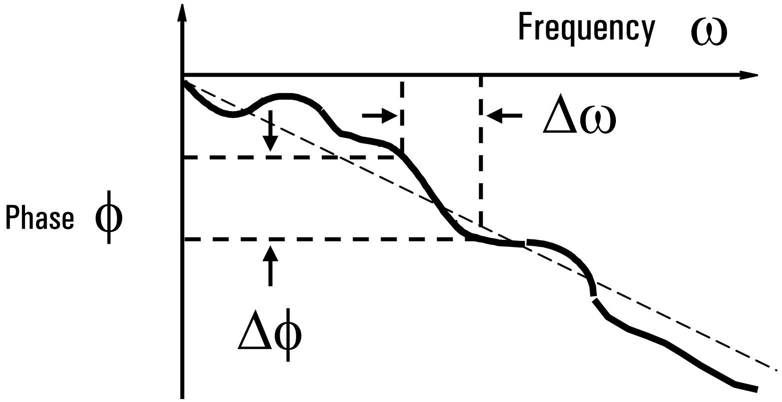
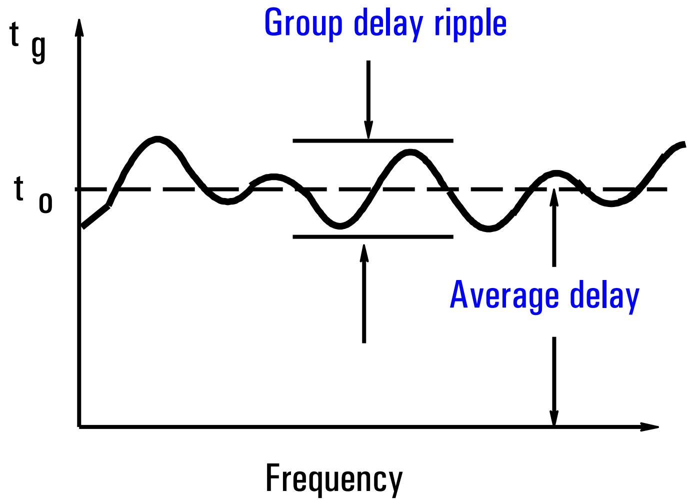
Group Delay





Group Delay (t_g) =

$$\frac{-d\phi}{d\omega} = \frac{-1}{360^{o}} * \frac{d\phi}{df}$$

ϕ in radians

ω in radians/sec

ϕ in degrees

f in Hertz ($\omega = 2\pi f$)

- group-delay ripple indicates phase distortion
- average delay indicates electrical length of DUT
- aperture of measurement is very important

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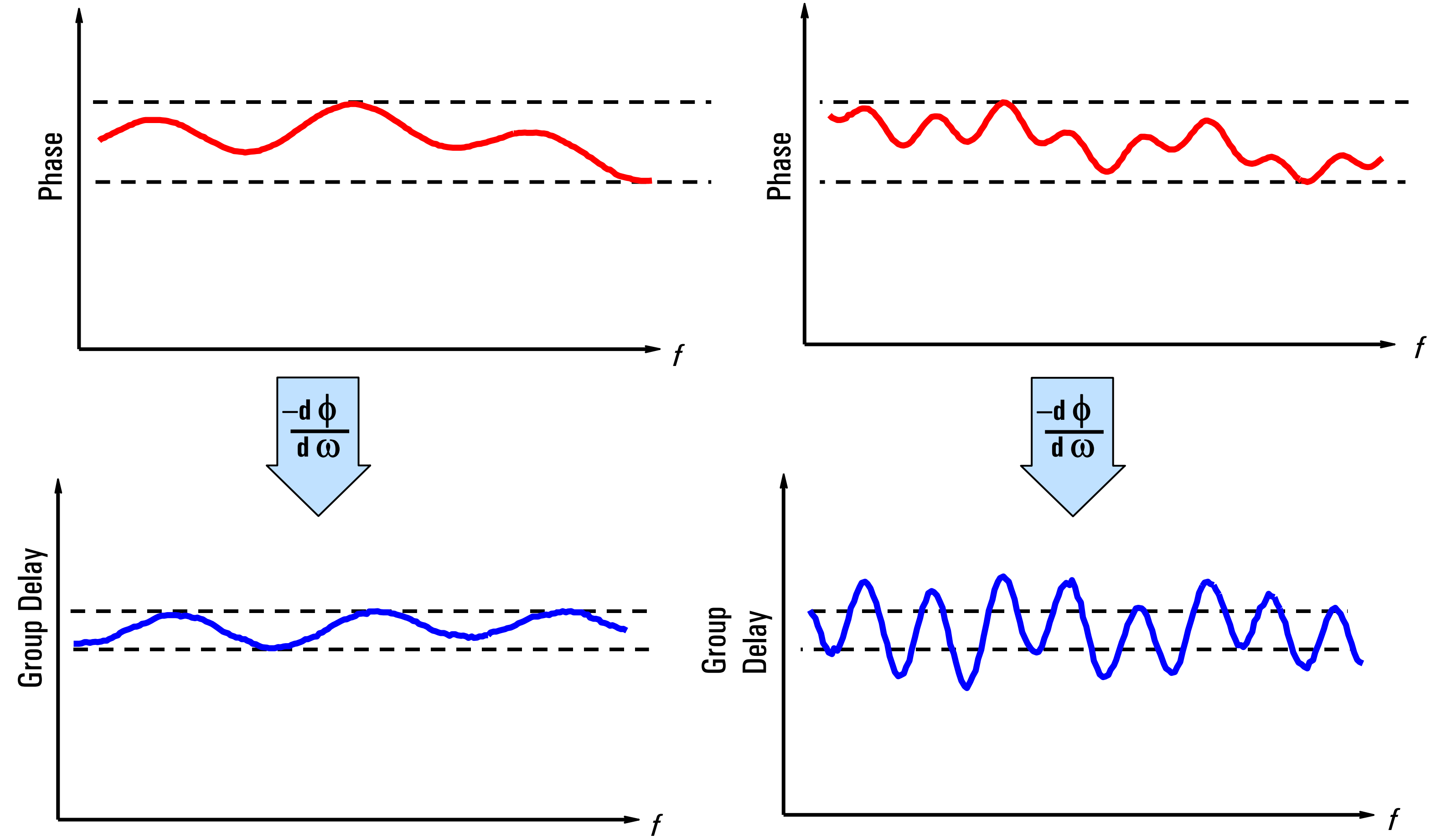
Why Measure Group Delay?



Same p-p phase ripple can result in different group delay

Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

- gives linear behavioral model of our device
- measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- compute device parameters from measured data
- predict circuit performance under any source and load conditions

H-parameters

$V_1 = h_{11}I_1 + h_{12}V_2$

$I_2 = h_{21}I_1 + h_{22}V_2$

Y-parameters

$I_1 = y_{11}V_1 + y_{12}V_2$

$I_2 = y_{21}V_1 + y_{22}V_2$

Z-parameters

$V_1 = z_{11}I_1 + z_{12}I_2$

$V_2 = z_{21}I_1 + z_{22}I_2$

$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$ *(requires **open circuit**)*

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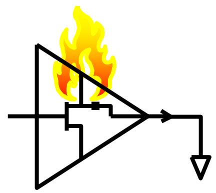
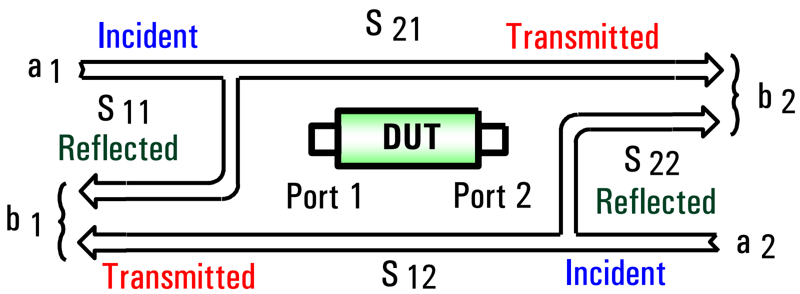
Why Use S-Parameters?



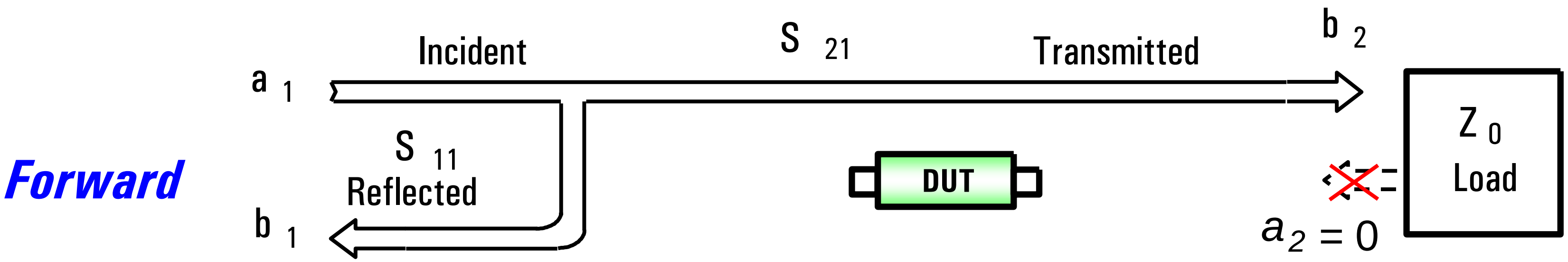
- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools



$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

Measuring S-Parameters

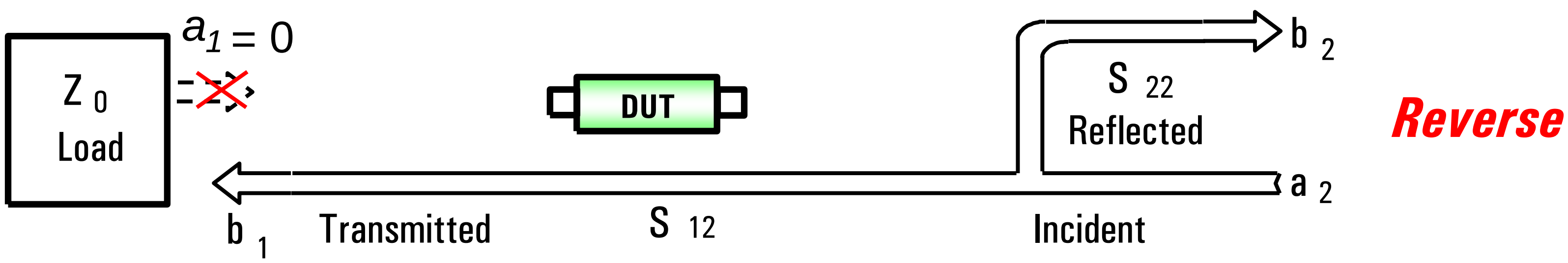


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0}$$



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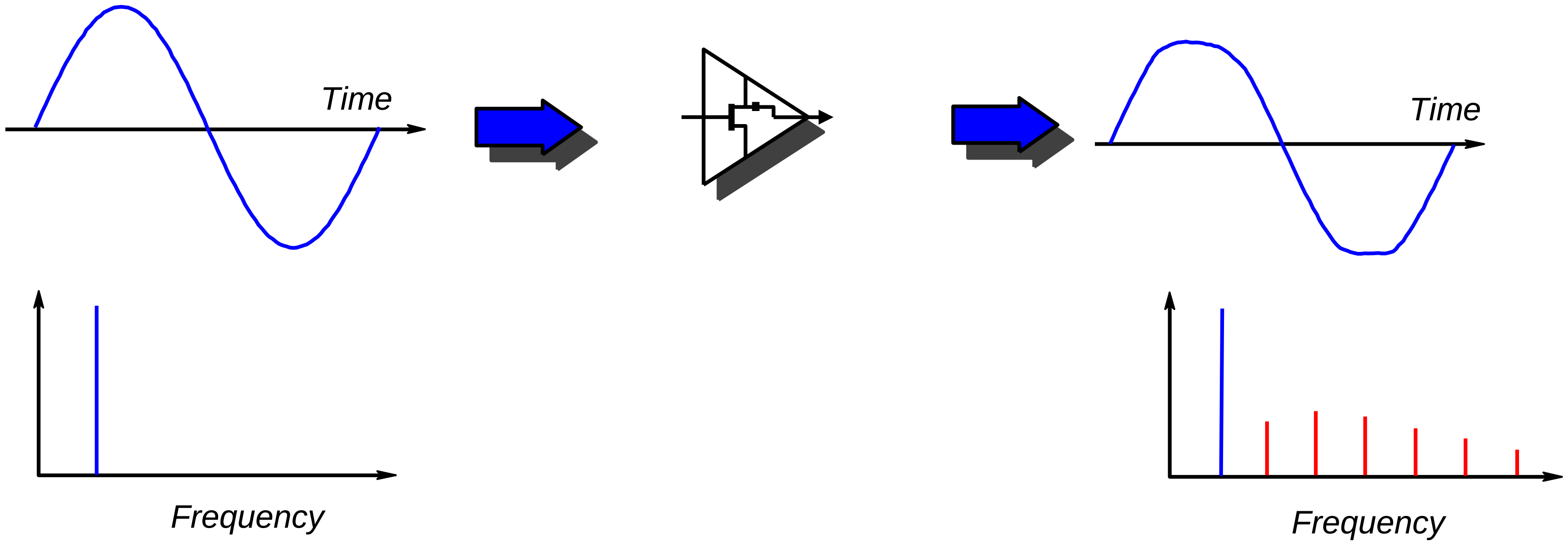
Equating S-Parameters with Common Measurement Terms

S11 = forward reflection coefficient ***(input match)***
S22 = reverse reflection coefficient ***(output match)***
S21 = forward transmission coefficient ***(gain or loss)***
S12 = reverse transmission coefficient ***(isolation)***

Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format

Criteria for Distortionless Transmission
Nonlinear Networks

- Saturation, crossover, intermodulation, and other nonlinear effects can cause signal distortion
- Effect on system depends on amount and type of distortion and system architecture



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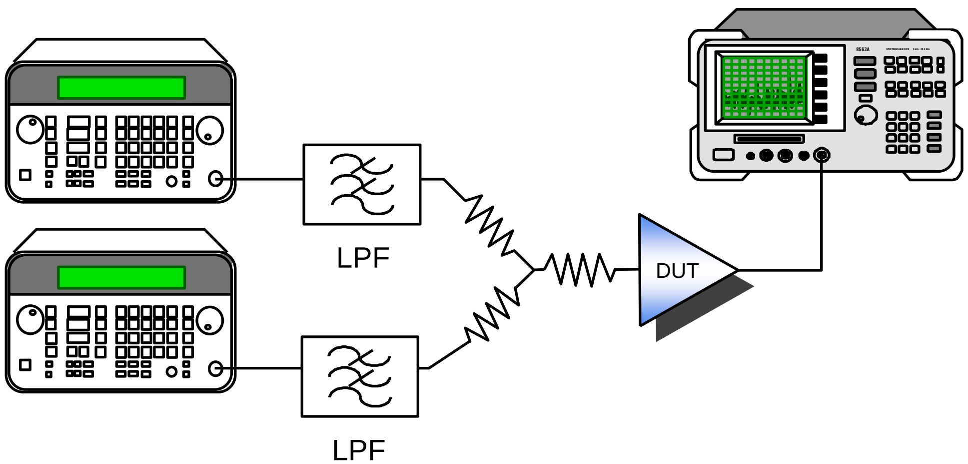
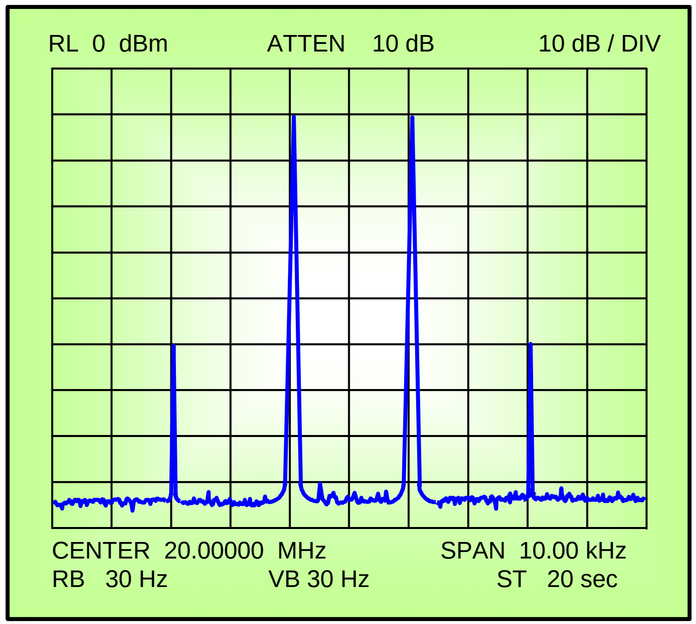
Measuring Nonlinear Behavior

Most common measurements:

- using a ***network analyzer*** and power sweeps
  - ➔ gain compression
  - ➔ AM to PM conversion
- using a ***spectrum analyzer*** + source(s)
  - ➔ harmonics, particularly second and third
  - ➔ intermodulation products resulting from two or more RF carriers





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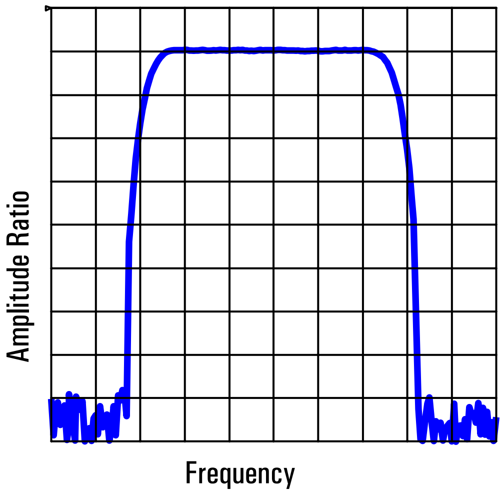
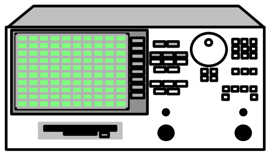
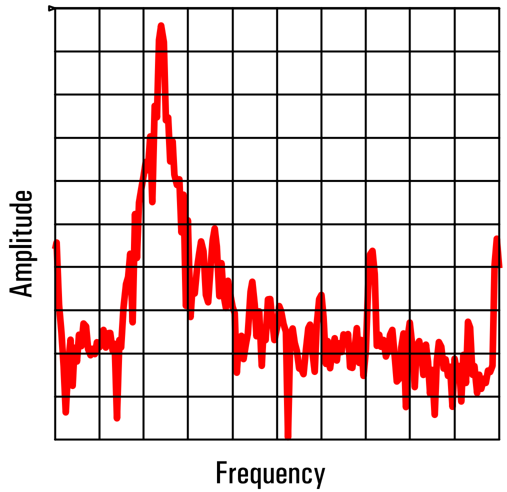
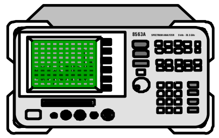
What is the Difference Between *Network* and *Spectrum* Analyzers?





Measures known signal





Measures unknown signals

Network analyzers:

- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase (frequency or power sweeps)
- offer advanced error correction

Spectrum analyzers:

- measure signal amplitude characteristics carrier level, sidebands, harmonics...)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (*no phase*) with tracking gen. or ext. source(s)

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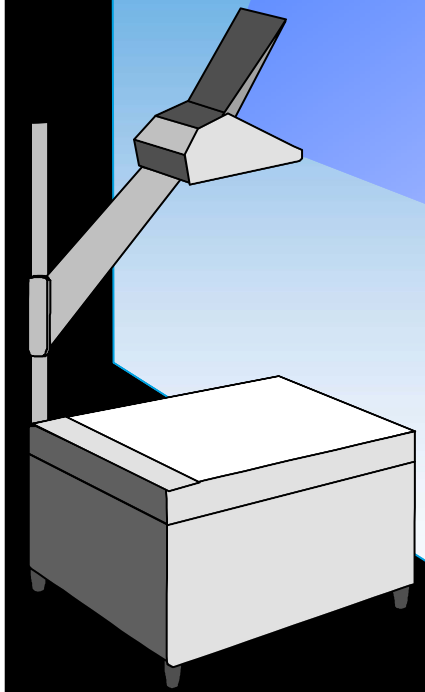
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix



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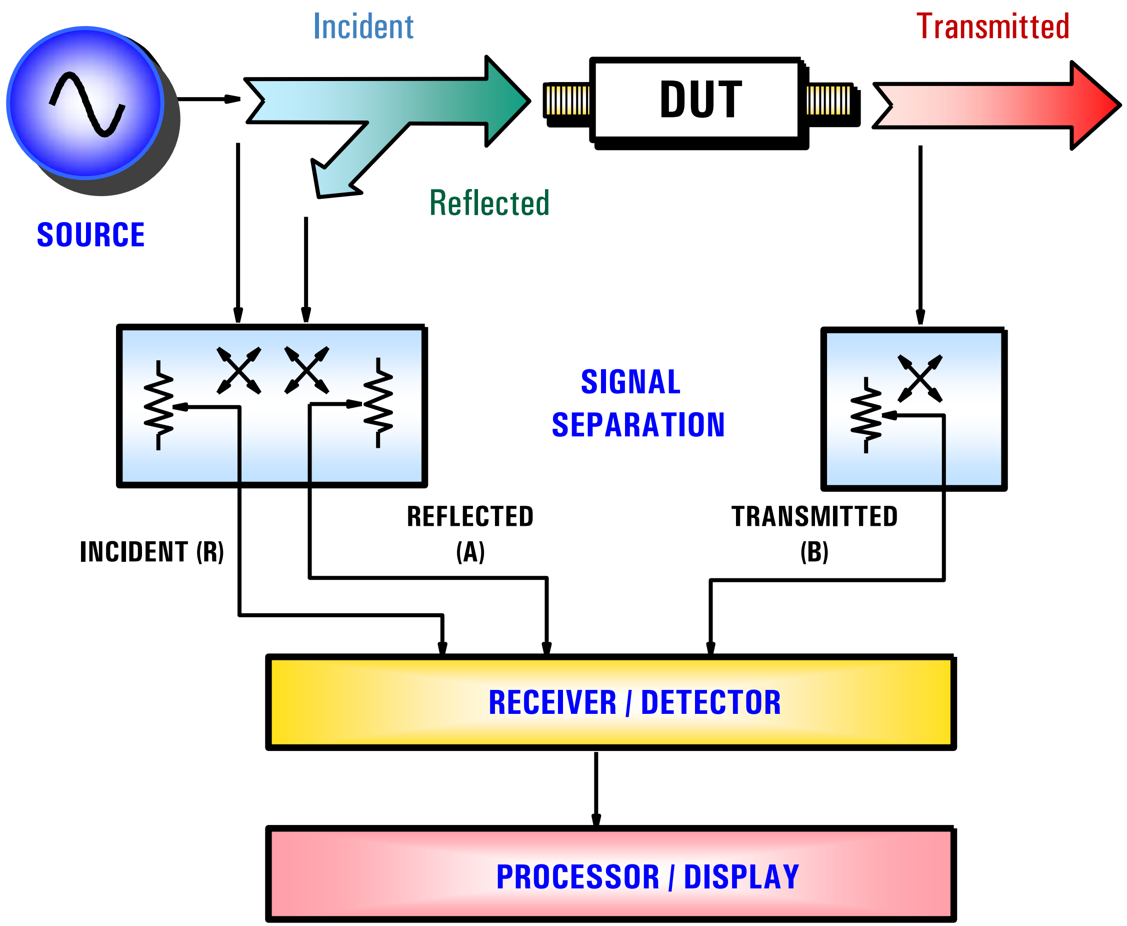
Generalized Network Analyzer Block Diagram



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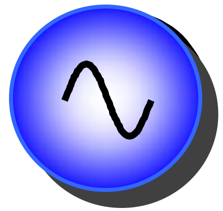
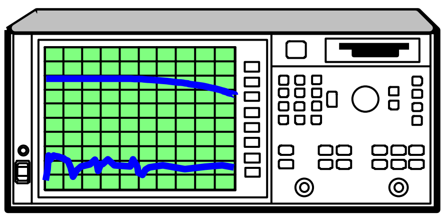
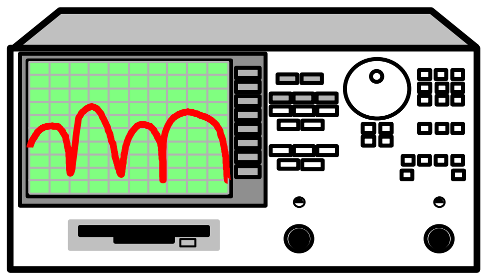
Source

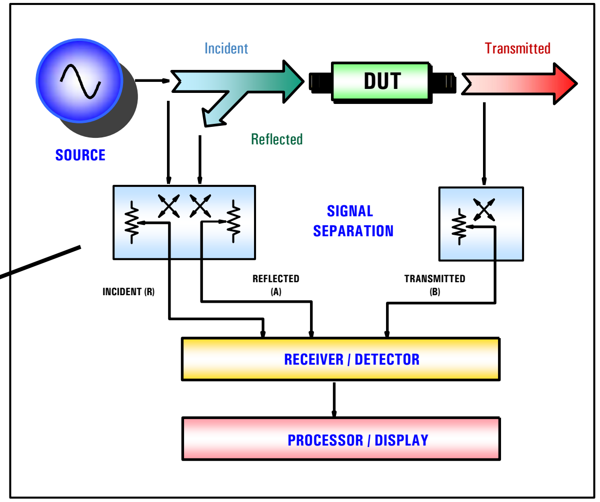
- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Agilent analyzers sold today have ***integrated, synthesized*** sources





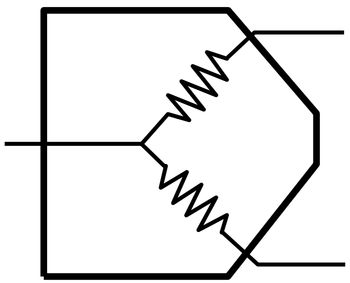


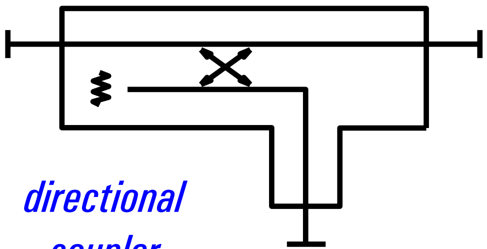
Signal Separation



- measure incident signal for reference
- separate incident and reflected signals

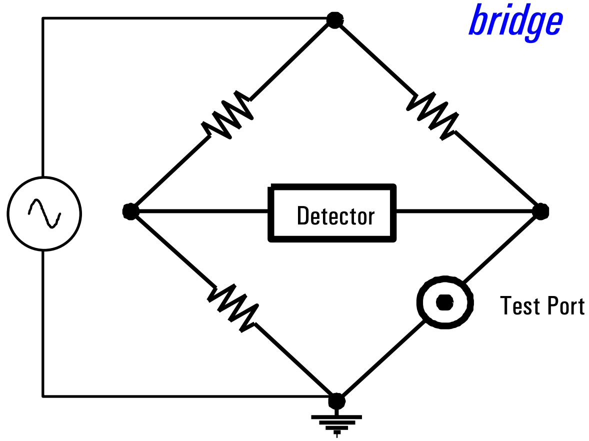
splitter





directional coupler

bridge



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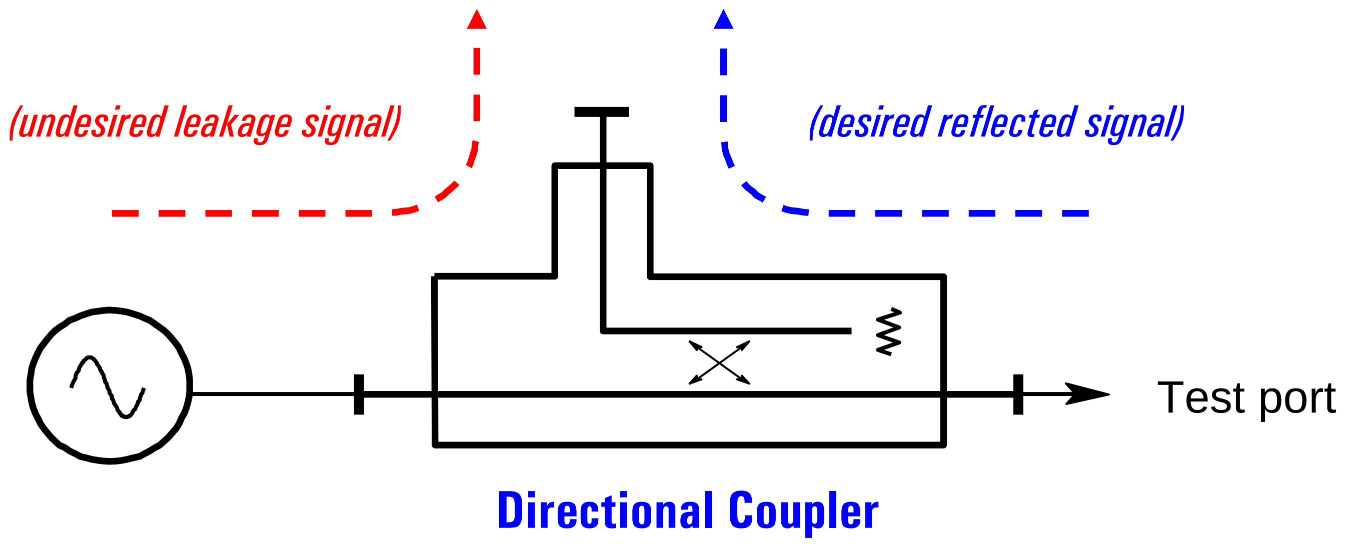
Directivity

Directivity is a measure of how well a coupler can separate signals moving in opposite directions



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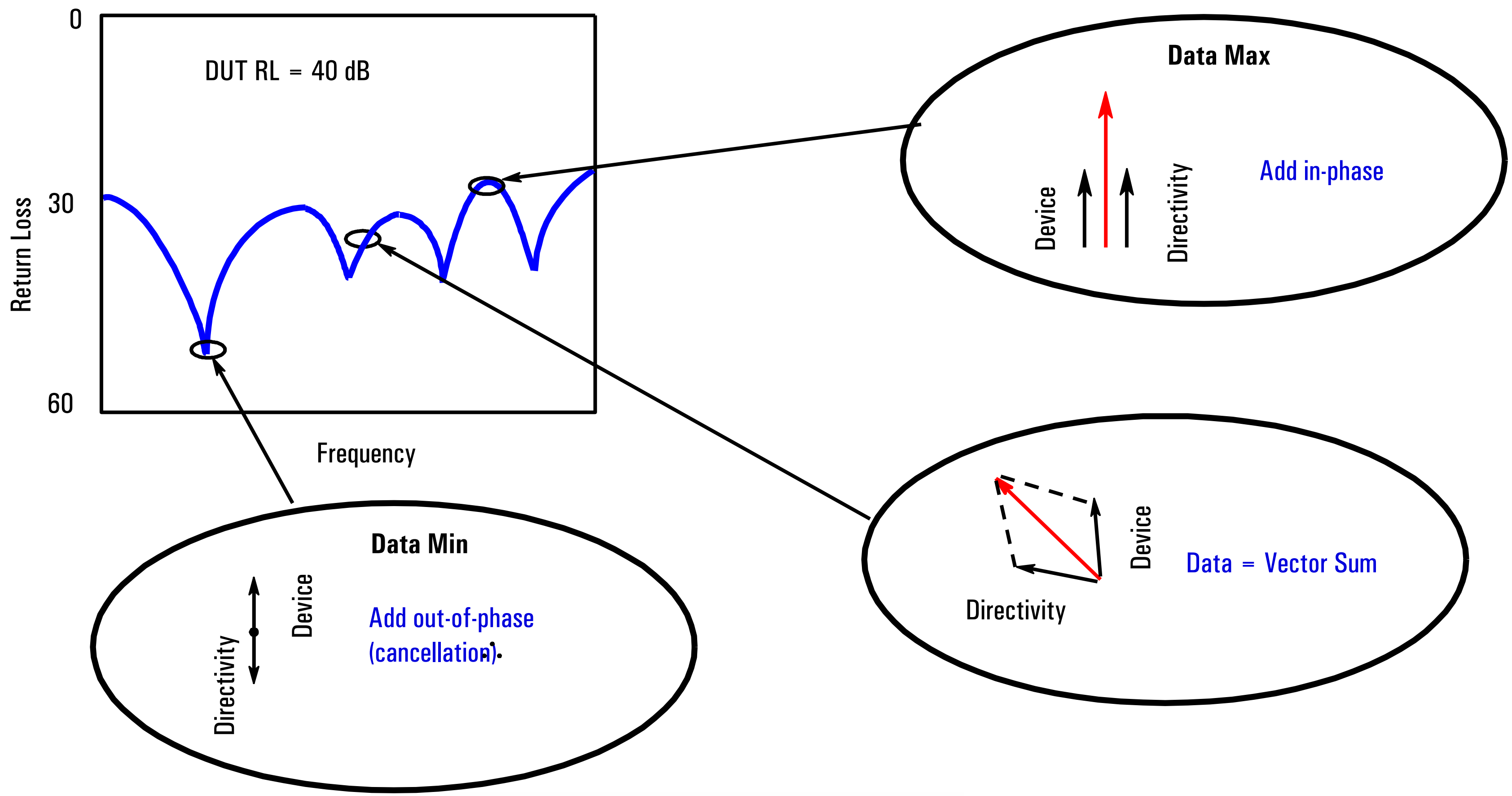
Interaction of Directivity with the DUT (Without Error Correction)



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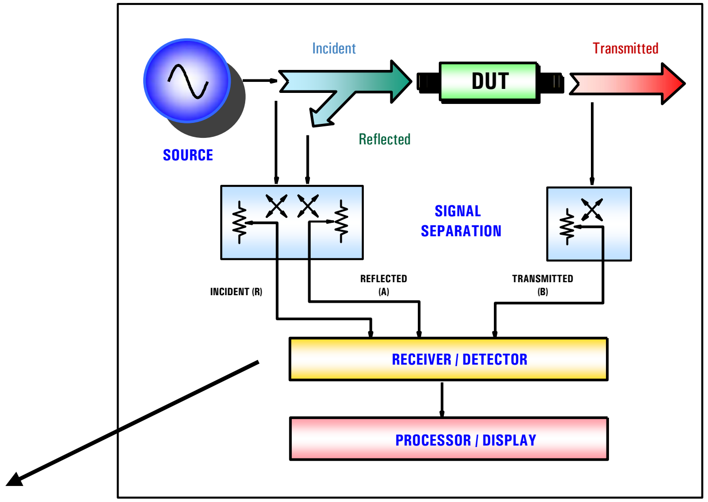
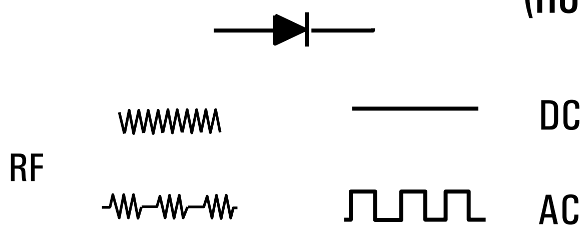
Detector Types

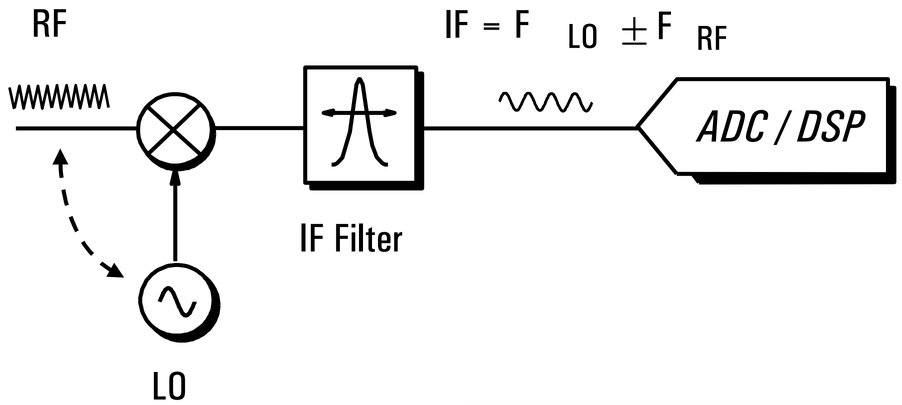


Diode

Scalar **broadband**
(no phase information)



Tuned Receiver



Vector
(magnitude and phase)

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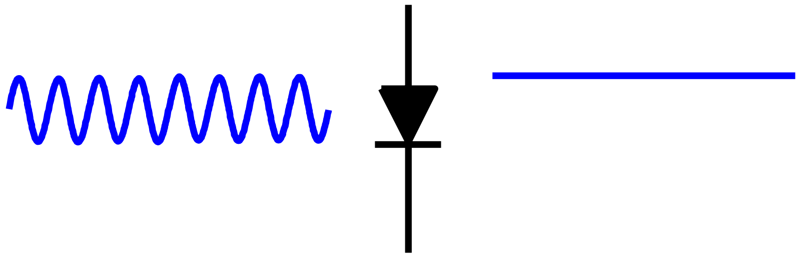
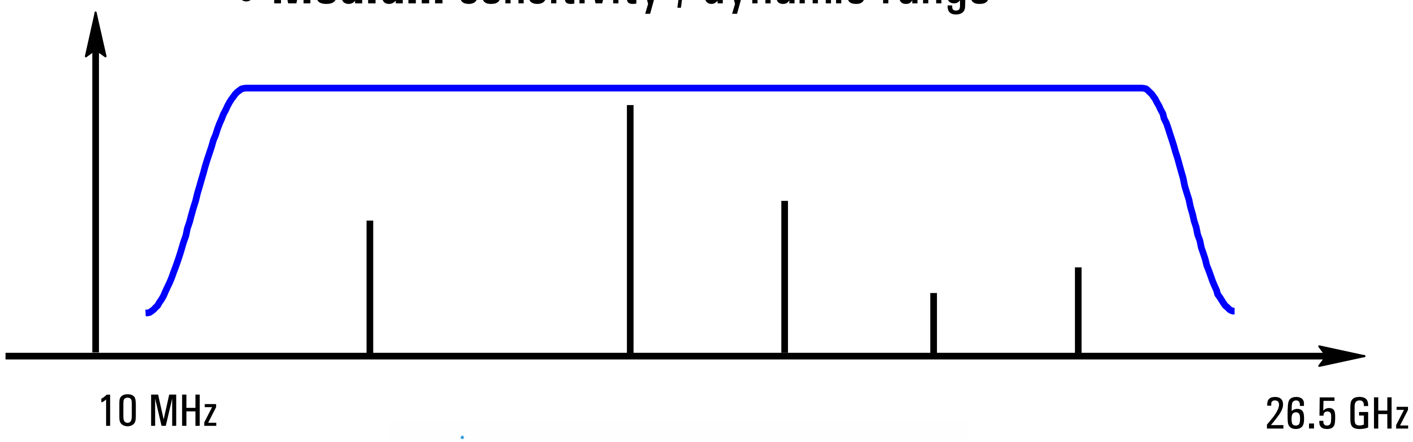
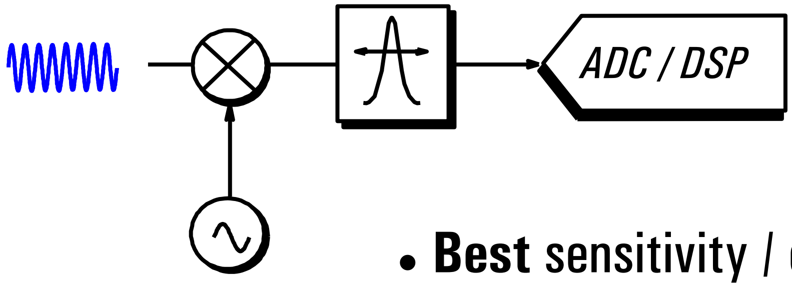
Broadband Diode Detection



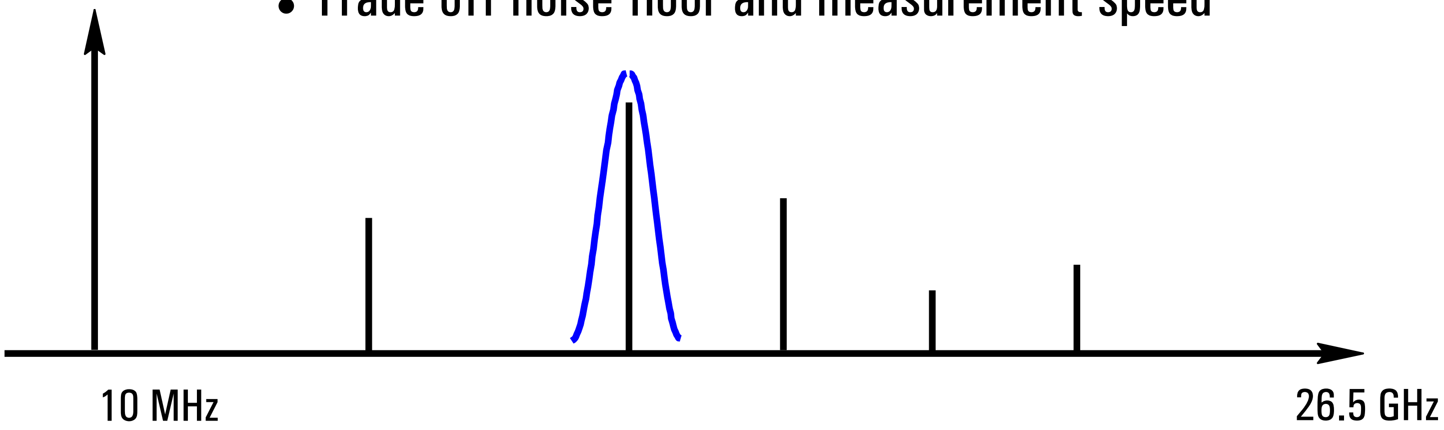
- Easy to make **broadband**
- **Inexpensive** compared to tuned receiver
- Good for measuring frequency-translating devices
- Improve dynamic range by increasing power
- **Medium** sensitivity / dynamic range



Narrowband Detection - Tuned Receiver

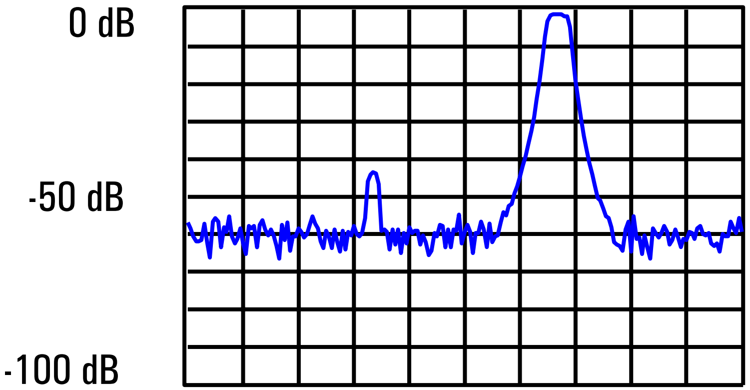


- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**, decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed



Comparison of Receiver Techniques

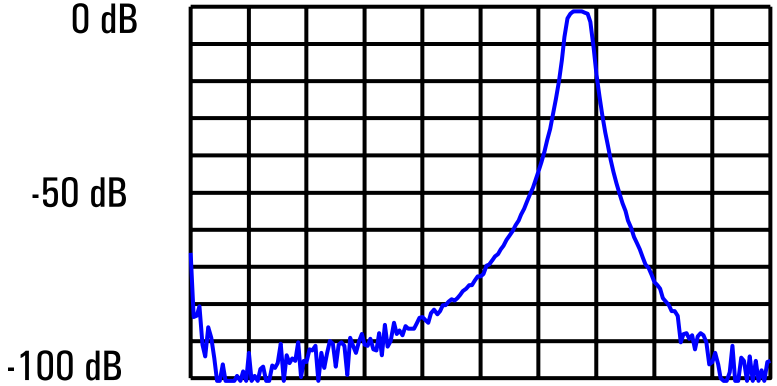
Broadband
(diode) detection



-60 dBm Sensitivity

- higher noise floor
- false responses

Narrowband
(tuned-receiver) detection

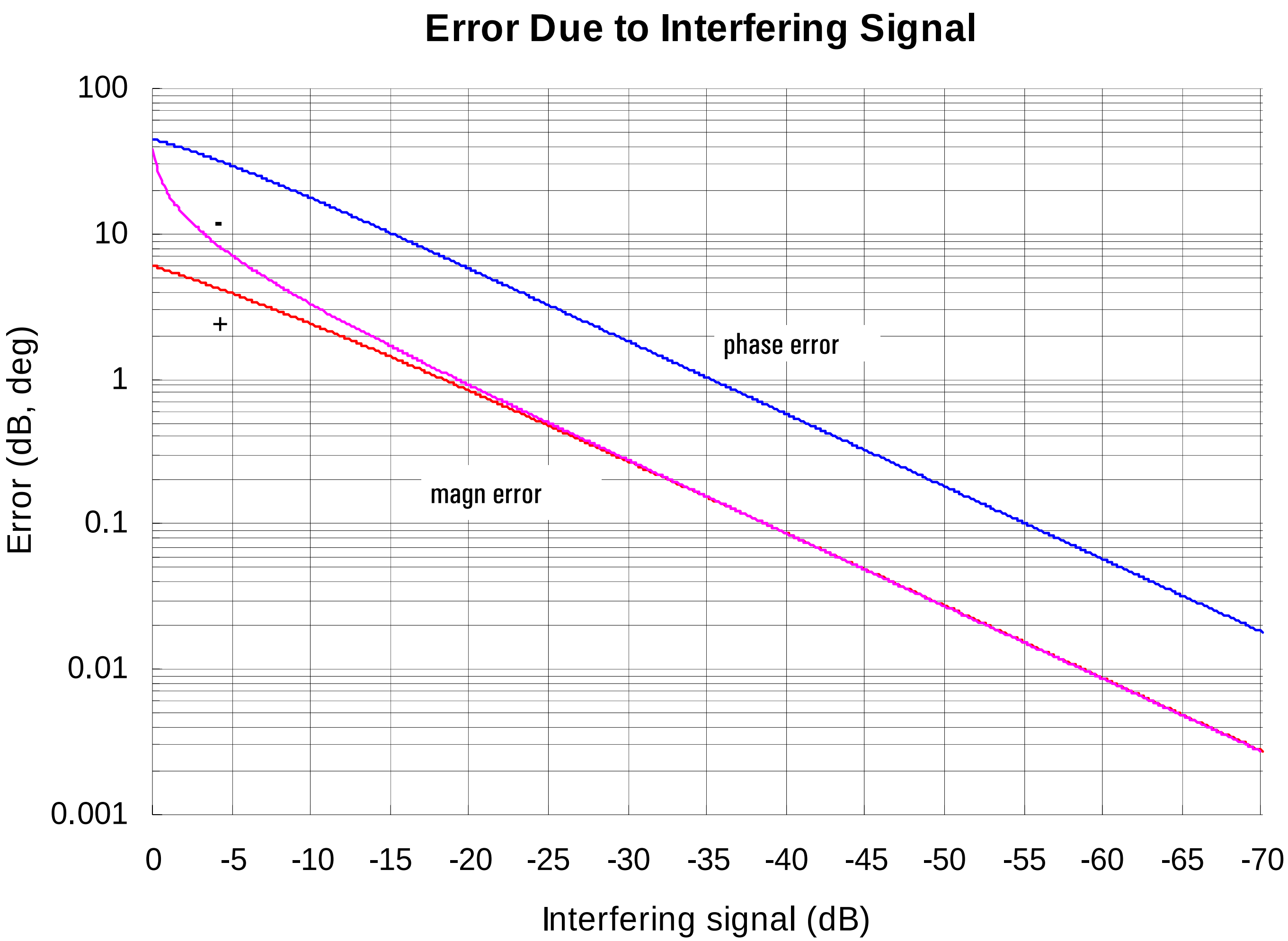


< -100 dBm Sensitivity

- high dynamic range
- harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor

Dynamic Range and Accuracy



Dynamic range is very important for measurement accuracy!

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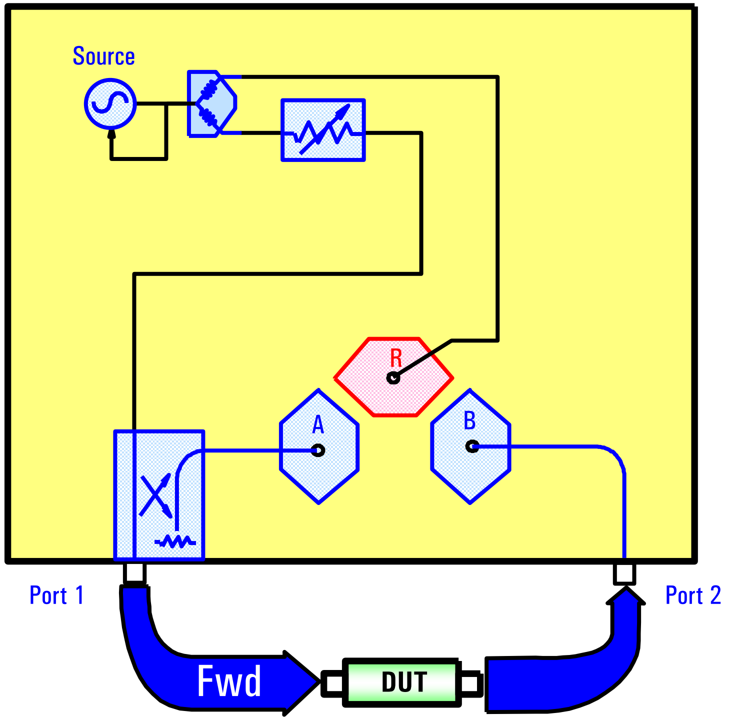
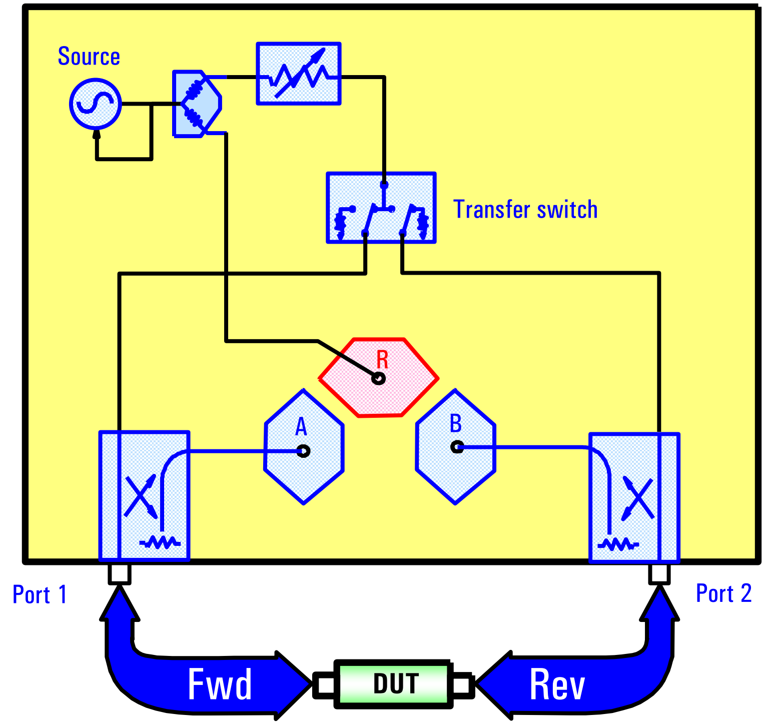
T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



- RF always comes out port 1
- port 2 is always receiver
- **response**, **one-port** cal available

S-Parameter Test Set



- RF comes out port 1 or port 2
- forward and reverse measurements
- **two-port** calibration possible

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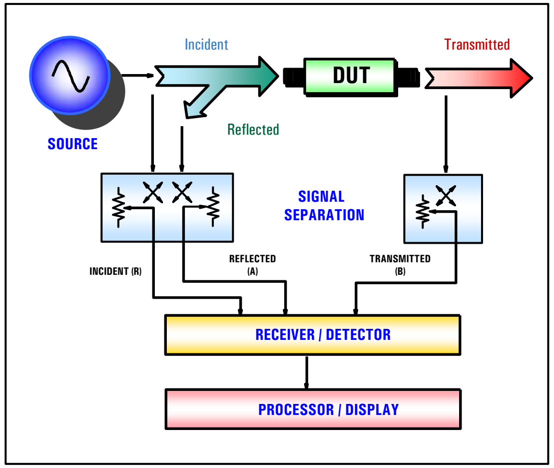
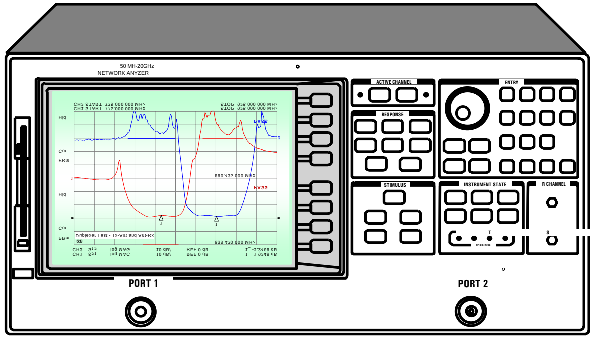
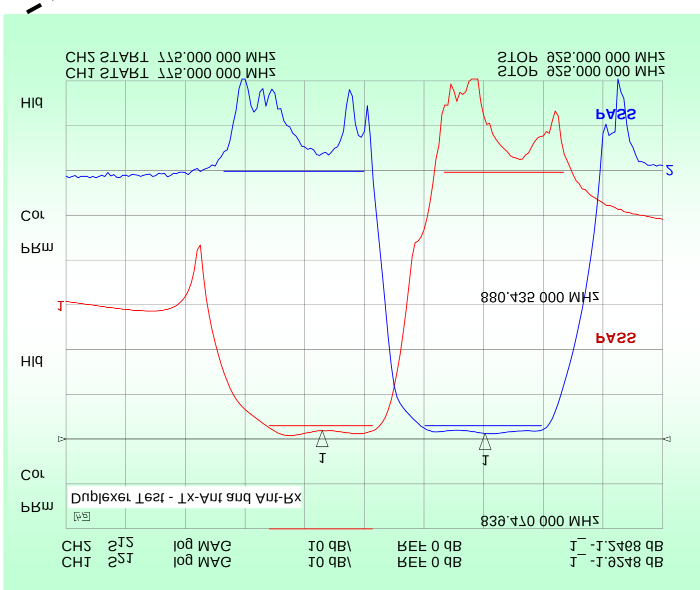
Processor / Display







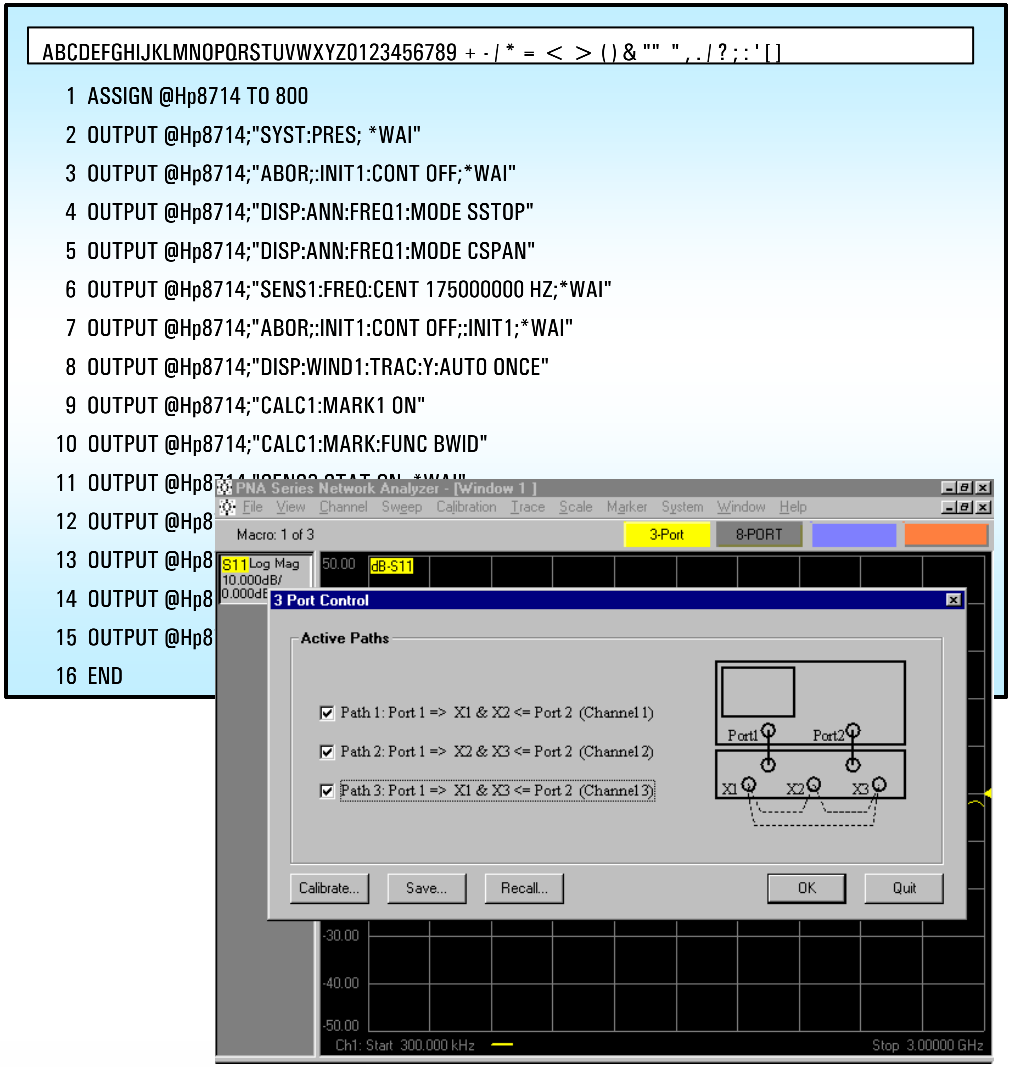
- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts

Internal Measurement Automation

Simple: **recall states**

More powerful:

- **Test sequencing**
  - available on 8753/ 8720 families
  - keystroke recording
  - some advanced functions
- **IBASIC**
  - available on 8712 family
  - sophisticated programs
  - custom user interfaces
- **Windows-compatible programs**
  - available on PNA Series
  - Visual Basic, VEE, LabView, C++, ...



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Agilent's Series of HF Vector Analyzers

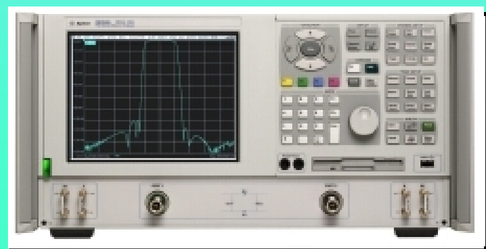
Microwave

8720/22 ET/ES series
- 13.5, 20, 40 GHz
- economical
- fast, small, integrated
- test mixers, high-power amps

8510C series
- 110 GHz *in coax*
- highest accuracy
- modular, flexible
- pulse systems

RF

8753ET/ES series
- 3, 6 GHz
- flexible hardware
- rich feature set
- offset and harmonic RF sweeps



PNA Series
- 3, 6, 9 GHz
- highest RF performance
- advanced connectivity
- internal automation, SCPI or COM/DCOM

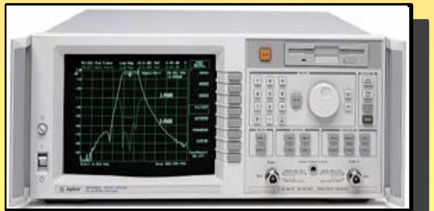
Agilent's LF/RF Vector Analyzers

Combination NA / SA

4395A/4396B

- 500 MHz (4395A), 1.8 GHz (4396B)
- impedance-measuring option
- fast, FFT-based spectrum analysis
- time-gated spectrum-analyzer option
- IBASIC
- standard test fixtures

RF



8712/14 ET/ES series

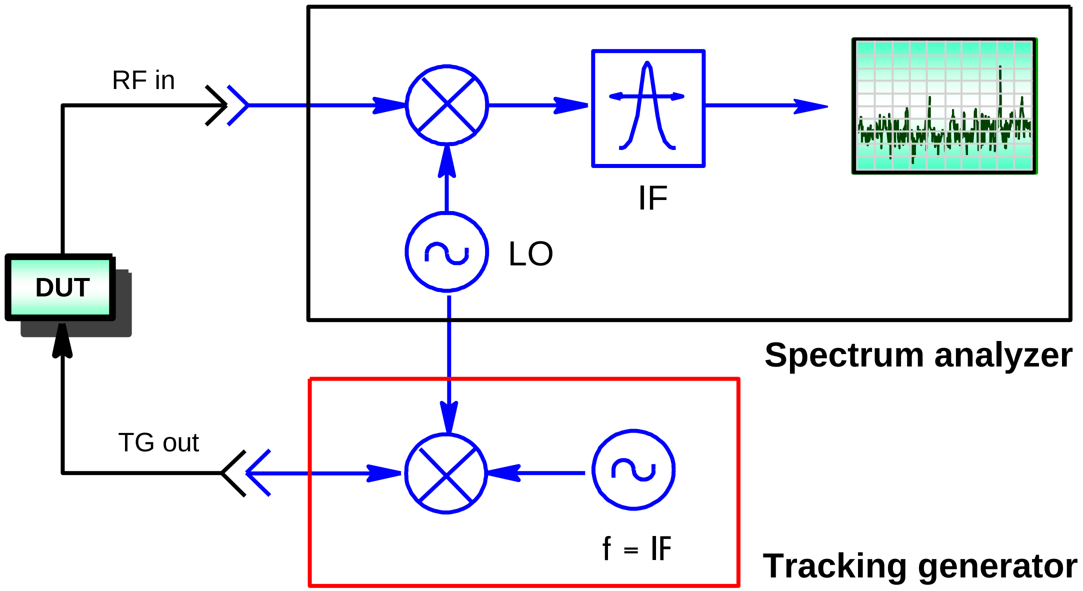
- 1.3, 3 GHz
- low cost
- narrowband and broadband detection
- IBASIC / LAN

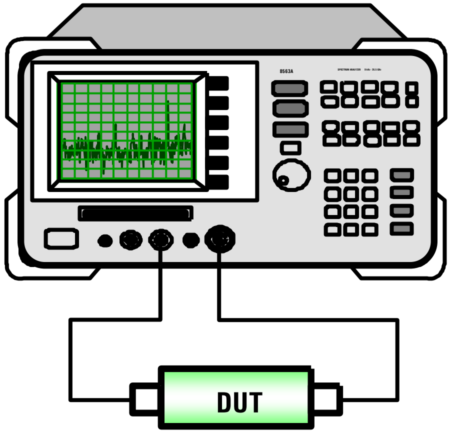
LF

E5100A/B

- 180, 300 MHz
- economical
- fast, small
- target markets: crystals, resonators, filters
- equivalent-circuit models
- evaporation-monitor-function option

Spectrum Analyzer / Tracking Generator





Key differences from network analyzer:

- **one channel** -- no ratioed or phase measurements
- More **expensive** than scalar NA (but better dynamic range)
- Only error correction available is **normalization** (and possibly open-short averaging)
- Less **accurate**
- Small **incremental cost** if SA is required for other measurements

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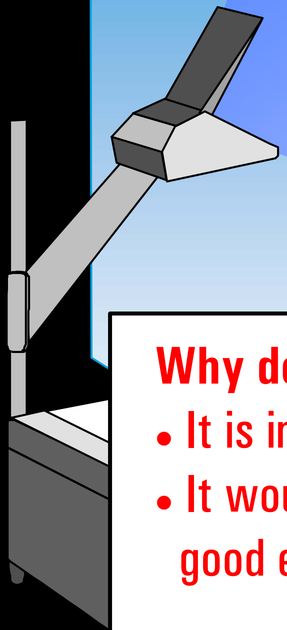
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix



Why do we even need error-correction and calibration?

- It is impossible to make perfect hardware
- It would be extremely expensive to make hardware good enough to eliminate the need for error correction

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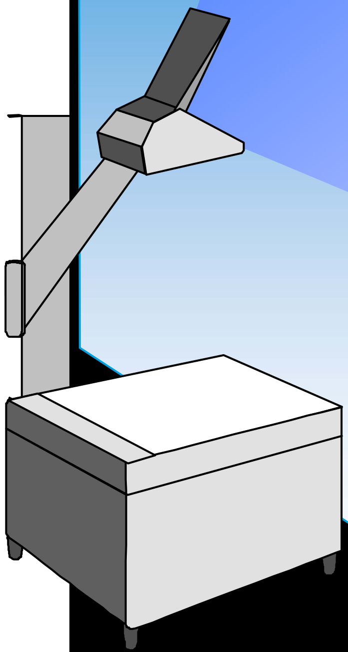
Calibration Topics



- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
  - measurement errors
  - what is vector error correction?
  - calibration types
  - accuracy examples
  - calibration considerations
- Example measurements
- Appendix

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Measurement Error Modeling

Systematic errors

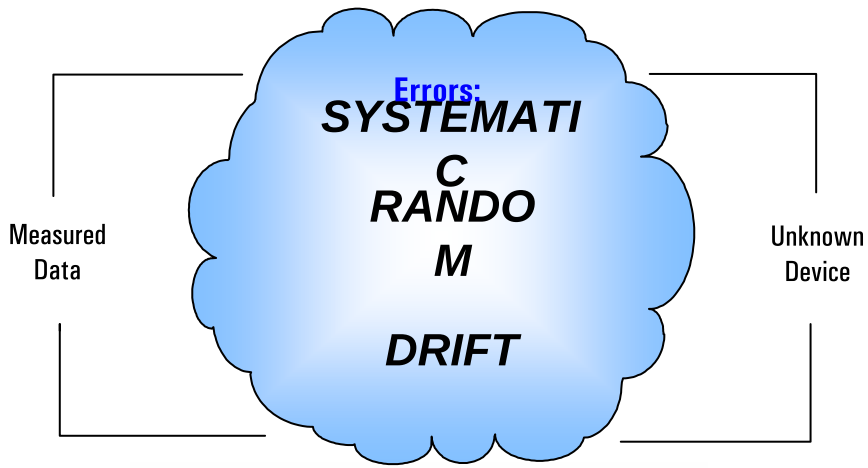
- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

Random errors

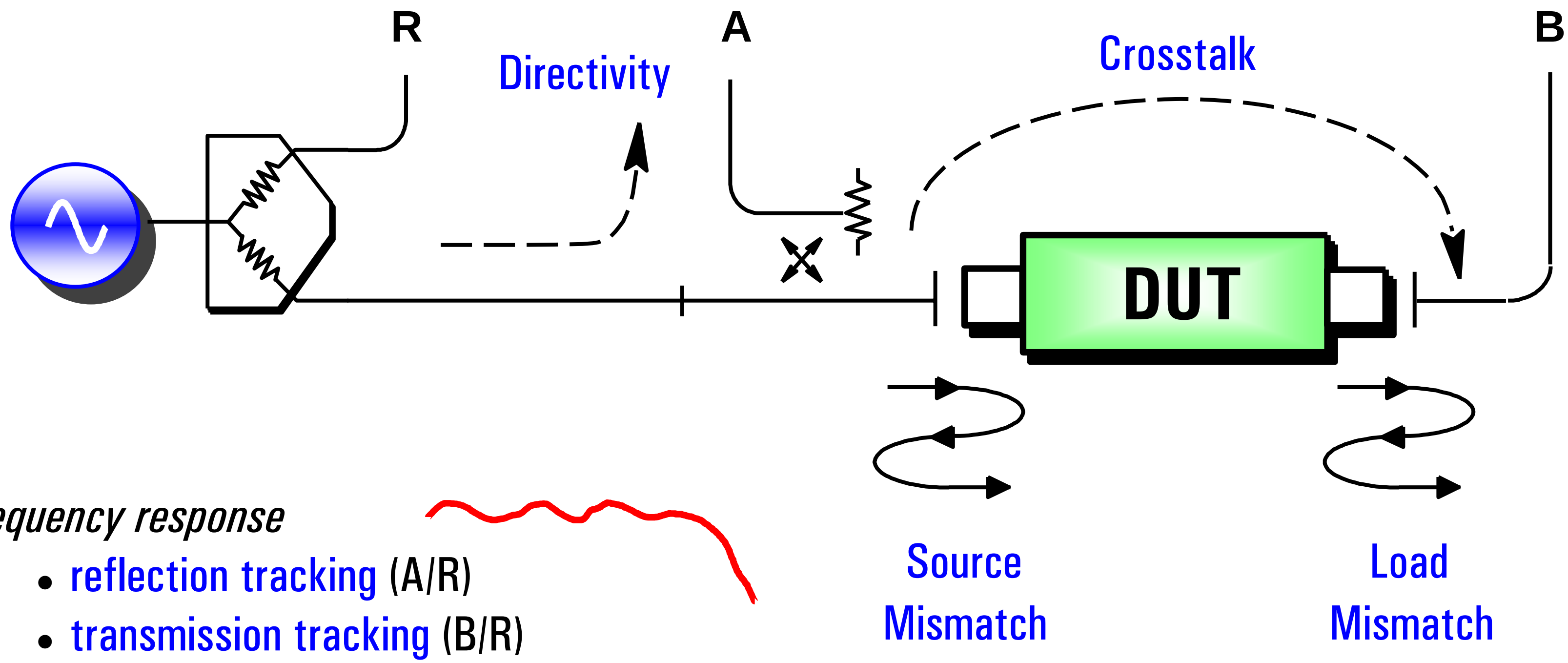
- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors

- due to system performance changing ***after*** a calibration has been done
- primarily caused by **temperature variation**



Systematic Measurement Errors



Frequency response

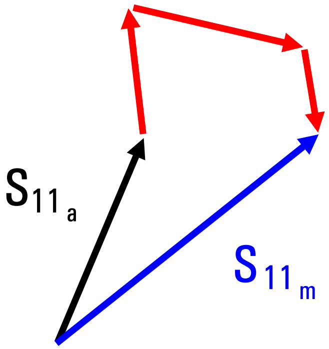
- reflection tracking (A/R)
- transmission tracking (B/R)

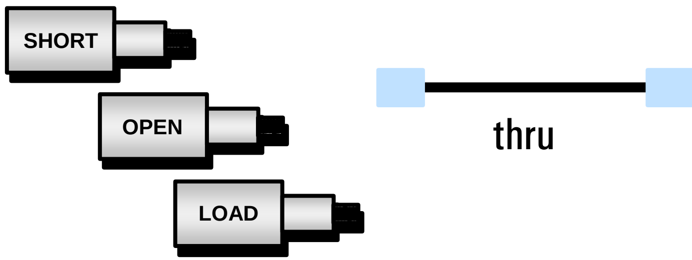
Six forward and six reverse error terms yields 12 error terms for two-port devices

Types of Error Correction

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





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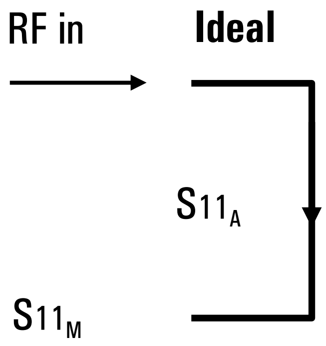
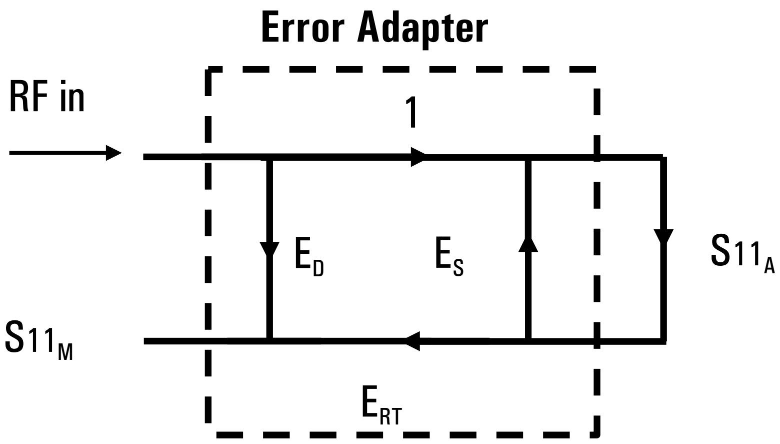
What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements
- **1-port calibration** *(reflection measurements)*
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit

Reflection: One-Port Model





E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

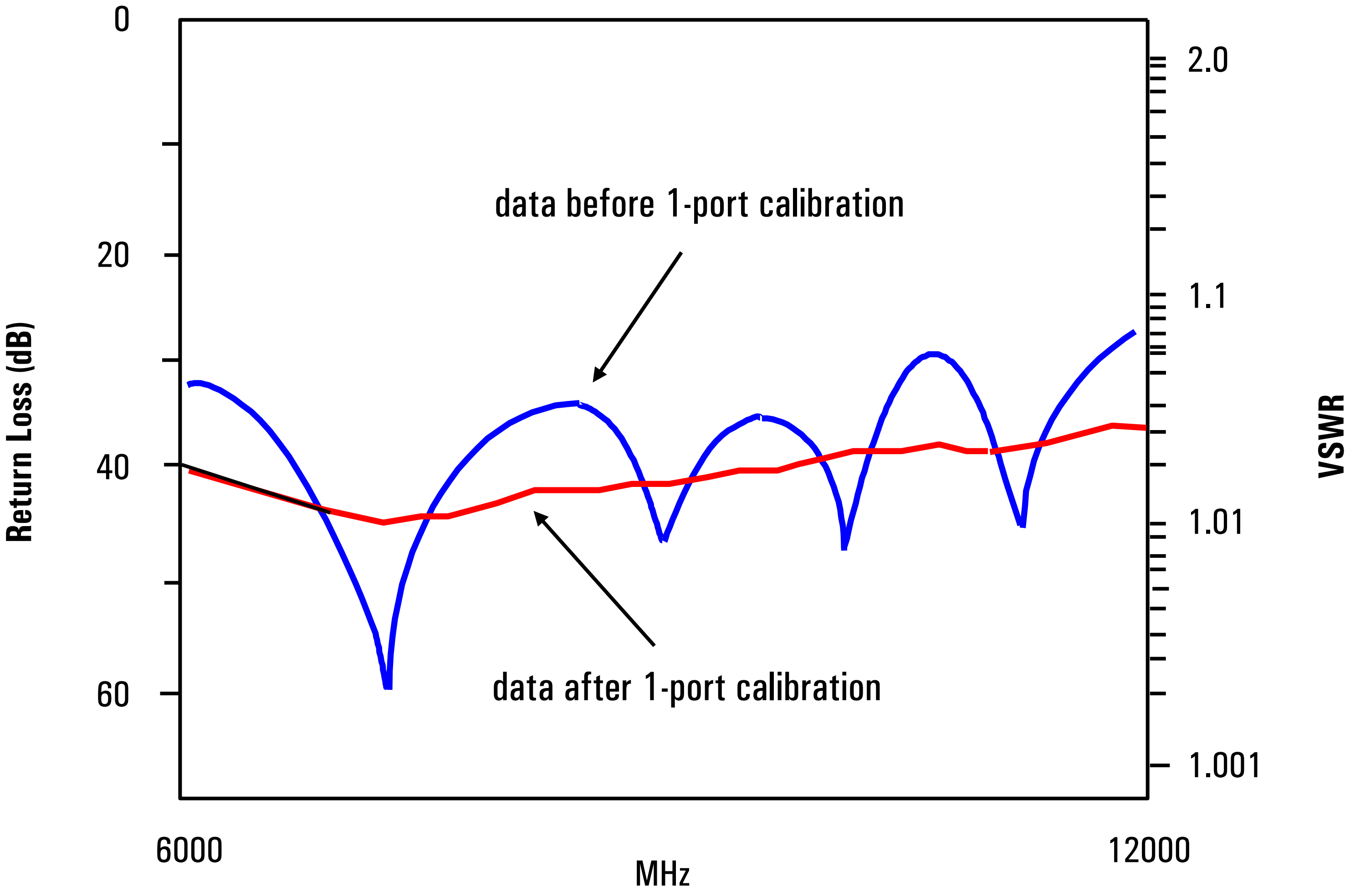
$S11_A$ = Actual

To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

$$S11_M = E_D + E_{RT}\left[\frac{S11_A}{1 - E_S\, S11_A}\right]$$

- Assumes good termination at port two if testing two-port devices
- If using port 2 of NA *and* DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results

Before and After One-Port Calibration



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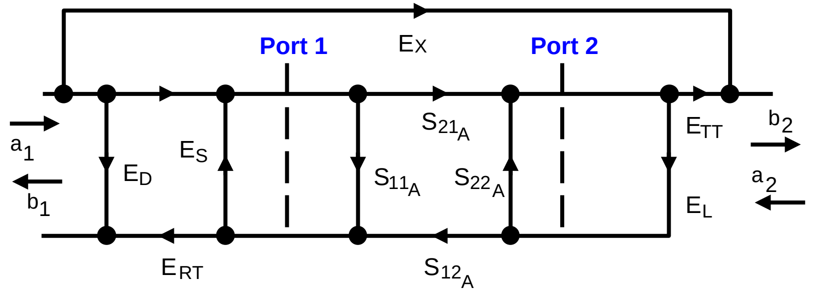
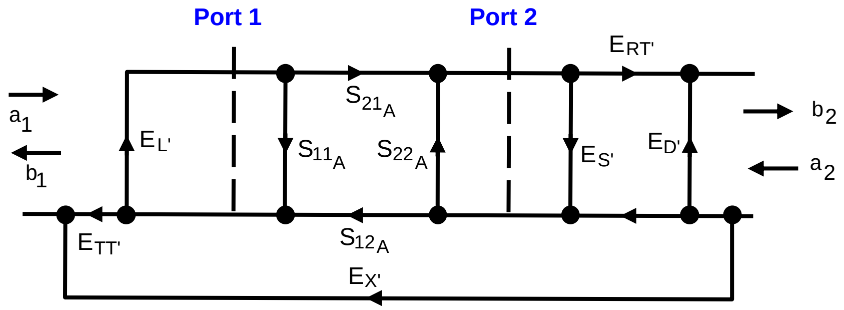
Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}E_{S'}\right) - E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}E_{S'}\right) - E_{L'}E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}(E_{S'}-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}E_{S'}\right) - E_{L'}E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_{L'})\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}E_{S'}\right) - E_{L'}E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m}-E_{D'}}{E_{RT'}}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right) - E_{L'}\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_{D'}}{E_{RT'}}E_{S'}\right) - E_{L'}E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_{X'}}{E_{TT'}}\right)}$$

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** network analyzers!!!

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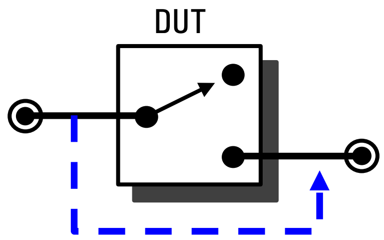
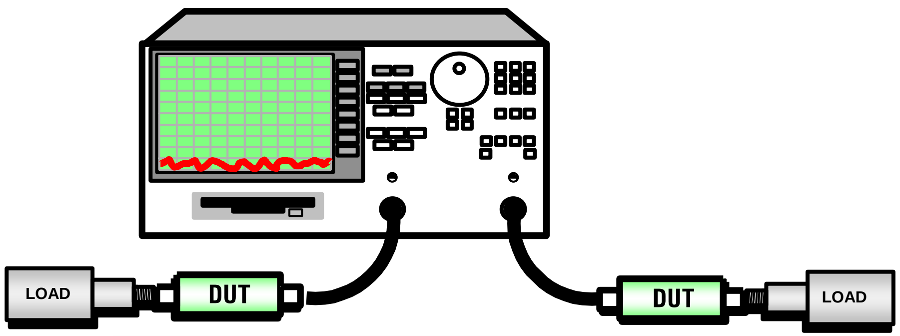
Crosstalk: Signal Leakage Between Test Ports During Transmission



- Can be a problem with:
  - high-isolation devices (e.g., switch in open position)
  - high-dynamic range devices (some filter stopbands)
- Isolation calibration
  - adds noise to error model (measuring near noise floor of system)
  - only perform if really needed (use averaging if necessary)
  - if crosstalk is **independent** of DUT match, use two terminations
  - if **dependent** on DUT match, use DUT with termination on output

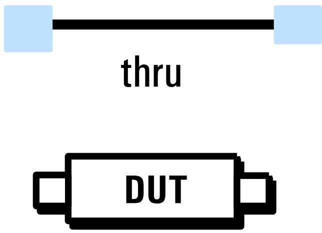


Errors and Calibration Standards

UNCORRECTED

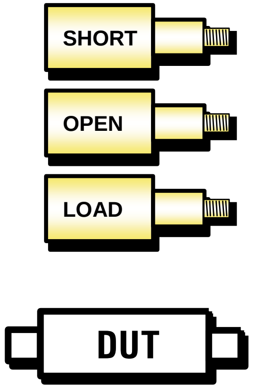
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



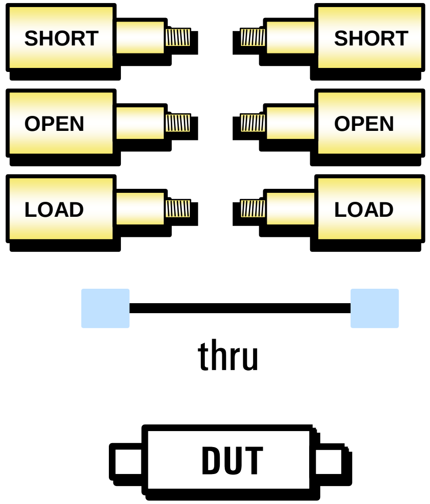
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

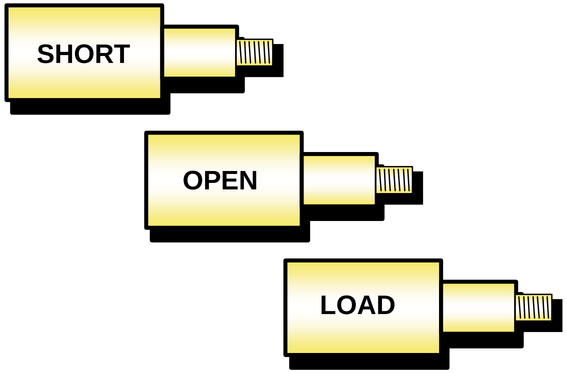
ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

Calibration Summary

Reflection

Reflection	Test Set (cal type): T/R (one-port)	Test Set (cal type): S-parameter (two-port)
• Reflection tracking	✓	✓
• Directivity	✓	✓
• Source match	✓	
• Load match	✗	



Transmission

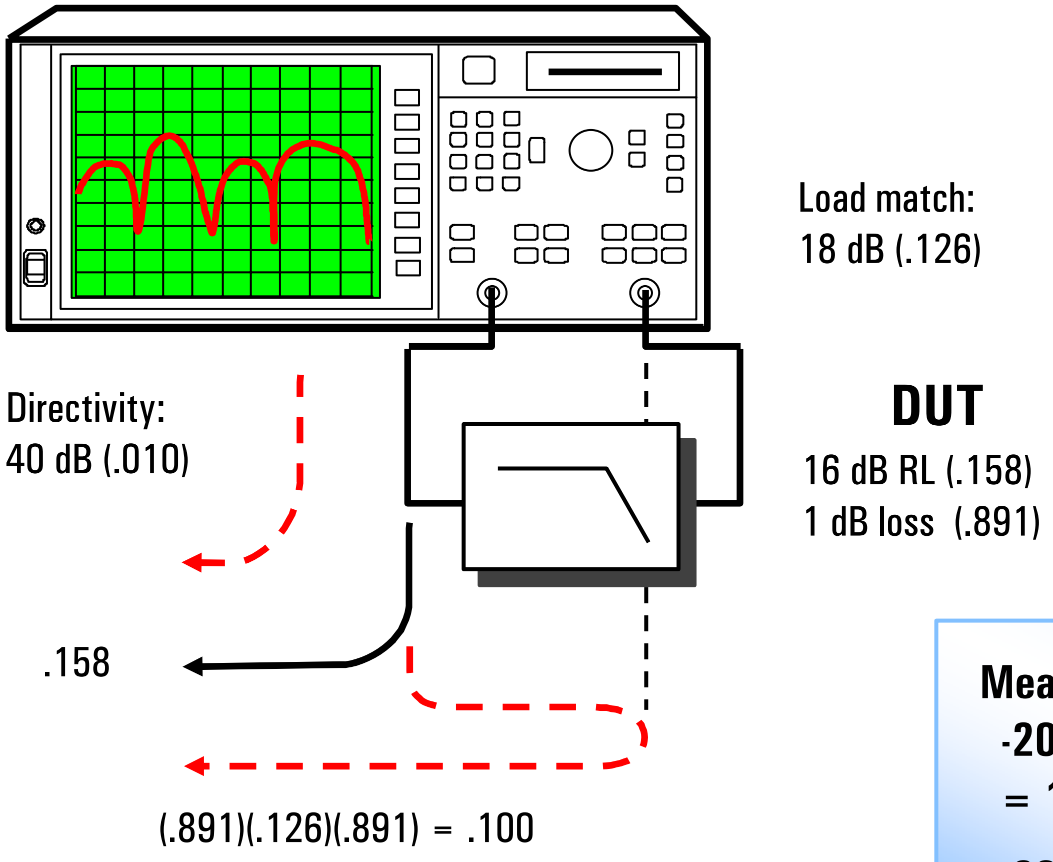
Transmission	Test Set (cal type): T/R (response, isolation)	Test Set (cal type): S-parameter (two-port)
• Transmission Tracking	✓	✓
• Crosstalk	✓	✓
• Source match	(✓*) ✗	✓
• Load match	✗	✓

✓ *error can be corrected*

✗ *error cannot be corrected*

✓ * *enhanced response cal* corrects for source match during transmission measurements

Reflection Example Using a One-Port Cal



Remember: convert all dB values to linear for uncertainty calculations!

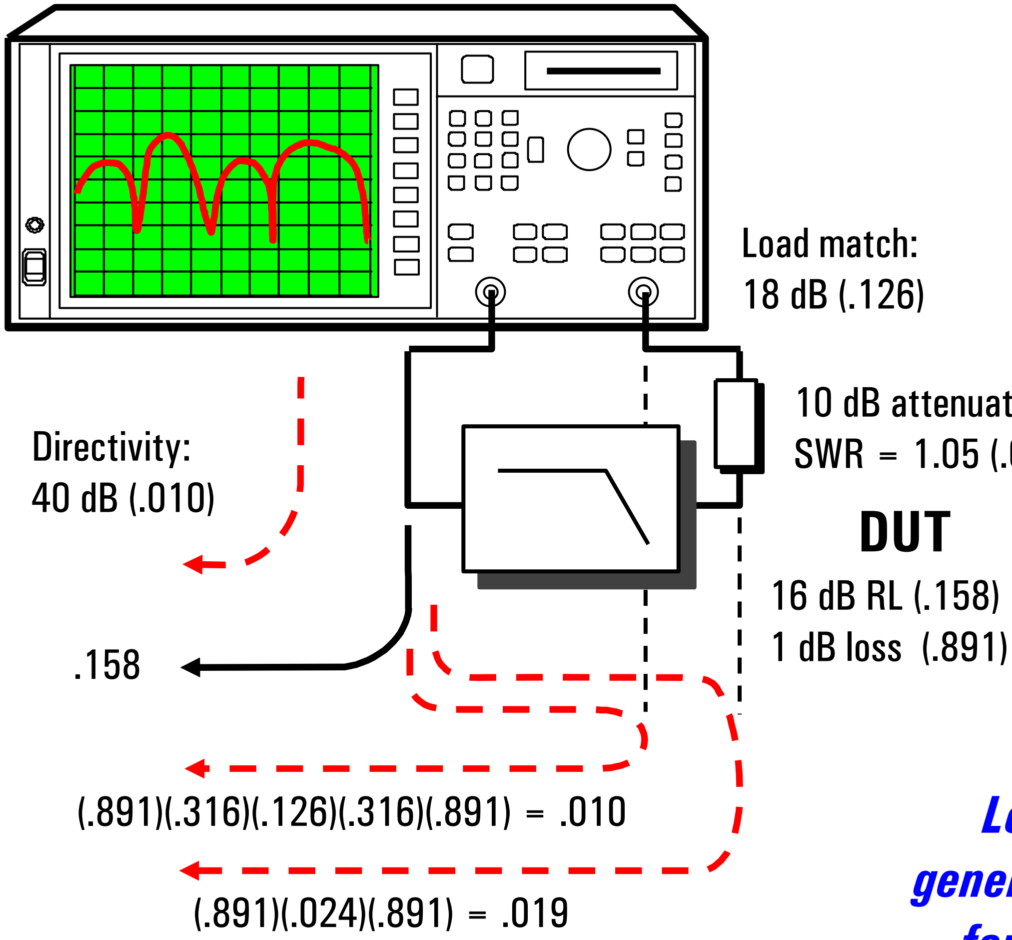
$$\rho \text{ or loss}_{(linear)} = 10^{\left(\frac{-dB}{20}\right)}$$

Measurement uncertainty:

-20 * log (.158 + .100 + .010)
= 11.4 dB (-4.6dB)

-20 * log (.158 - .100 - .010)
= 26.4 dB (+10.4 dB)

Using a One-Port Cal + Attenuator



Worst-case error = .010 + .010 + .019 = .039

Measurement uncertainty:

-20 * log (.158 + .039)

= 14.1 dB (-1.9 dB)

-20 * log (.158 - .039)

= 18.5 dB (+2.5 dB)

Low-loss bi-directional devices generally require two-port calibration for low measurement uncertainty

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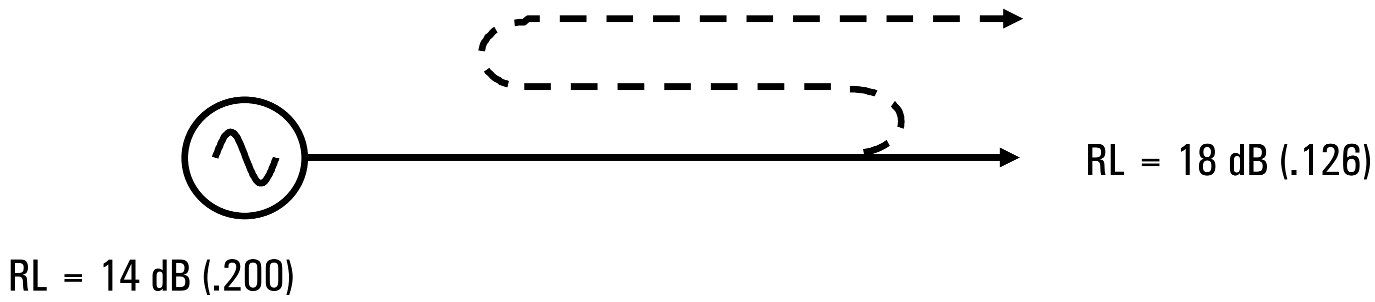
Transmission Example Using Response Cal



Thru calibration (normalization) builds error into measurement due to source and load match interaction

Calibration Uncertainty

$= (1 \pm \rho_S \rho_L)$

$= (1 \pm (.200)(.126)$

$= \pm 0.22$ dB

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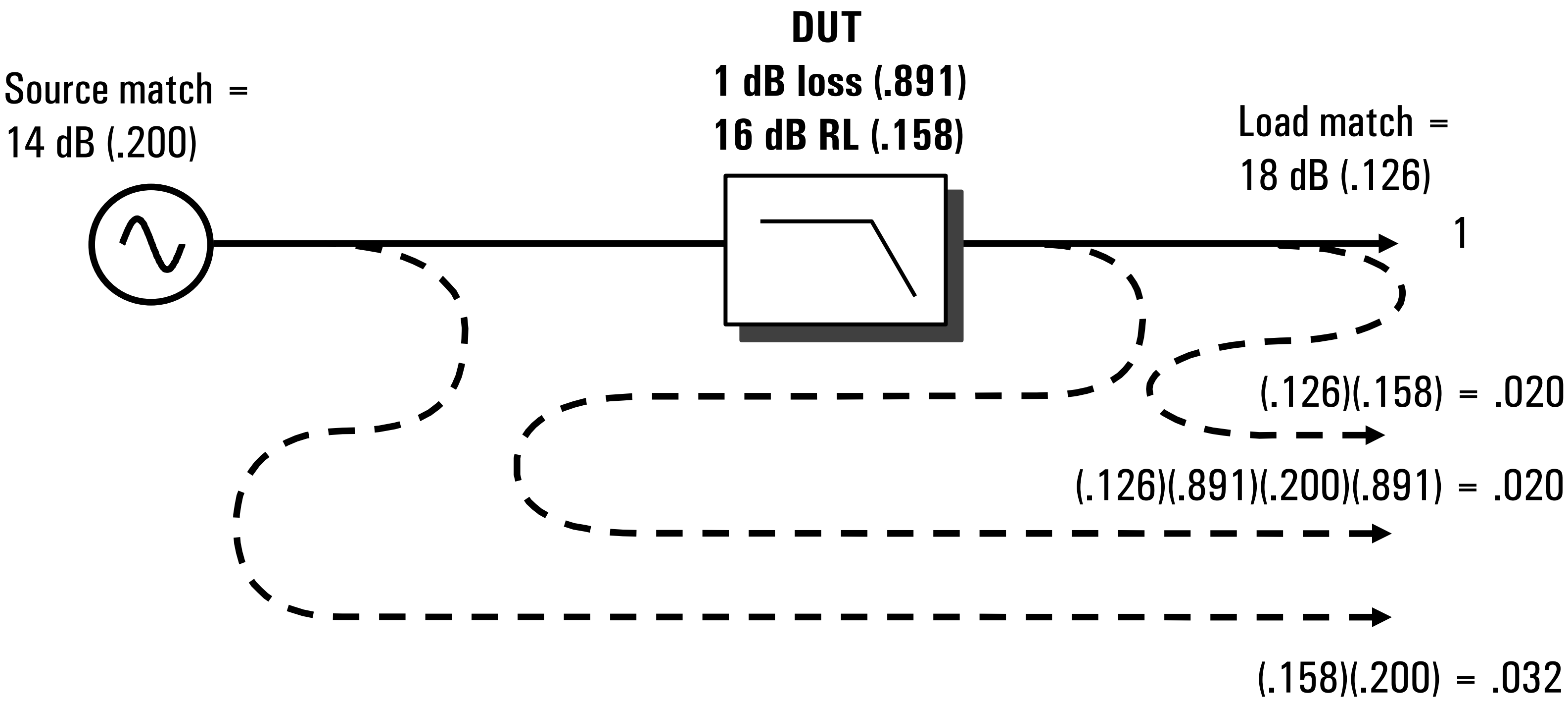
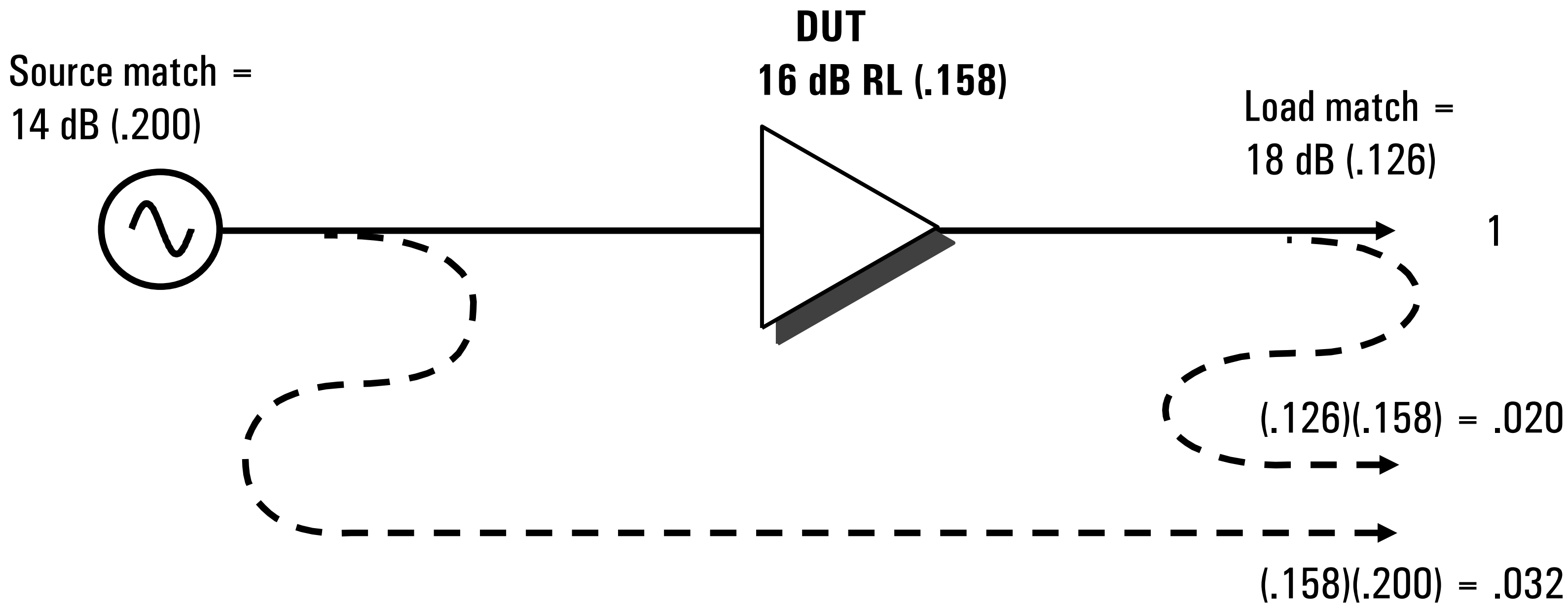
Filter Measurement with Response Cal



Total measurement uncertainty:
+0.60 + 0.22 = + 0.82 dB
-0.65 - 0.22 = - 0.87 dB

Measurement uncertainty
$= 1 \pm (.020 + .020 + .032)$
$= 1 \pm .072$
$= + 0.60$ dB
$- 0.65$ dB

Measuring Amplifiers with a Response Cal



Total measurement uncertainty:
+0.44 + 0.22 = + 0.66 dB
-0.46 - 0.22 = - 0.68 dB

Measurement uncertainty
= 1 ± (.020+.032)
= 1 ± .052
= + 0.44 dB
- 0.46 dB

Filter Measurements using the *Enhanced Response* Calibration

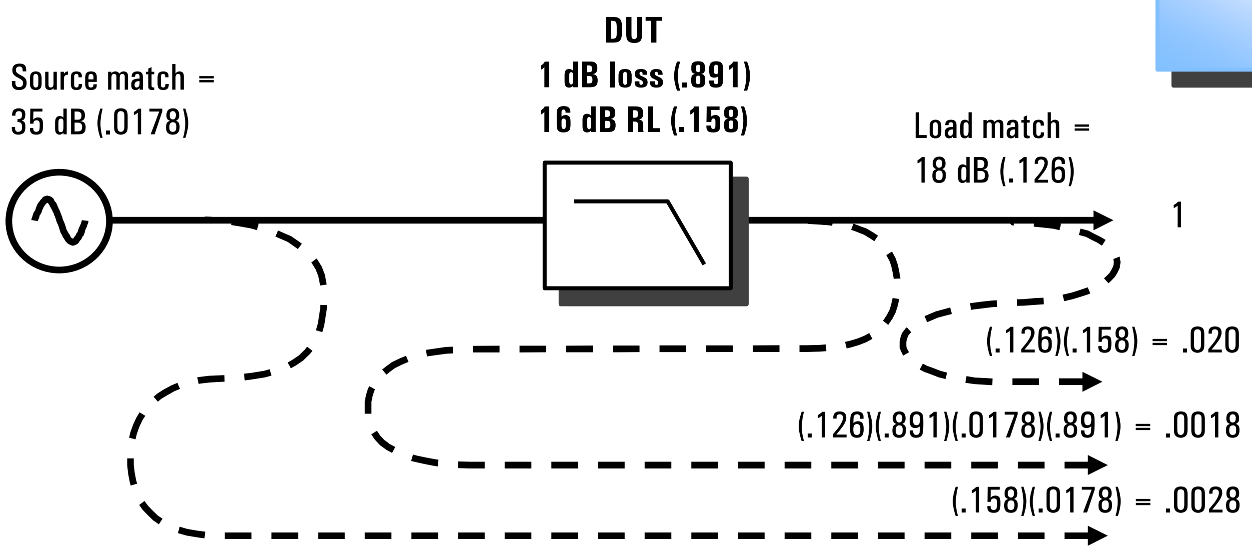
Effective source match = 35 dB!

Calibration Uncertainty

$= (1 \pm \rho_S \, \rho_L)$

$= (1 \pm (.0178)(.126)$

$= \pm .02$ dB



Measurement uncertainty

$= 1 \pm (.020 + .0018 + .0028)$

$= 1 \pm .0246$

$= + 0.211$ dB

$- 0.216$ dB

Total measurement uncertainty:
0.22 + .02 = ± 0.24 dB

Using the *Enhanced Response* Calibration Plus an Attenuator

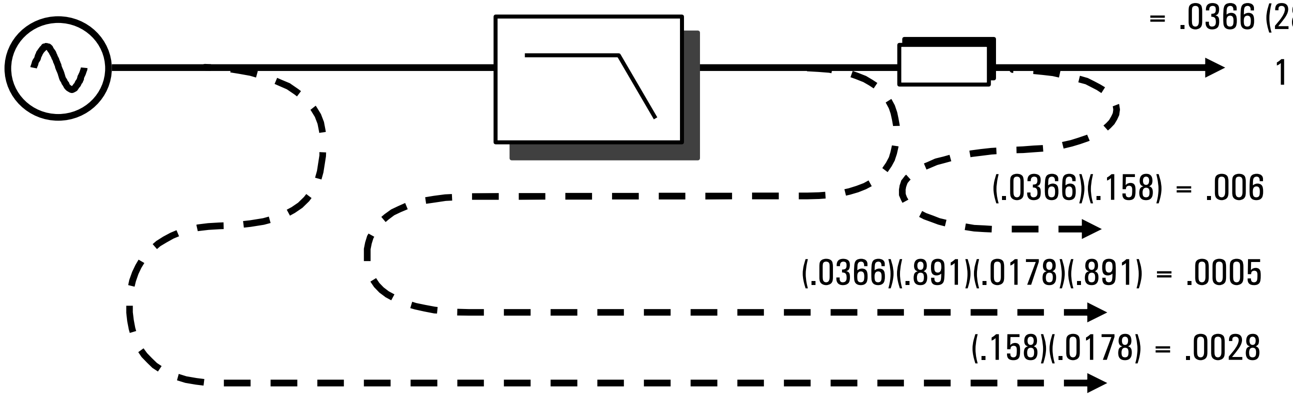
10 dB attenuator (.316)
SWR = 1.05 (.024 linear or 32.4 dB)
Analyzer load match = 18 dB (.126)

Calibration Uncertainty
$= (1 \pm \rho_S \rho_L)$
$= (1 \pm (.0178)(.0366)$
$= \pm .01$ dB

Source match = 35 dB (.0178)

DUT
1 dB loss (.891)
16 dB RL (.158)

Effective load match = (.316)(.316)(.126) + .024
= .0366 (28.7dB)



Measurement uncertainty
$= 1 \pm (.006 + .0005 + .0028)$
$= 1 \pm .0093$
$= \pm 0.08$ dB

Total measurement uncertainty:
$0.01 + .08 = \pm 0.09$ dB

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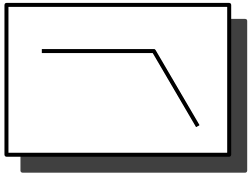
Calculating Measurement Uncertainty After a Two-Port Calibration



DUT
1 dB loss (.891)
16 dB RL (.158)

Corrected error terms:
(8753ES 1.3-3 GHz Type-N)

Directivity	=	47 dB
Source match	=	36 dB
Load match	=	47 dB
Refl. tracking	=	.019 dB
Trans. tracking	=	.026 dB
Isolation	=	100 dB

Reflection uncertainty

$$S_{11m} = S_{11a} \pm (E_D + S_{11a}^2 E_S + S_{21a} S_{12a} E_L + S_{11a}(1 - E_{RT}))$$

$$= 0.158 \pm (.0045 + 0.158^2 * .0158 + 0.891^2 * .0045 + 0.158 * .0022)$$

$= 0.158 \pm .0088 = 16$ dB **+0.53 dB, -0.44 dB (worst-case)**

Transmission uncertainty

$$S_{21m} = S_{21a} \pm S_{21a}(E_I / S_{21a} + S_{11a} E_S + S_{21a} S_{12a} E_S E_L + S_{22a} E_L + (1 - E_{TT}))$$

$$= 0.891 \pm 0.891(10^{-5} / 0.891 + 0.158 * .0158 + 0.891^2 * .0158 * .0045 + 0.158 * .0045 + .003)$$

$= 0.891 \pm .0056 = 1$ dB **±0.05 dB (worst-case)**

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Comparison of Measurement Examples

Reflection

Calibration type	Measurement uncertainty
One-port	-4.6/ 10.4 dB
One-port + attenuator	-1.9/ 2.5 dB
Two-port	-0.44/ 0.53 dB

Transmission

Calibration type	Calibration uncertainty	Measurement uncertainty	Total uncertainty
Response	±0.22 dB	0.60/ -0.65 dB	0.82/ -0.87
Enhanced response	±0.02 dB	±0.22 dB	±0.24
Enh. response + attenuator	±0.01 dB	±0.08 dB	±0.09
Two port	-----		±0.05

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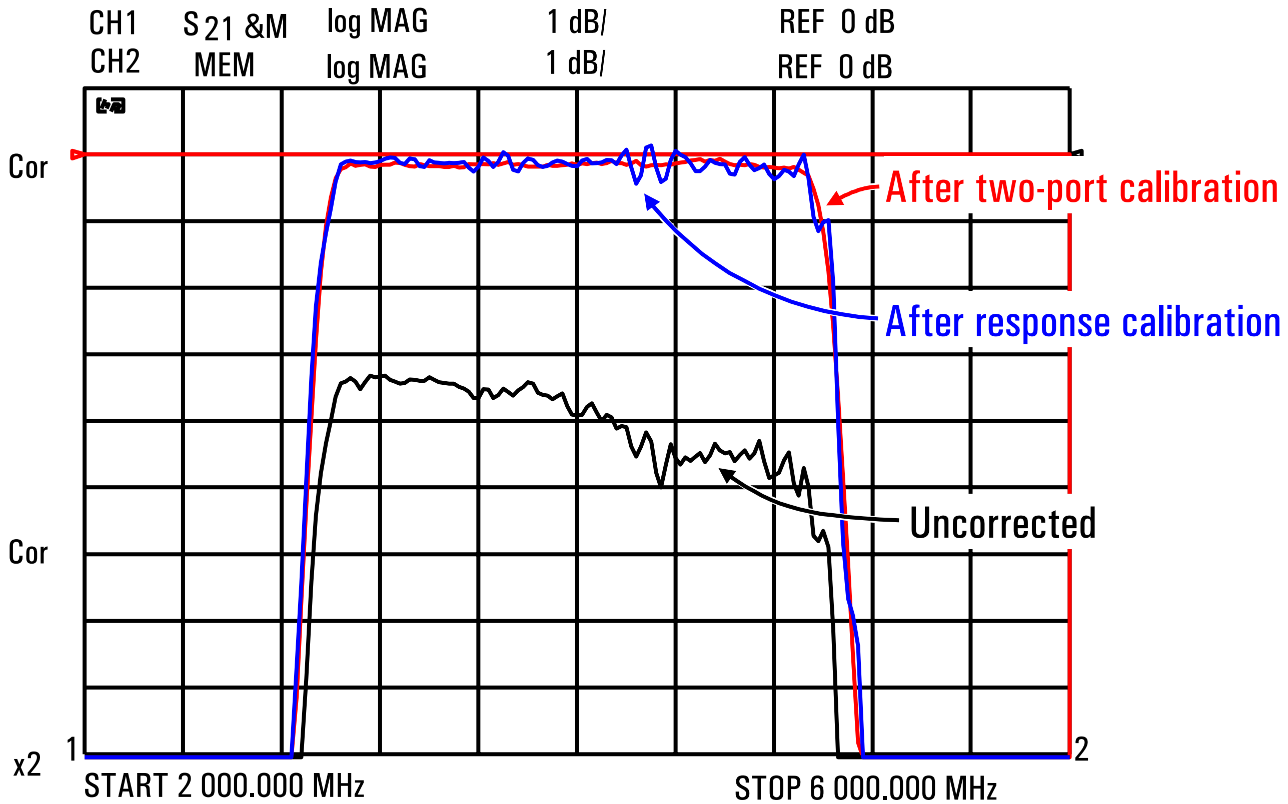
Response versus Two-Port Calibration

Measuring filter insertion loss



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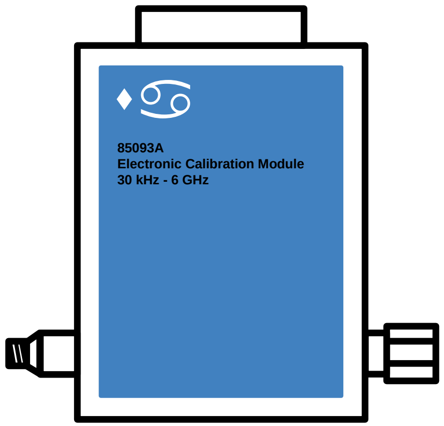
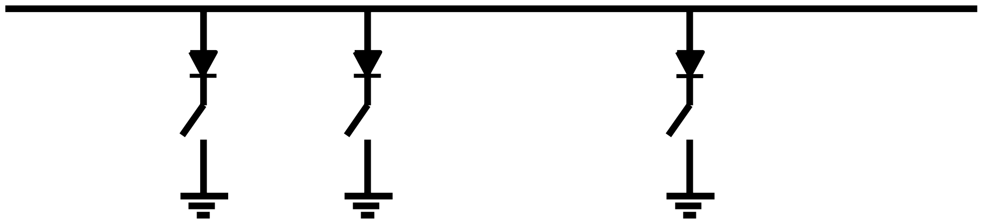
ECal: Electronic Calibration (85060/90 series)

- Variety of modules cover 30 kHz to 26.5 GHz
- Six connector types available (50 Ω and 75 Ω)
- Single-connection
  - reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated terminations provide excellent accuracy





Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

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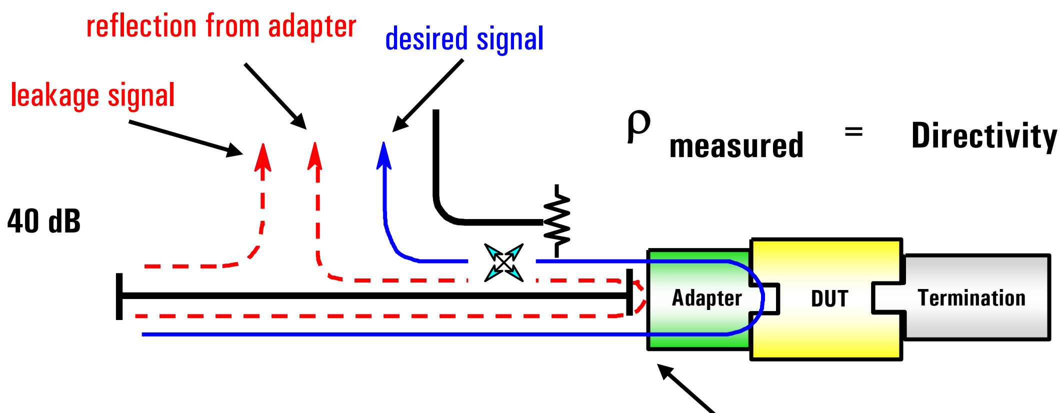
Adapter Considerations



Coupler directivity = 40 dB

$$\rho_{\text{measured}} = \text{Directivity} + \rho_{\text{adapter}} + \rho_{\text{DUT}}$$

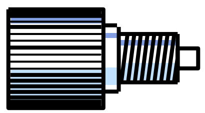
DUT has SMA (f) connectors

APC-7 calibration done here

Worst-case
System Directivity

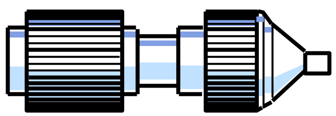
Adapting from APC-7 to SMA (m)

28 dB



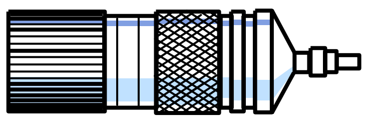
APC-7 to SMA (m)
SWR:1.06

17 dB



APC-7 to N (f) + N (m) to SMA (m)
SWR:1.05 SWR:1.25

14 dB

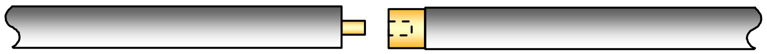


APC-7 to N (m) + N (f) to SMA (f) + SMA (m) to (m)
SWR:1.05 SWR:1.25 SWR:1.15

Calibrating Non-Insertable Devices

When doing a through cal, normally test ports mate directly

- cables can be connected directly without an adapter
- result is a zero-length through

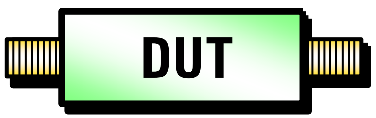


What is an insertable device?

- has same type of connector, but different sex on each port
- has same type of sexless connector on each port (e.g. APC-7)

What is a non-insertable device?

- one that cannot be inserted in place of a zero-length through
- has same connectors on each port (type and sex)
- has different type of connector on each port
  (e.g., waveguide on one port, coaxial on the other)



What calibration choices do I have for non-insertable devices?

- use an *uncharacterized* through adapter
- use a *characterized* through adapter (modify cal-kit definition)
- swap equal adapters
- adapter removal

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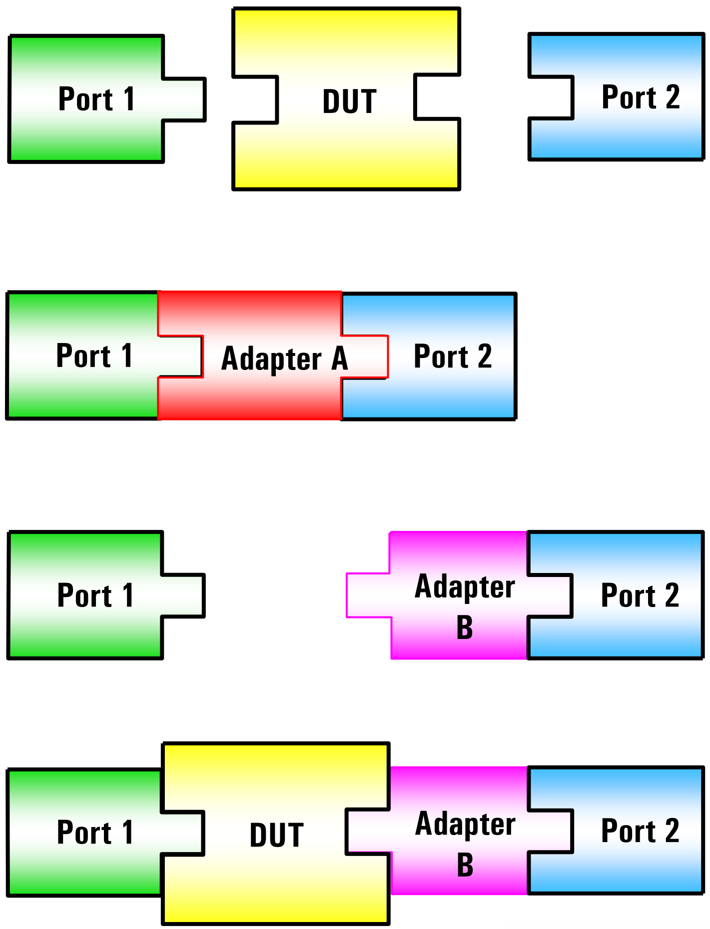
Swap Equal Adapters Method



Accuracy depends on how well the adapters are matched - loss, electrical length, match and impedance should all be equal

1. Transmission cal using adapter A.
2. Reflection cal using adapter B.
3. Measure DUT using adapter B.

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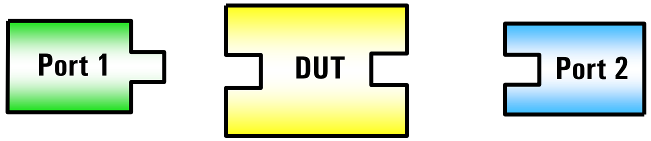
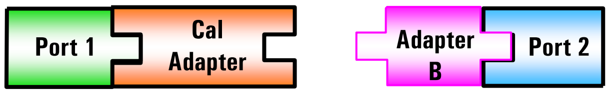
Adapter Removal Calibration

- Calibration is very accurate and traceable
- In firmware of 8753, 8720 and 8510 series
- Also accomplished with ECal modules (85060/90)
- Uses adapter with same connectors as DUT
- Must specify electrical length of adapter to within 1/4 wavelength of highest frequency (to avoid phase ambiguity)



Cal Set 1

1. Perform 2-port cal with adapter on port 2. Save in cal set 1.

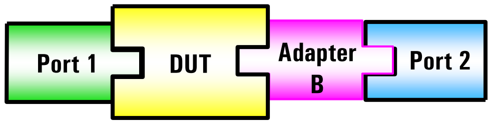


Cal Set 2

2. Perform 2-port cal with adapter on port 1. Save in cal set 2.

[CAL] [MORE] [MODIFY CAL SET]
[ADAPTER REMOVAL]

3. Use ADAPTER REMOVAL to generate new cal set.



4. Measure DUT without cal adapter.

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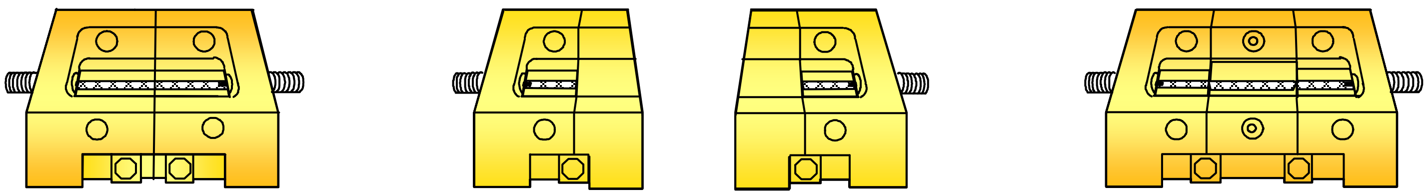
Thru-Reflect-Line (TRL) Calibration

We know about Short-Open-Load-Thru (SOLT) calibration...
What is TRL?

- A two-port calibration technique
- Good for noncoaxial environments (waveguide, fixtures, wafer probing)
- Uses the same 12-term error model as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Two variations: TRL (requires 4 receivers) and TRL* (only three receivers needed)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

TRL was developed for ***non-coaxial microwave*** *measurements*



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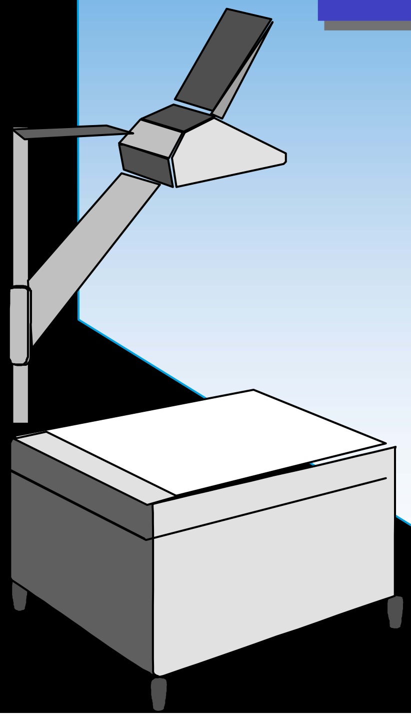
Agenda



- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix

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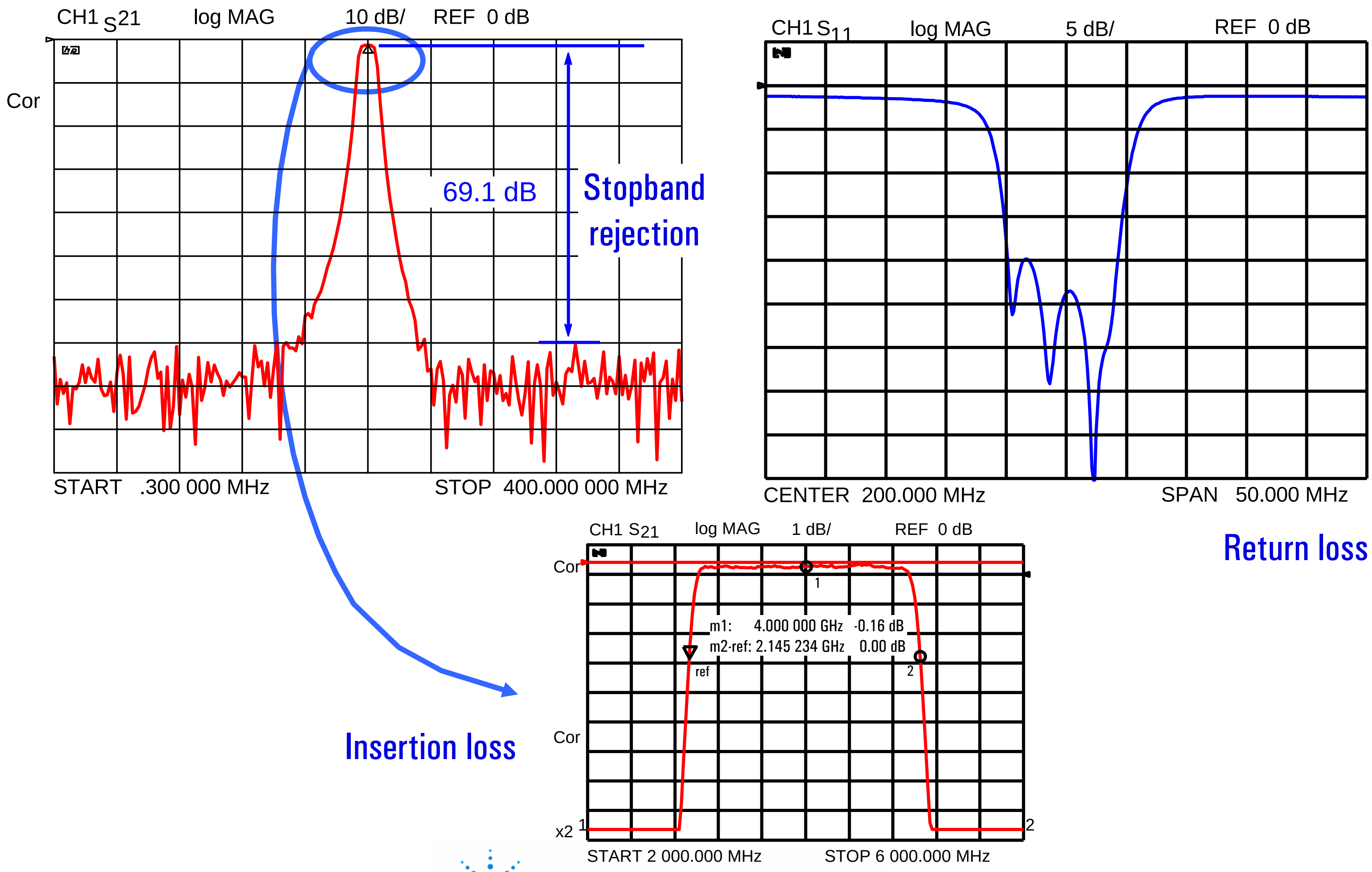
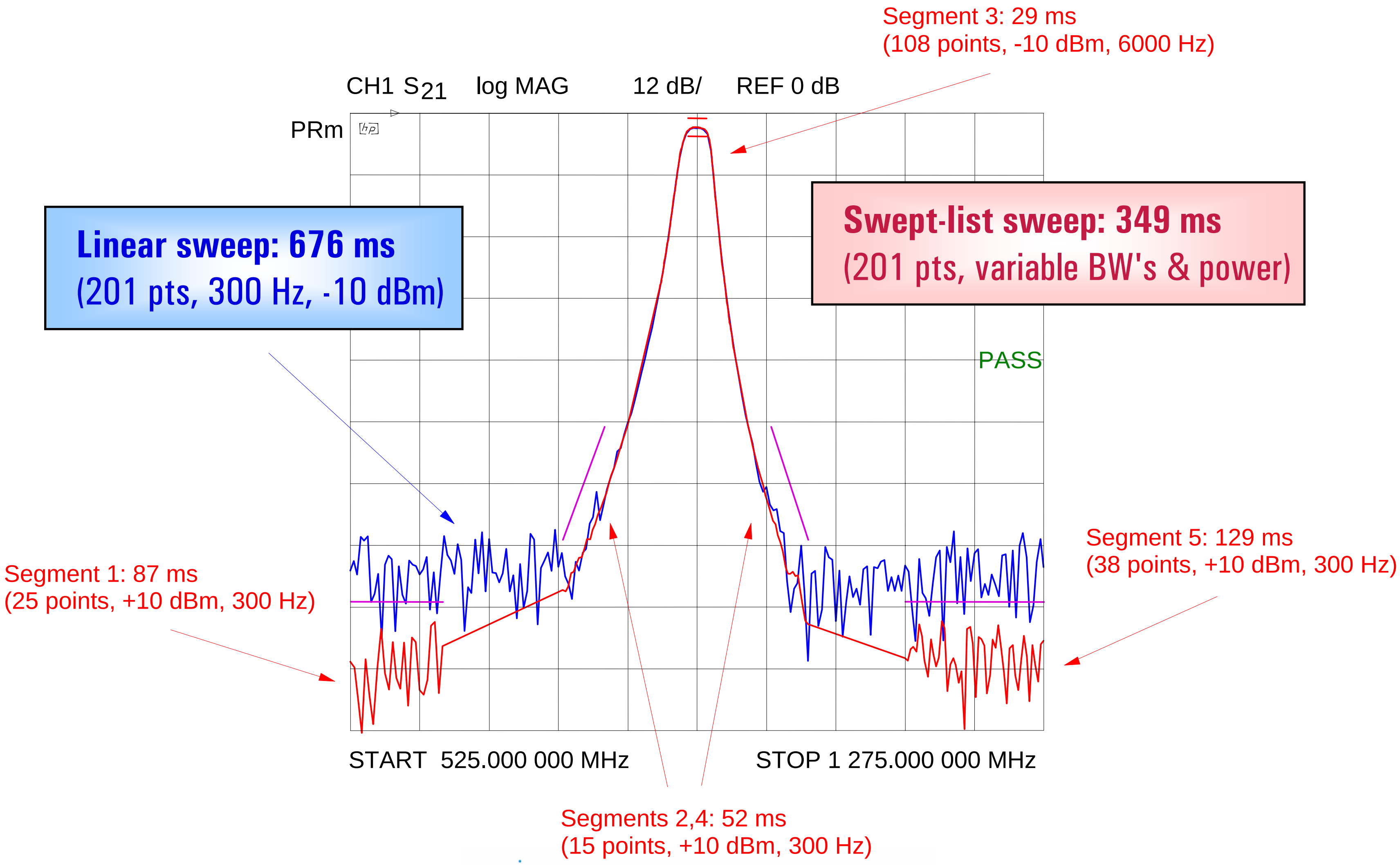
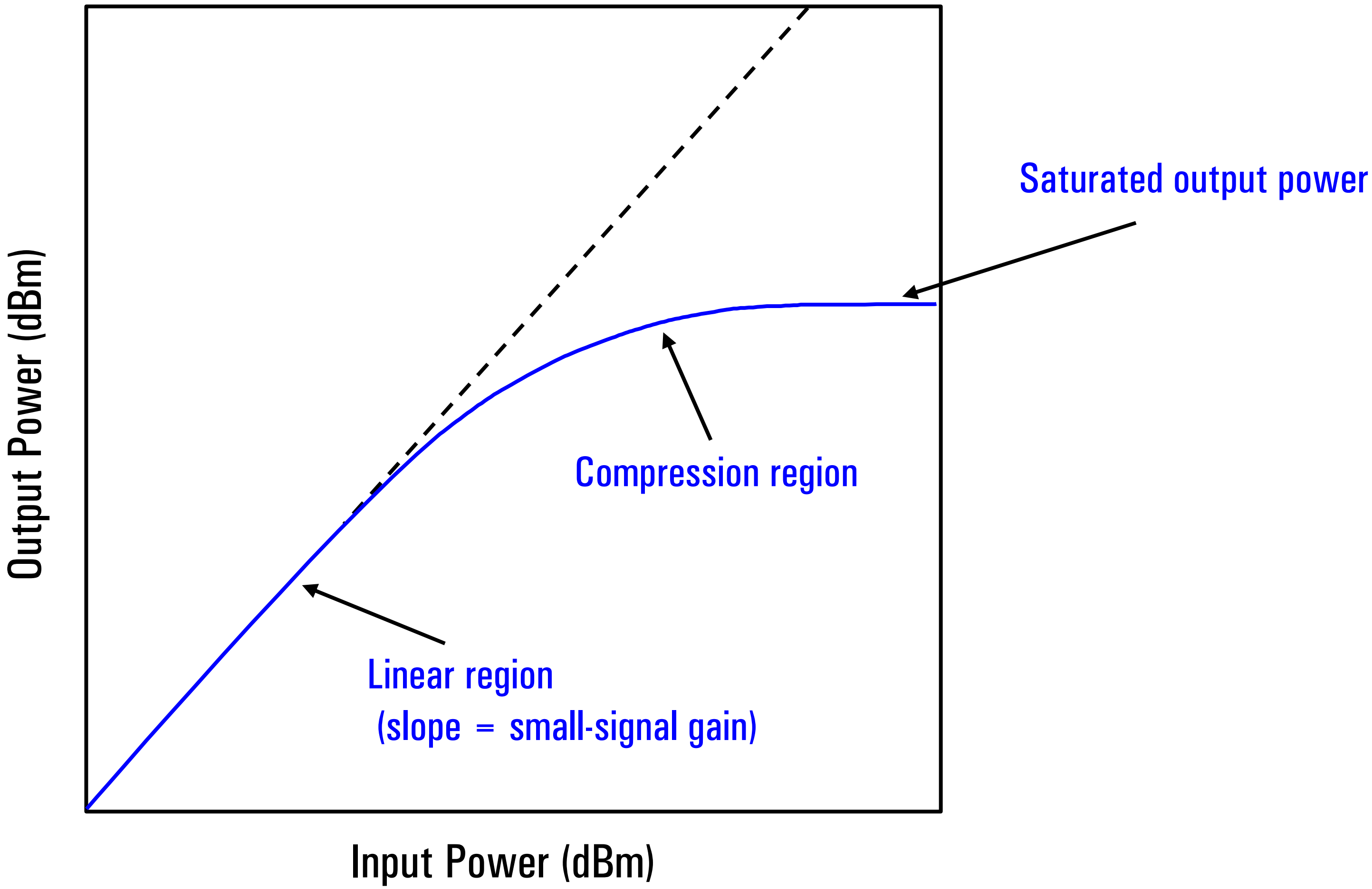
Frequency Sweep - Filter Test



Optimize Filter Measurements with Swept-List Mode



Power Sweeps - Compression



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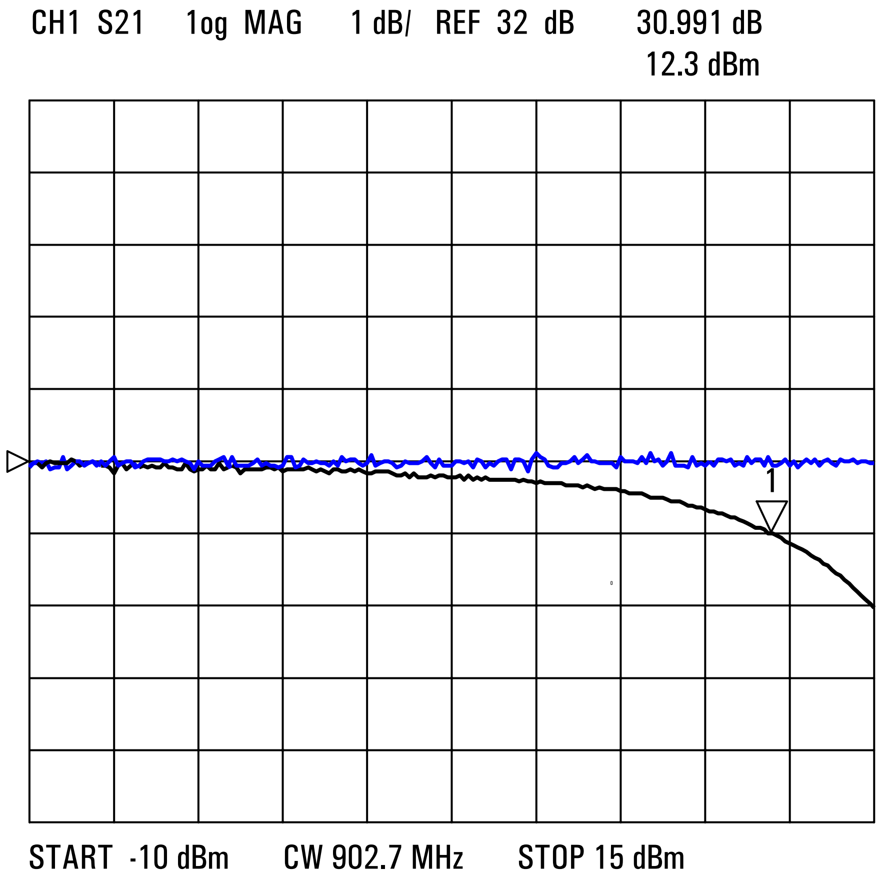
Power Sweep - Gain Compression



1 dB compression:
input power resulting in 1 dB *drop* in gain

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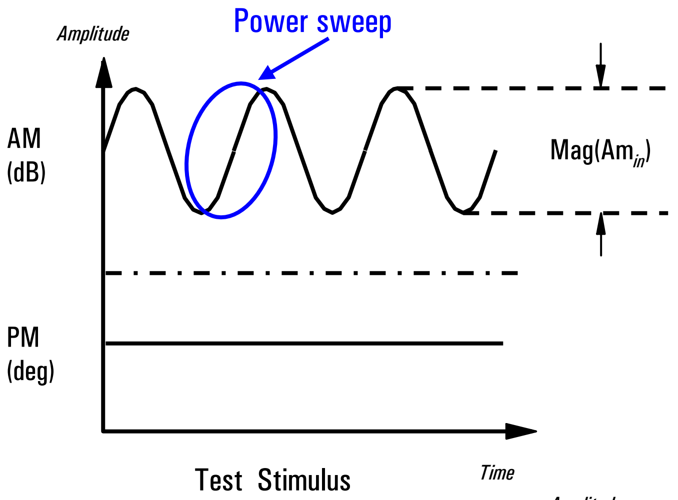
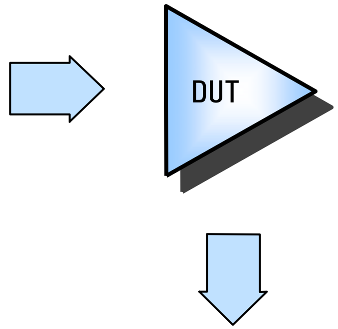
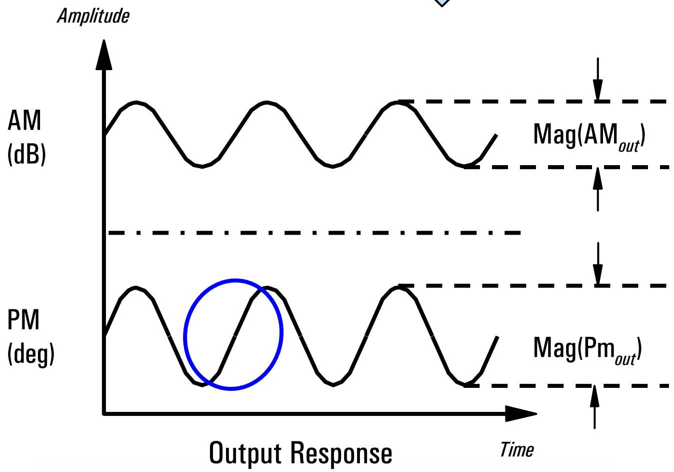
AM to PM Conversion

Measure of phase deviation caused by amplitude variations



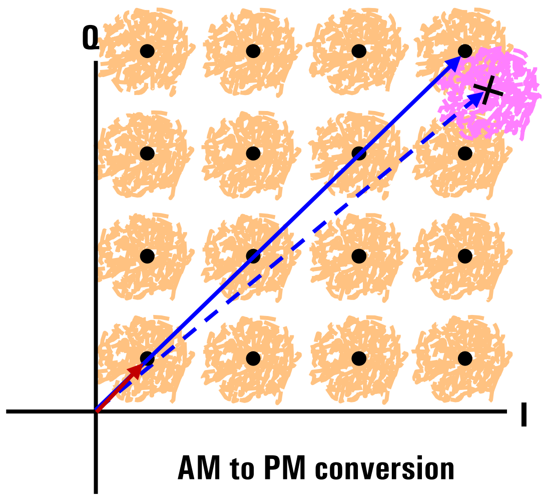


- AM can be undesired:
  supply ripple, fading, thermal
- AM can be desired:
  modulation (e.g. QAM)



AM - PM Conversion =

$$\frac{Mag(Pm_{out})}{Mag(Am_{in})} \quad \text{(deg/dB)}$$



AM to PM conversion can cause bit errors

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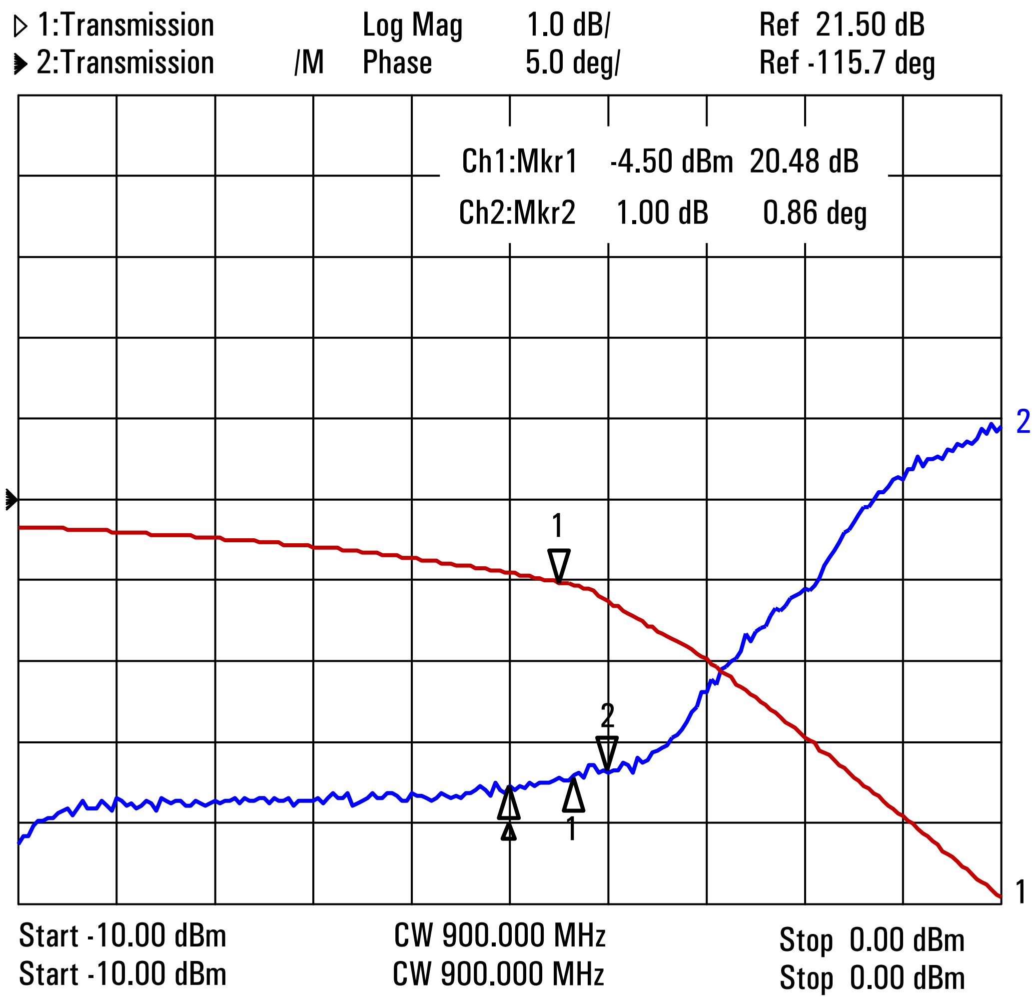
Measuring AM to PM Conversion



- Use transmission setup with a power sweep
- Display phase of S21
- AM - PM = 0.86 deg/dB

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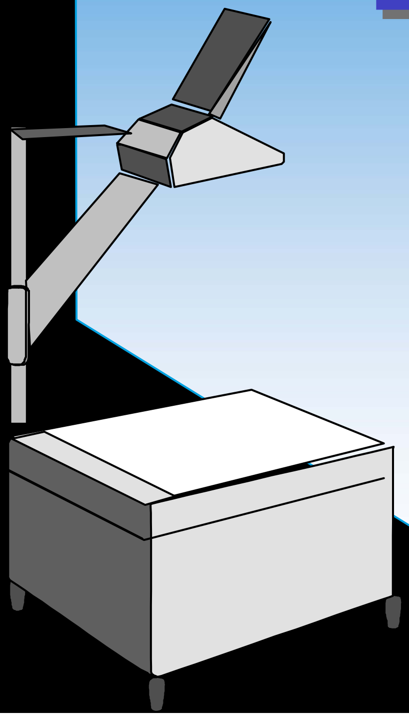
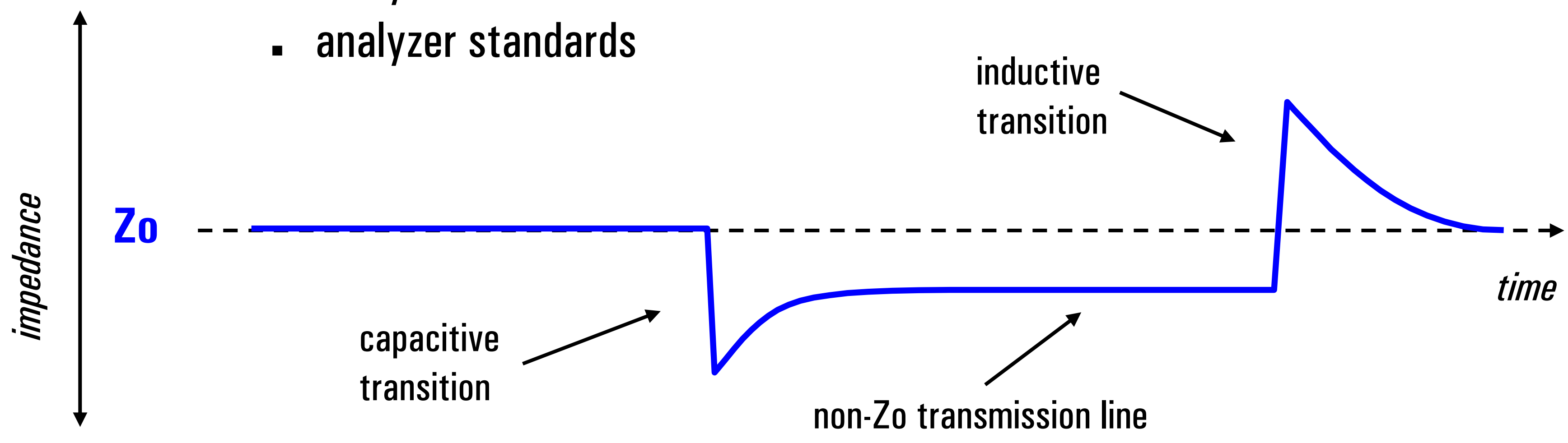


- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- **Appendix**
  - Advanced Topics
    - time domain
    - frequency-translating devices
    - high-power amplifiers
    - extended dynamic range
    - multiport devices
    - in-fixture measurements
    - crystal resonators
    - balanced measurements
  - Inside the network analyzer
  - Challenge quiz!

Time-Domain Reflectometry (TDR)

- What is TDR?
  - time-domain reflectometry
  - analyze impedance versus time
  - distinguish between inductive and capacitive transitions
- With gating:
  - analyze transitions
  - analyzer standards



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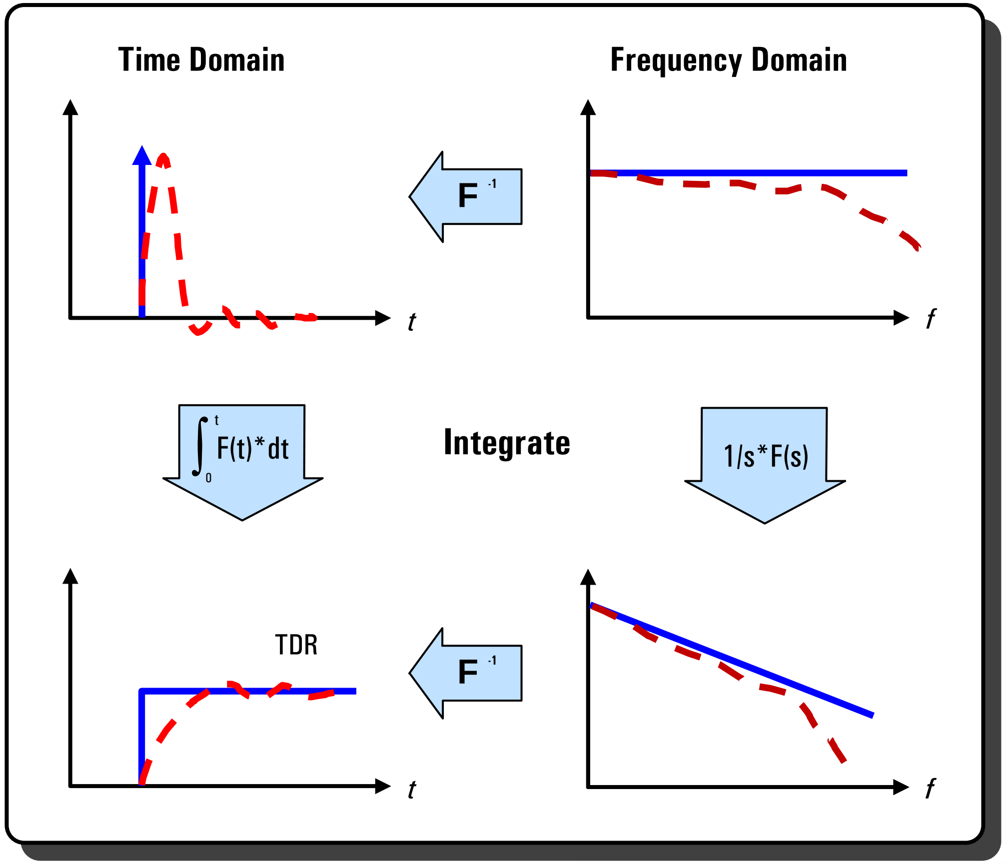
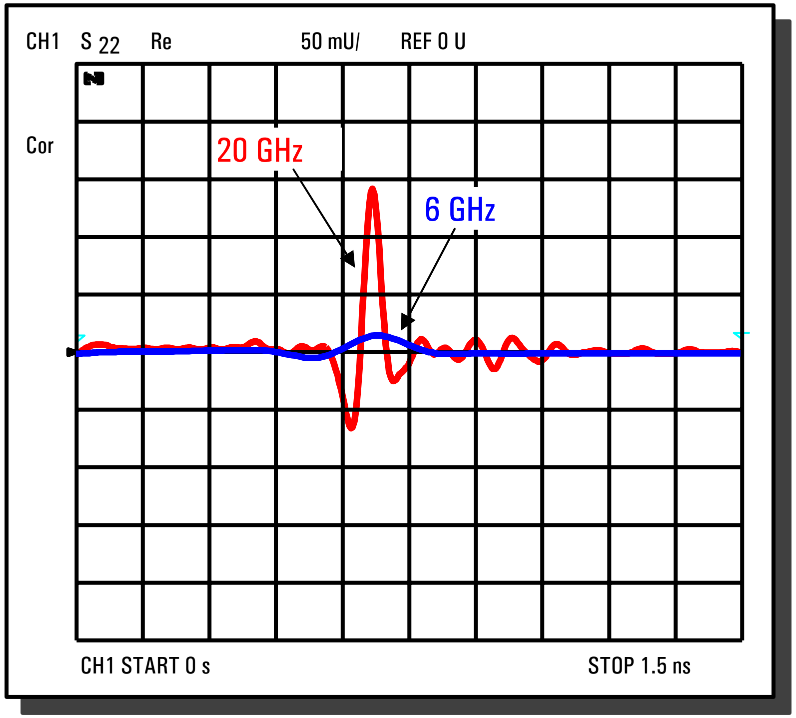
TDR Basics Using a Network Analyzer

- start with broadband frequency sweep (often requires microwave VNA)
- use inverse-Fourier transform to compute time-domain
- resolution inversely proportionate to frequency span





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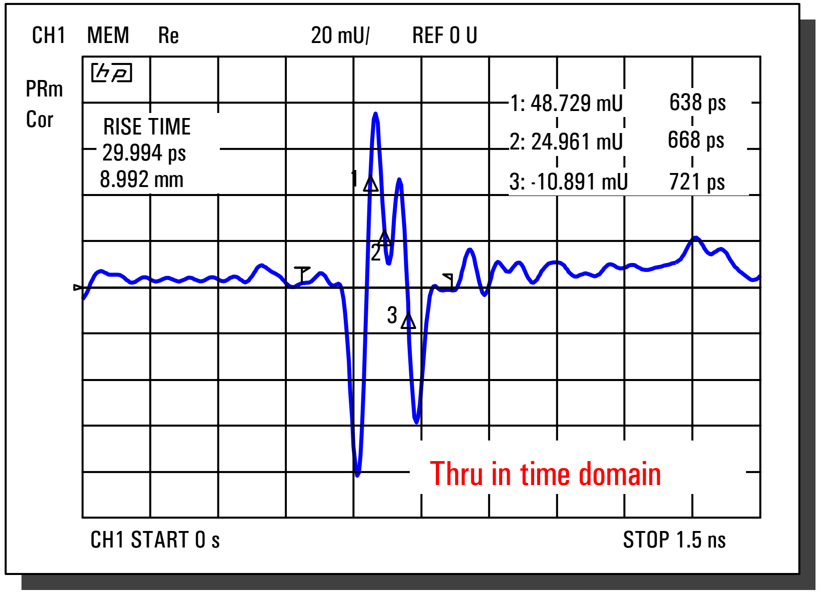
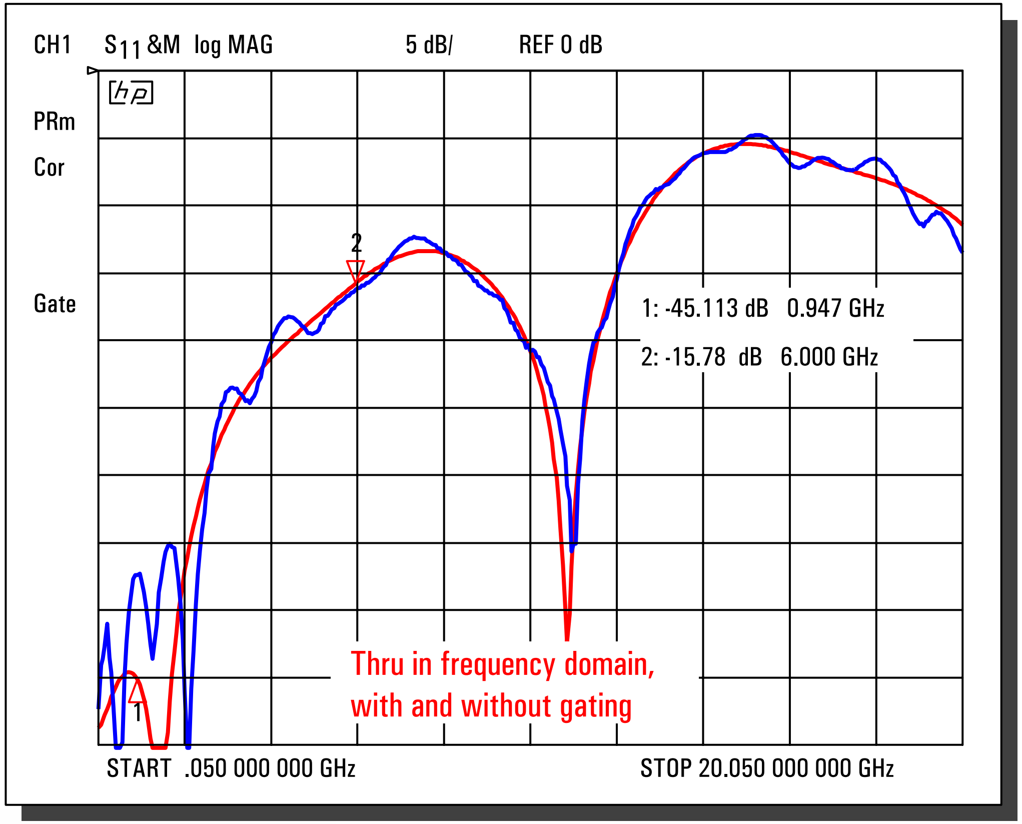
Time-Domain Gating

- TDR and gating can **remove** undesired reflections (a form of error **correction)**
- Only useful for **broadband** devices (a load or thru for example)
- Define **gate** to only include DUT
- Use two-port calibration





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Ten Steps for Performing TDR

1. Set up desired frequency range (need wide span for good spatial resolution)
2. Under SYSTEM, transform menu, press "set freq low pass"
3. Perform one- or two-port calibration
4. Select S11 measurement *
5. Turn on transform (low pass step) *
6. Set format to real *
7. Adjust transform window to trade off rise time with ringing and overshoot *
8. Adjust start and stop times if desired
9. For gating:
   - set start and stop frequencies for gate
   - turn gating on *
   - adjust gate shape to trade off resolution with ripple *
10. To display gated response in frequency domain
    - turn transform off (leave gating on) *
    - change format to log-magnitude *

* *If using two channels (even if coupled), these parameters must be set independently for second channel*

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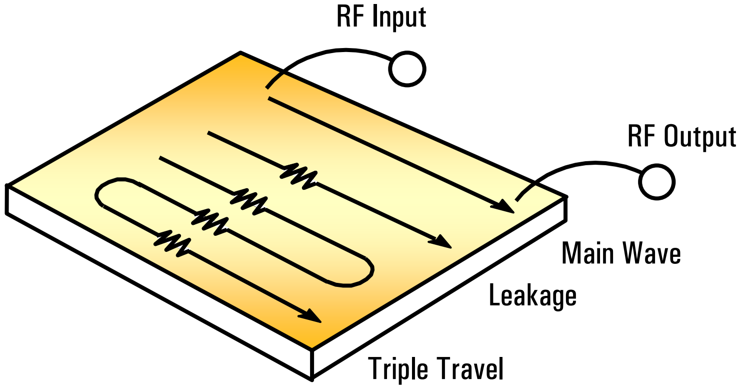
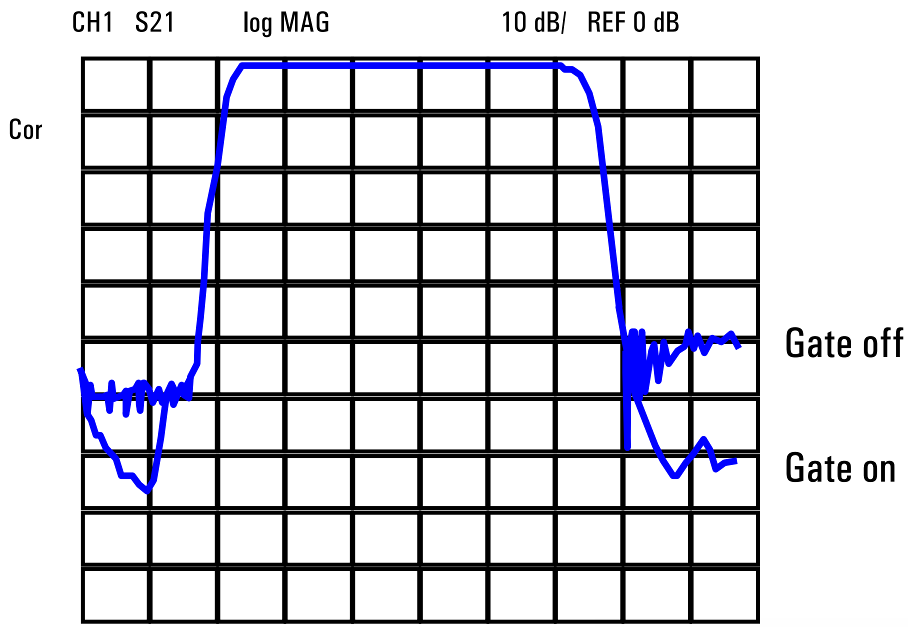
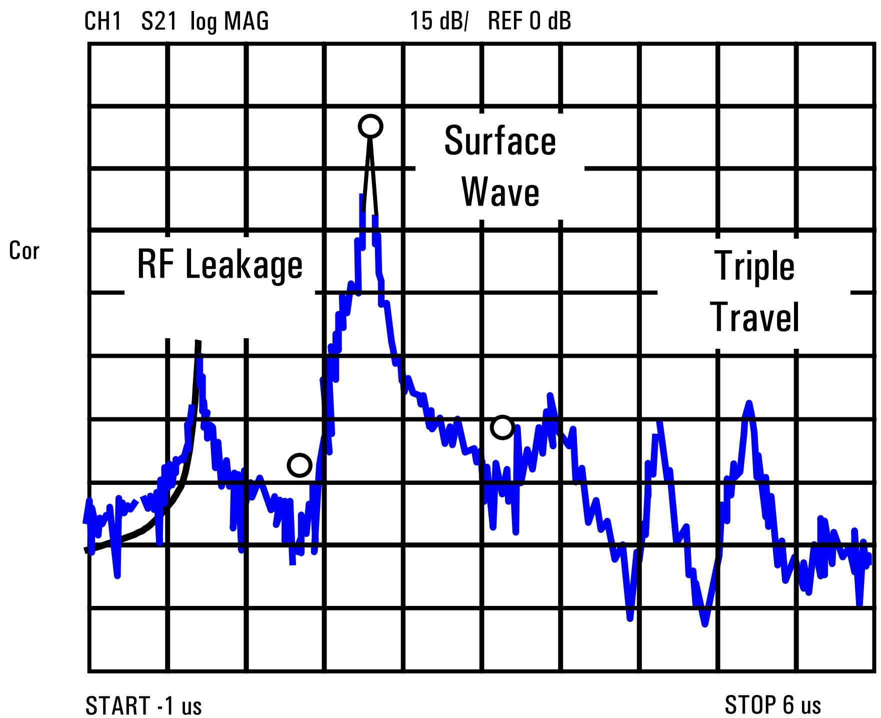
Time-Domain Transmission







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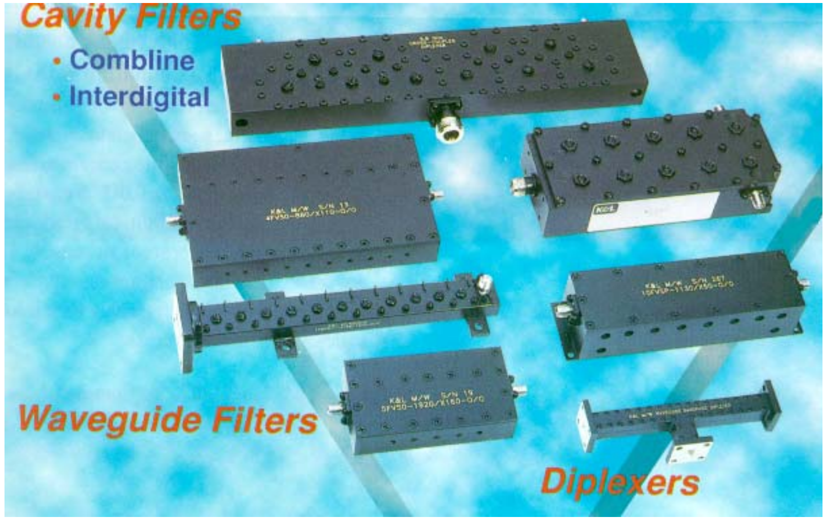
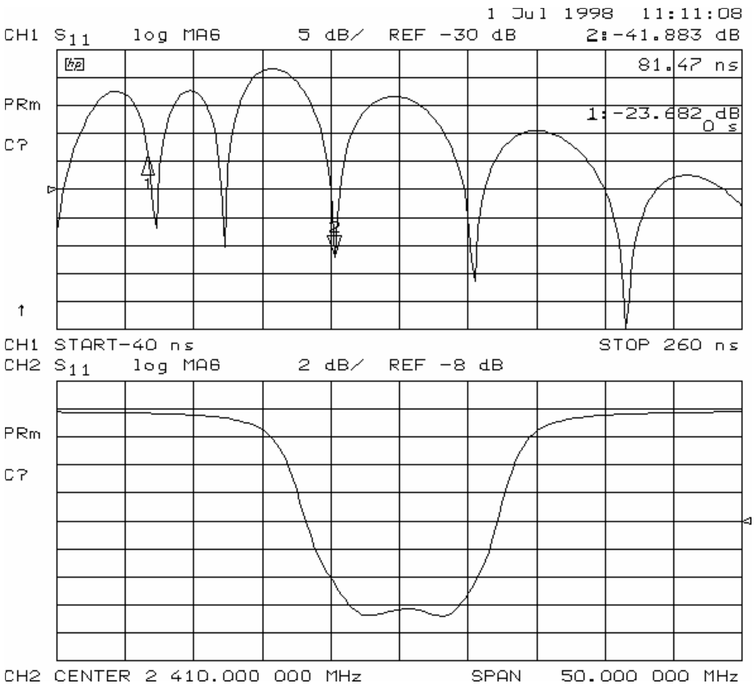
Time-Domain Filter Tuning



- Deterministic method used for tuning cavity-resonator filters
- Traditional frequency-domain tuning is very difficult:
  - lots of training needed
  - may take 20 to 90 minutes to tune a single filter
- Need VNA with fast sweep speeds and fast time-domain processing

Filter Reflection in Time Domain



- Set analyzer's center frequency
  = center frequency of the filter
- Measure S_{11} or S_{22} in the time domain
- Nulls in the time-domain response correspond to individual resonators in filter

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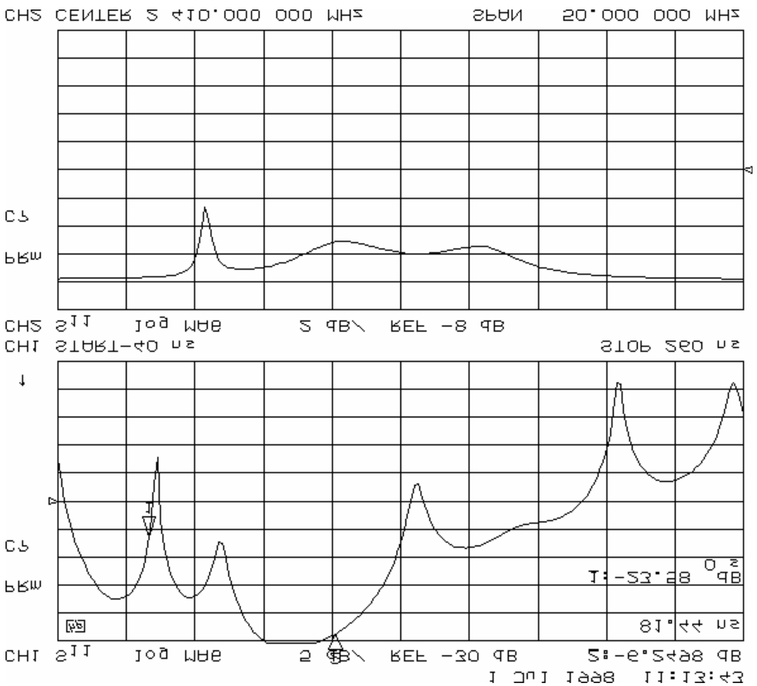
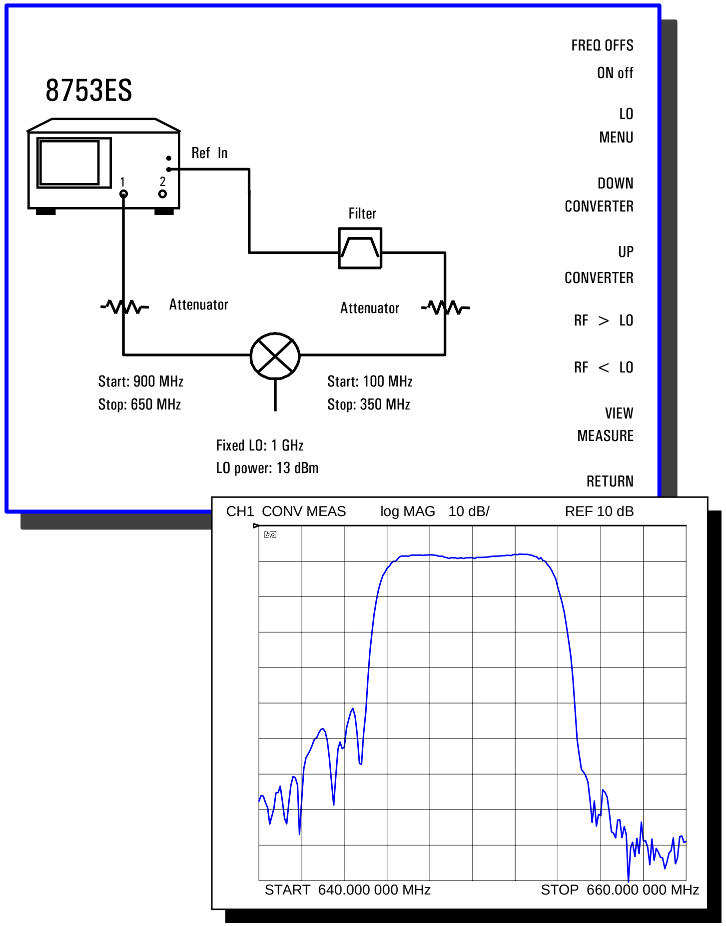
Tuning Resonator #3



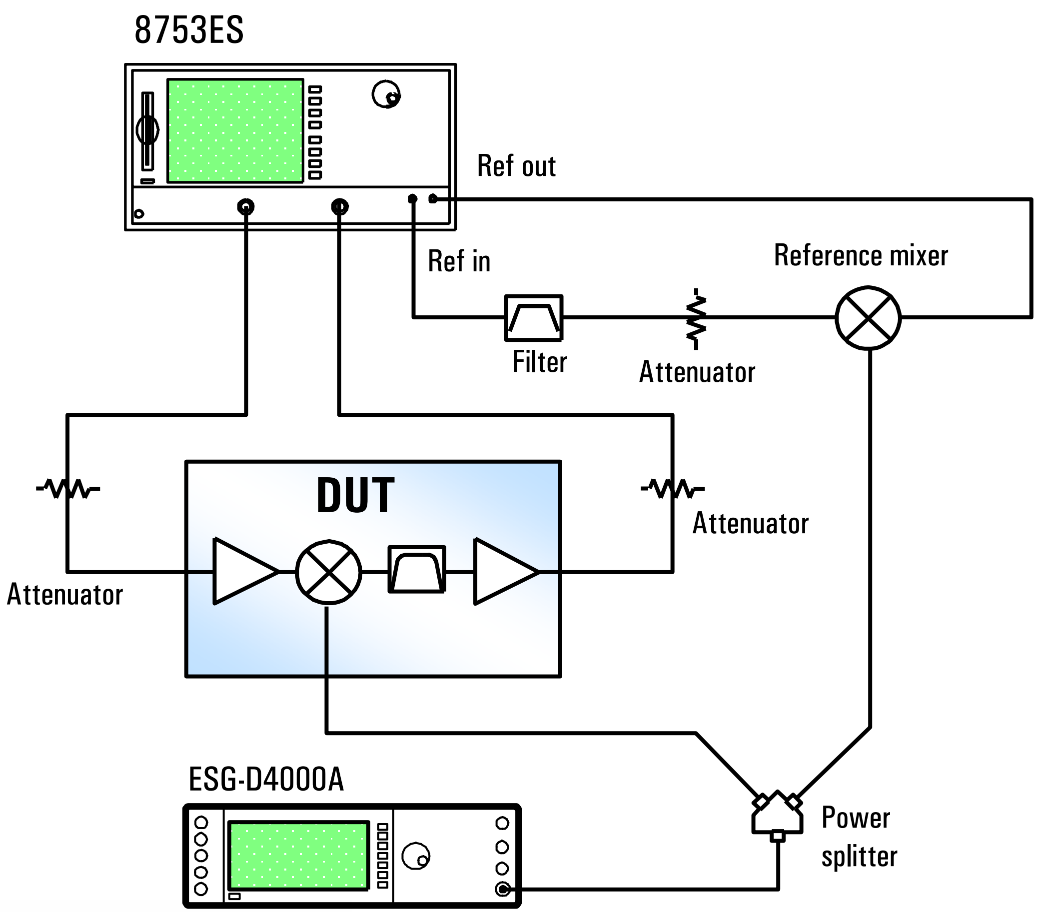
- Easier to identify mistuned resonator in time-domain: null #3 is missing
- Hard to tell which resonator is mistuned from frequency-domain response
- Adjust resonators by minimizing null
- Adjust coupling apertures using the peaks in-between the dips

Frequency-Translating Devices

Medium-dynamic range measurements (35 dB)



High-dynamic range measurements (100 dB)



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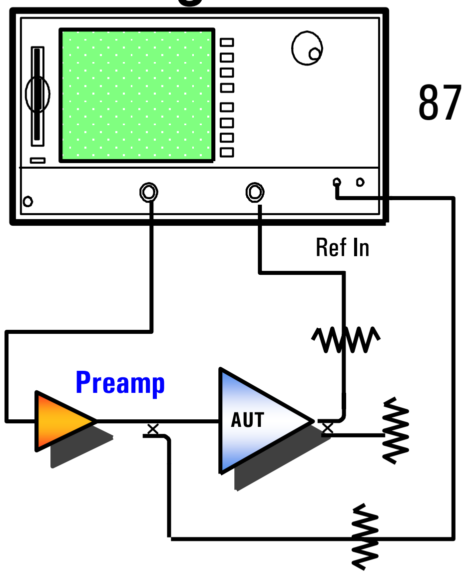
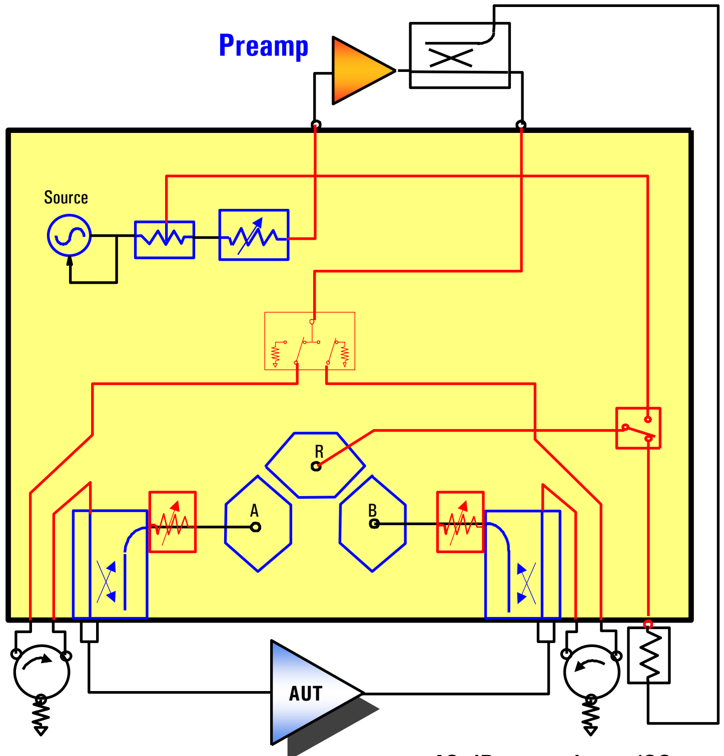
High-Power Amplifiers

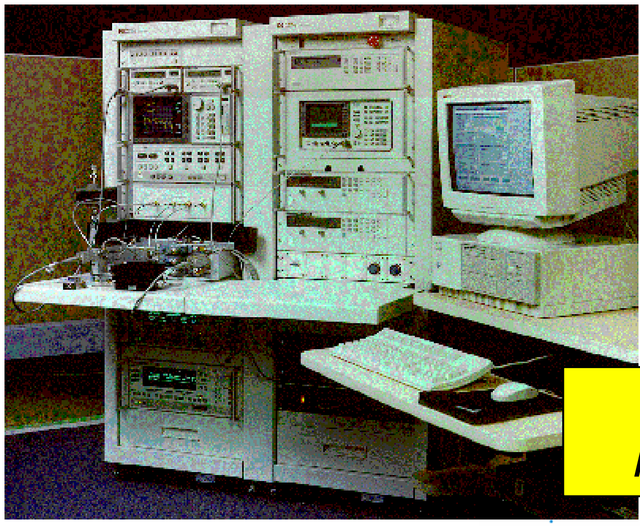


8753ES



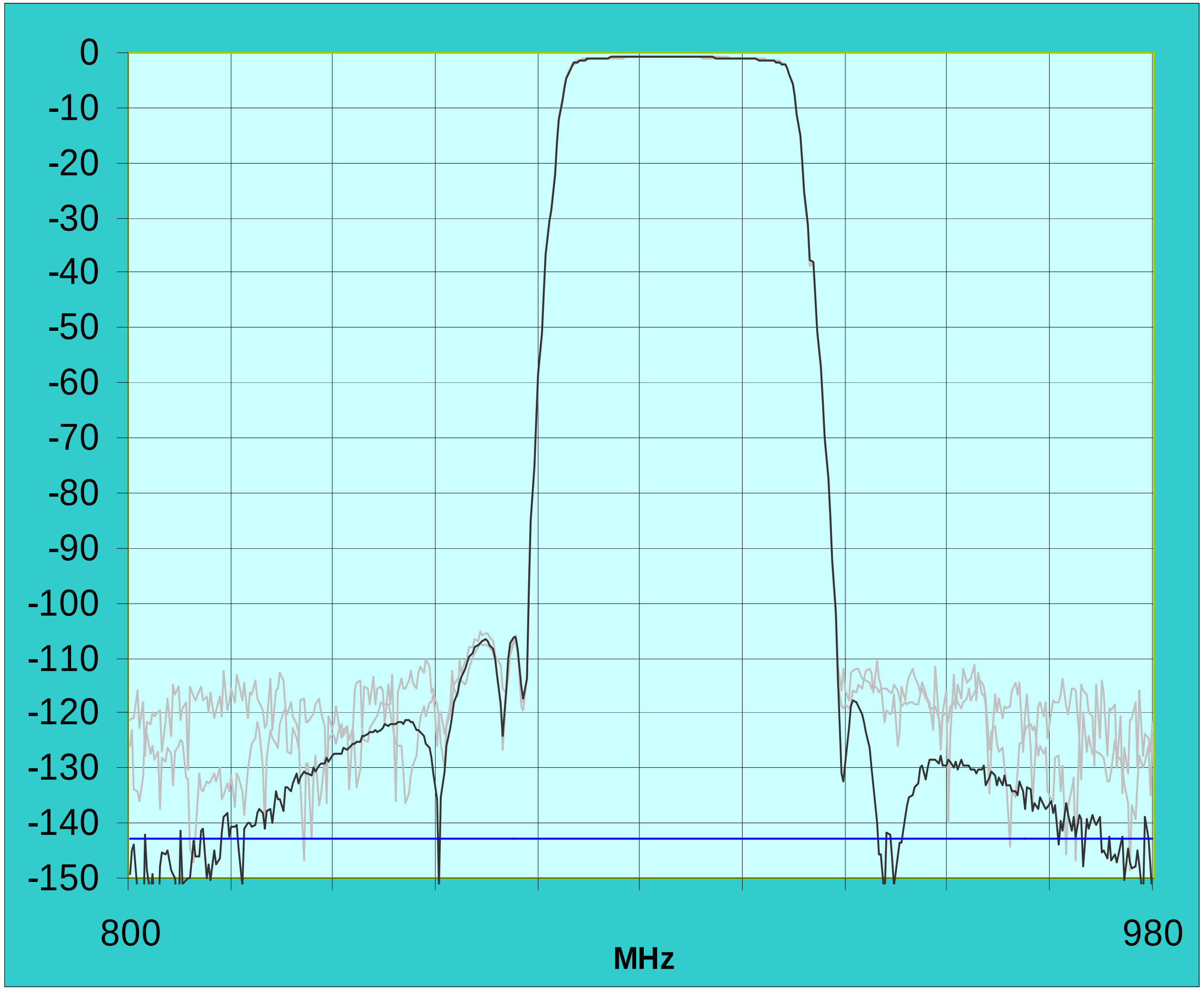
+43 dBm max input (20 watts!)

8720ES Option 085



85118A High-Power Amplifier Test System

High-Dynamic Range Measurements



Take advantage of extended dynamic range with direct-receiver access

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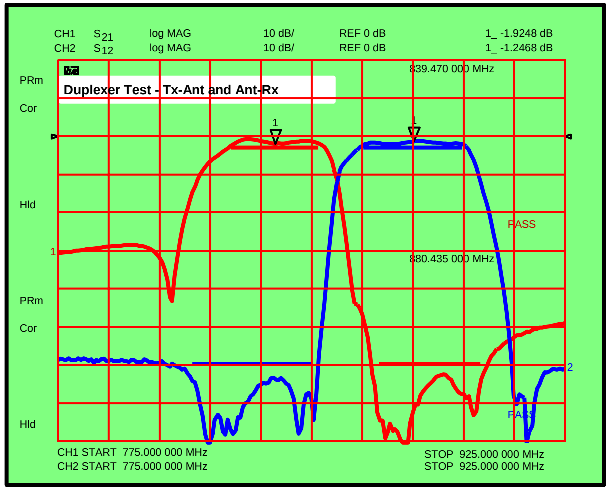
Multiport Device Test

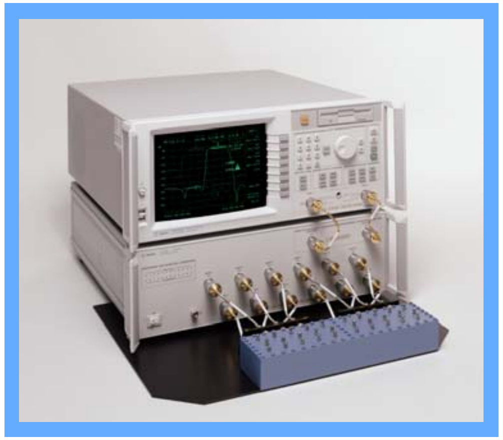
8753 H39

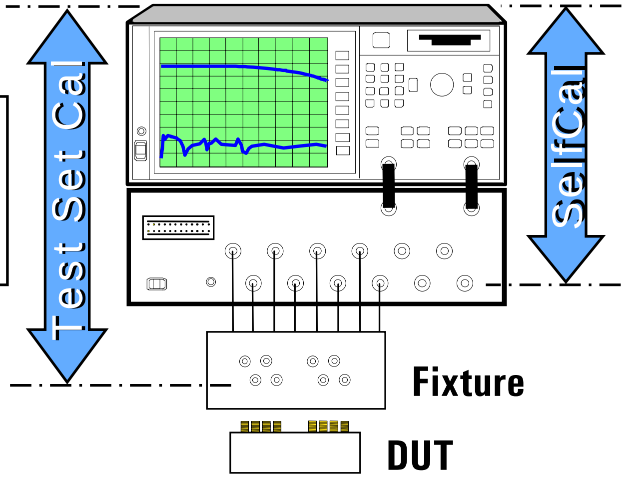


Multiport analyzers and test sets:

- improve **throughput** by reducing the number of connections to DUTs with more than two ports
- allow **simultaneous** viewing of two paths (good for tuning duplexers)
- include **mechanical** or **solid-state** switches, **50** or **75** ohms
- degrade raw performance so **calibration** is a ***must*** (use two-port cals whenever possible)
- Agilent offers a variety of standard and custom multiport analyzers and test sets

87050E/87075C Standard Multiport Test Sets



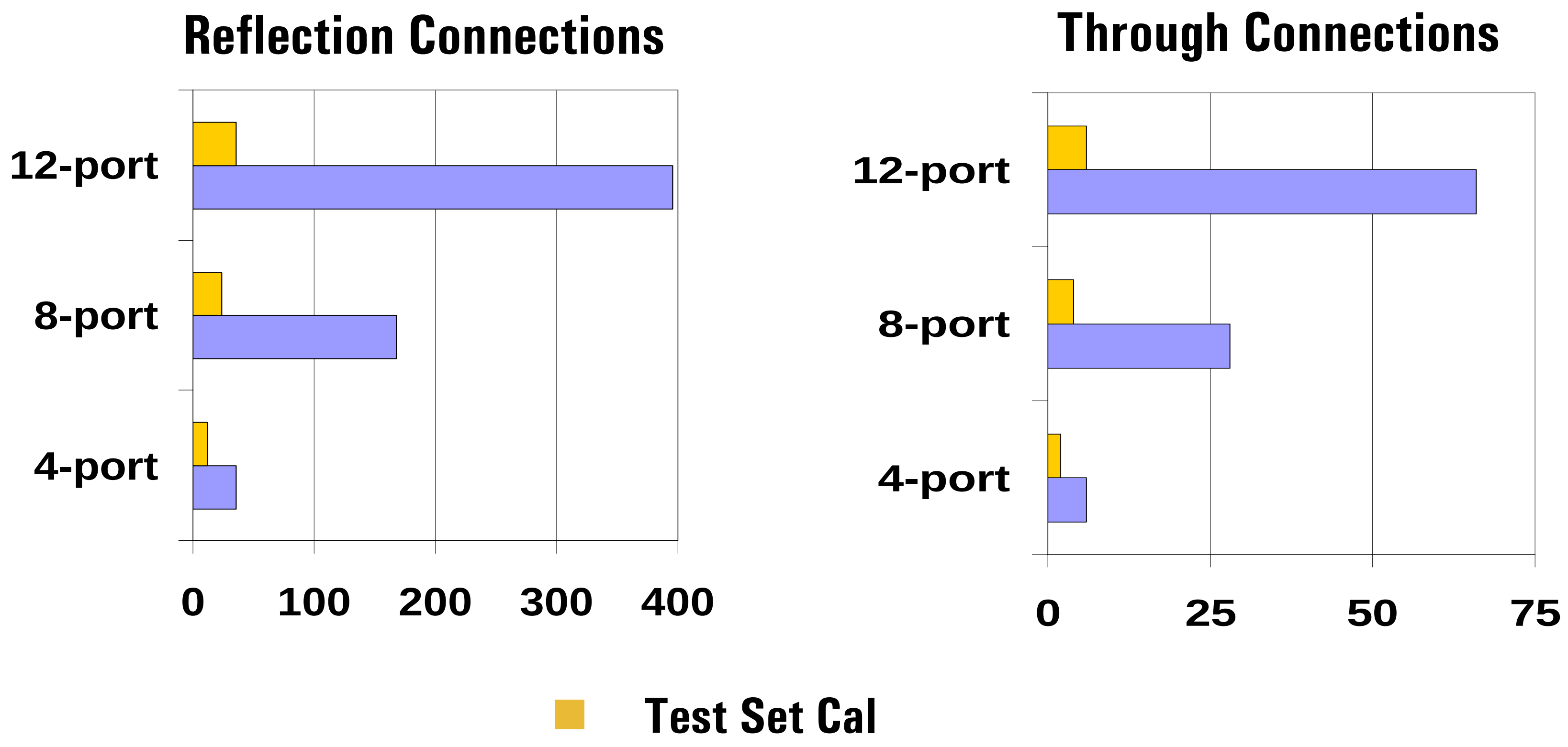


Once a month:
perform a **Test Set Cal** with external standards to remove systematic errors in the analyzer, test set, cables, and fixture

Once an hour:
automatically perform a **SelfCal** using internal standards to remove systematic errors in the analyzer and test set

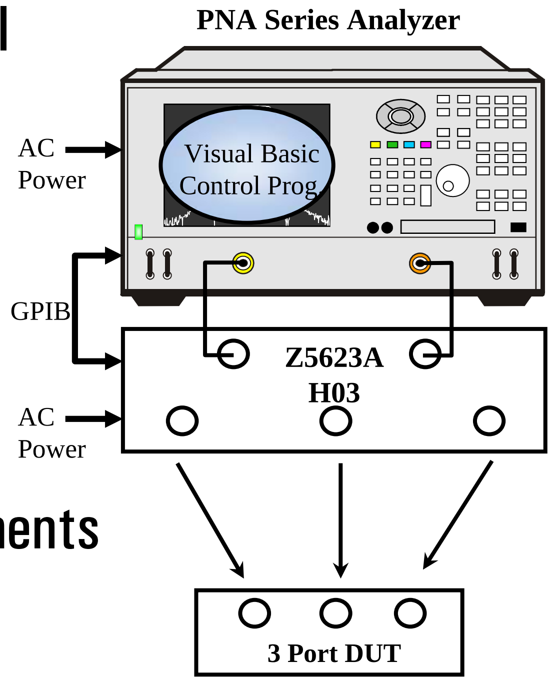
- For use with 8712E family
- 50 Ω: 3 MHz to 2.2 GHz, 4, 8, or 12 ports
- 75 Ω: 3 MHz to 1.3 GHz, 6 or 12 ports
- Test Set Cal and SelfCal dramatically improve calibration times
- Systems offer fully-specified performance at test ports

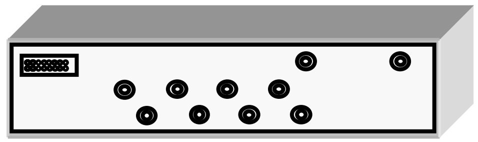
Test Set Cal Eliminates Redundant Connections of Calibration Standards



PNA Series plus External Test Set

- Test set controlled via GPIB and Agilent-supplied Visual Basic program executed from PNA Series analyzer
- Two port error correction available
- Z5623A H03
  - 3 port external test set
  - Solid-state switching for fast, repeatable measurements
- Z5623A H08
  - 8 port external test set
  - Mechanical switching for best RF performance





Z5623A H08

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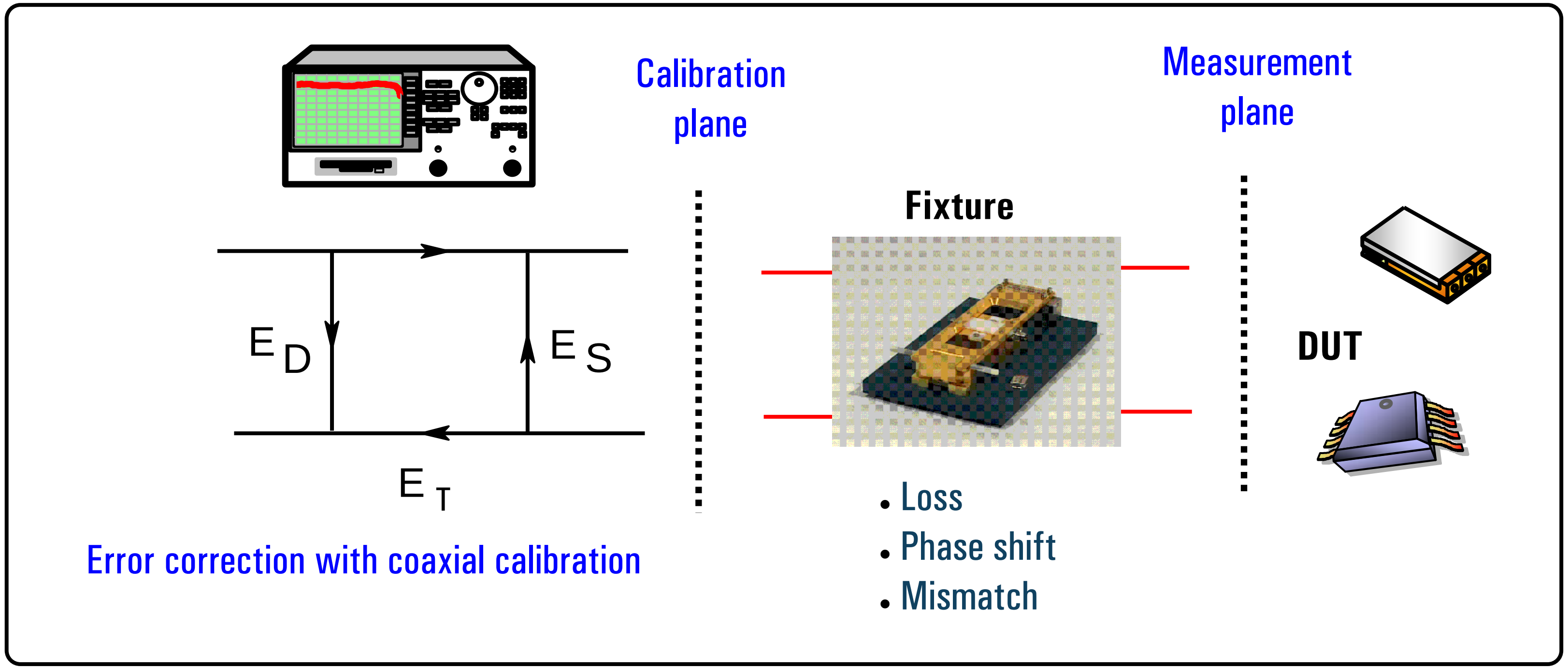
In-Fixture Measurements

Measurement problem: coaxial calibration plane is not the same as the in-fixture measurement plane



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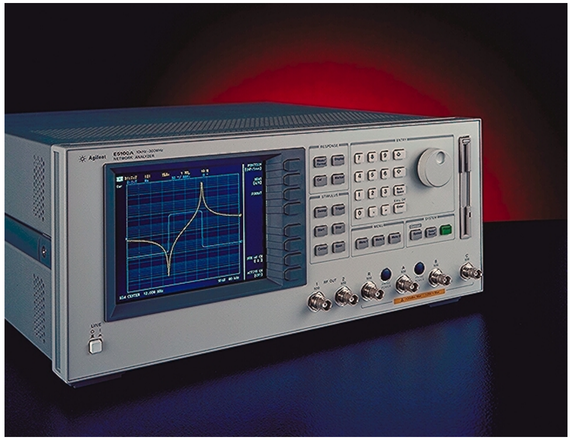
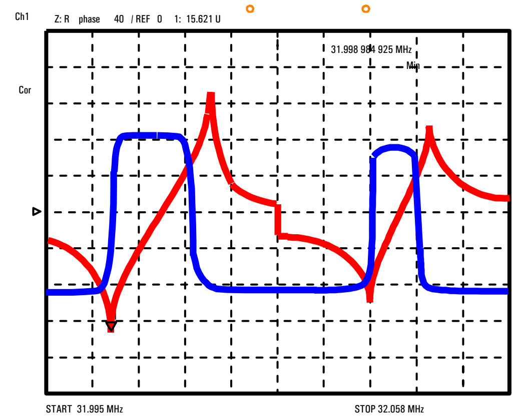
Characterizing Crystal Resonators/Filters

E5100A/B Network Analyzer





SEG	START	STOP	POINTS	POWER	IFBW
1	31.995 MHz	32.008 MHz	200	0 dBm	200Hz
> 2	32.052 MHz	32.058 MHz	200	0 dBm	200Hz
END					

Example of crystal resonator measurement

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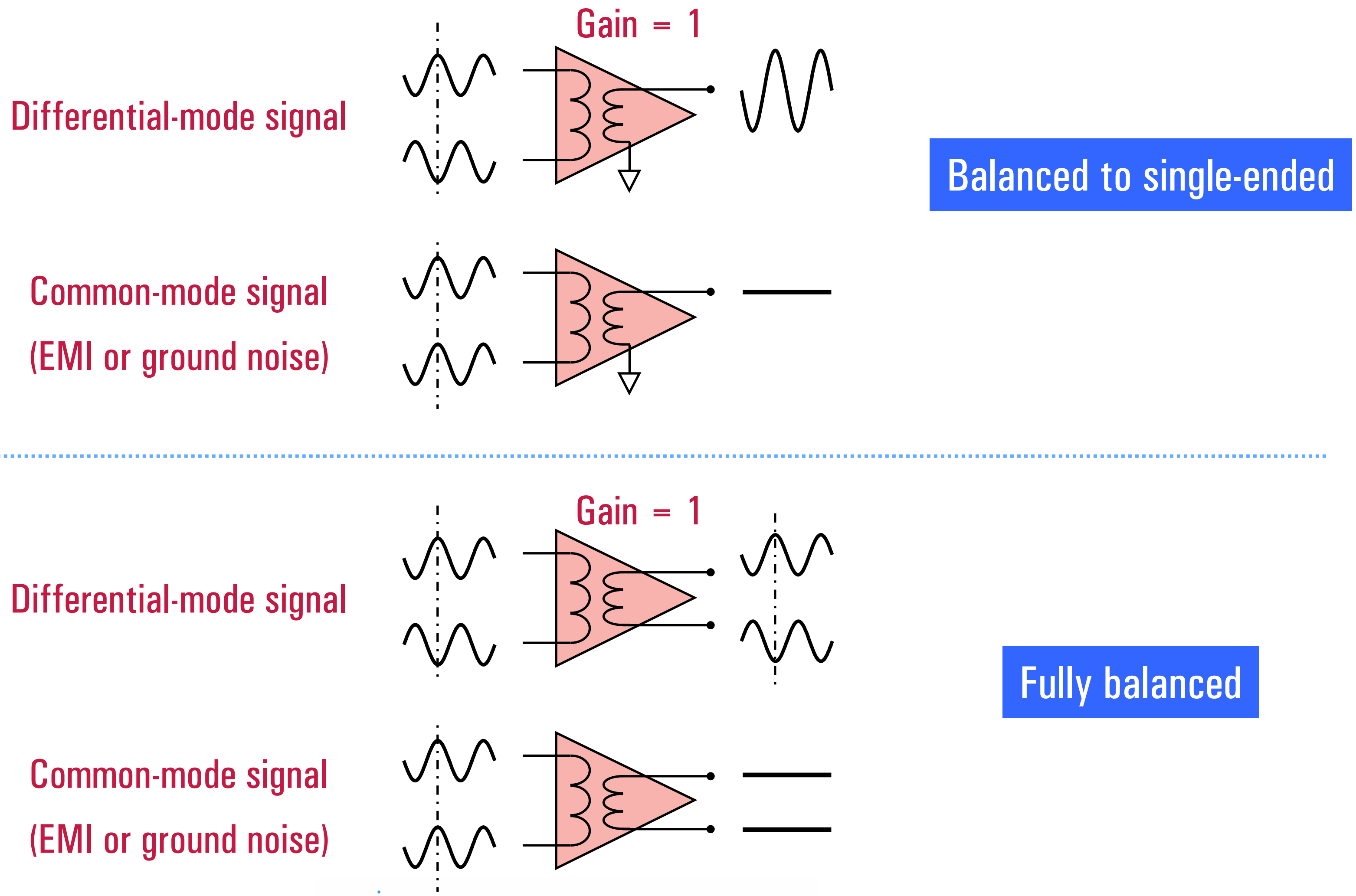
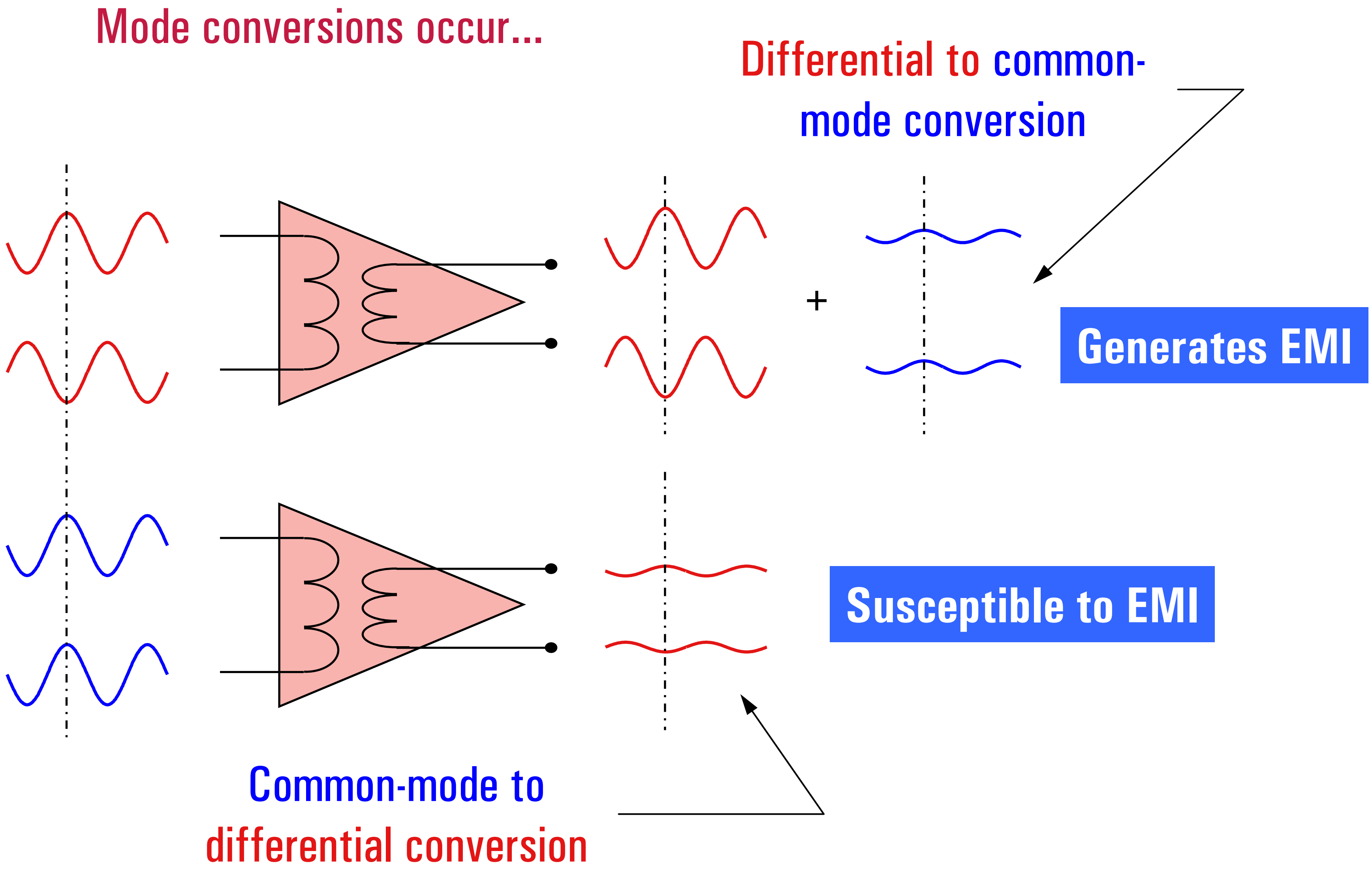
What are Balanced Devices?

Ideally, respond to differential and reject common-mode signals



What about Non-Ideal Devices?



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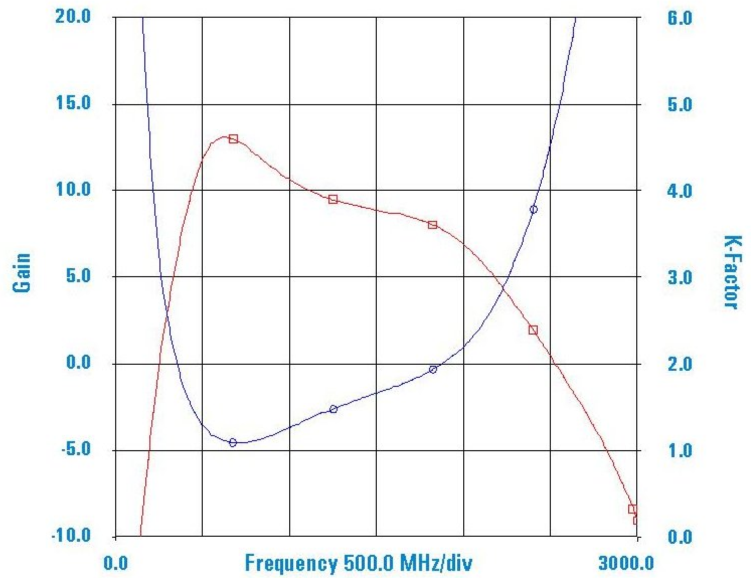
So What?

RF and digital designers need to characterize:

- Differential to differential mode (desired operation)
- Mode conversions (undesired operation)
- Operation in non-50-ohm environments
- Other differential parameters:
  - common-mode rejection ratio
  - K-factor
  - phase/amplitude balance
  - conjugate matches



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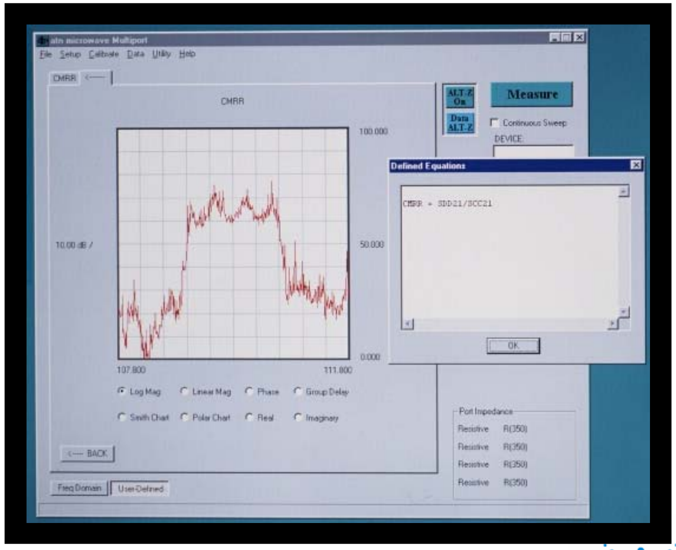
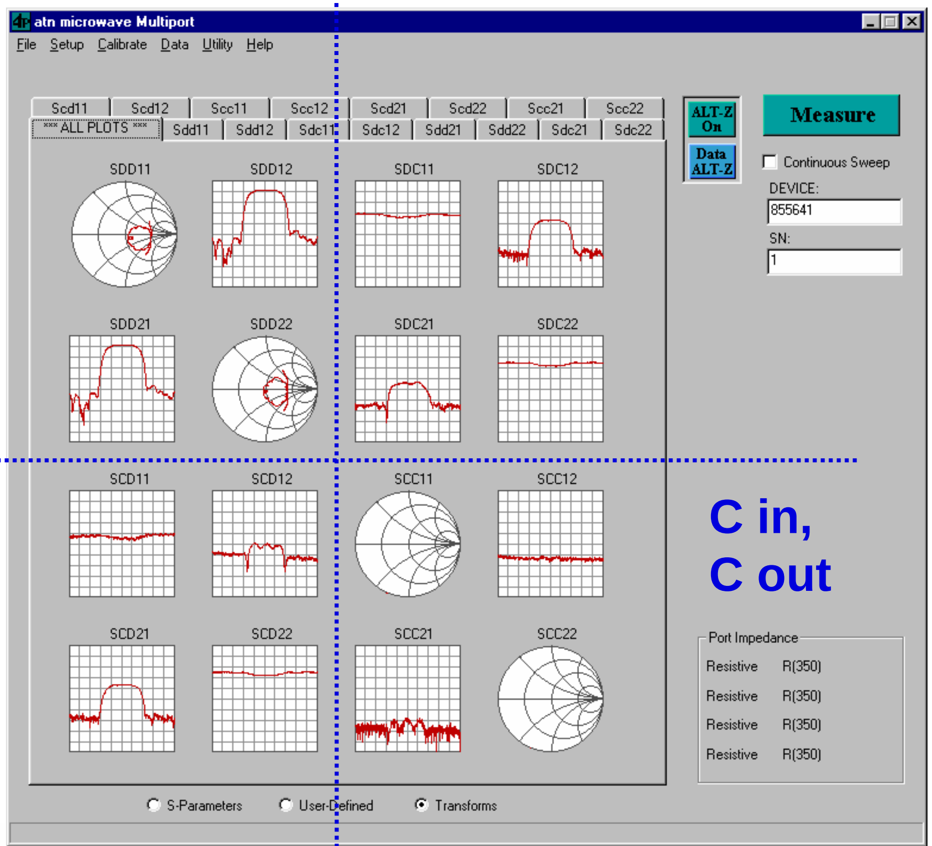
Agilent Solution for Balanced Measurements

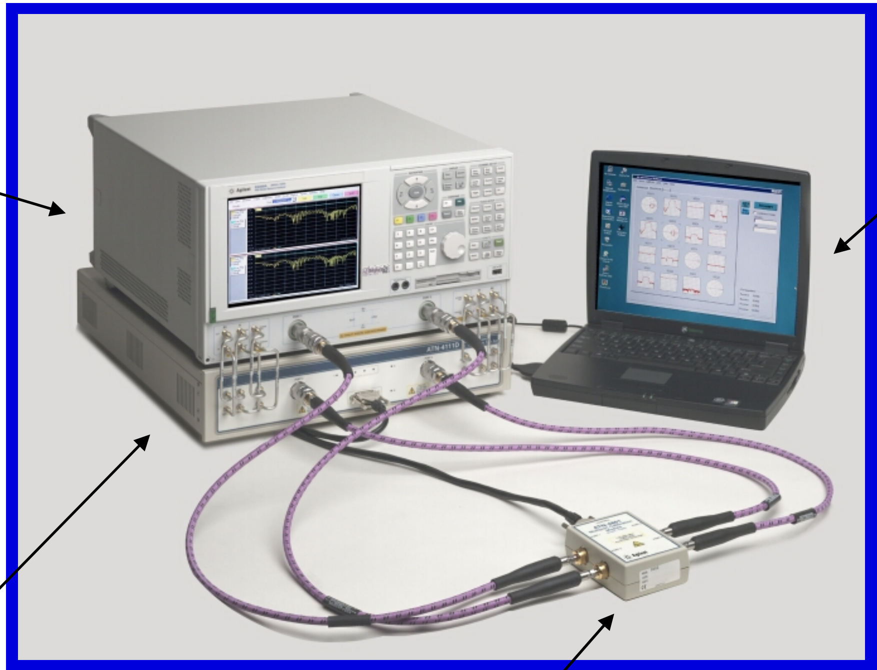
- Data presented as mixed-mode S-parameters
- Excellent dynamic range and accuracy
- Many important features such as time domain, impedance re-normalization, user parameters...

D = differential mode
C = common mode





6 GHz Solution based on the PNA Series



Network Analyzer

- option 015 (allows standard VNA use)
- signal source
- receiver

Software

- instrument control
- calibration routines
- error correction
- measurement routines
- “user” features
- time domain

Test Set

- adds 2 ports to VNA
- includes switches, 2 couplers

Optional 4-port ECal module

Target Markets

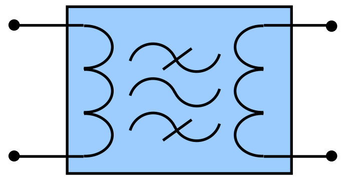
- Wireless Communications
  - Balanced topology less susceptible to EMI, noise
  - Less shielding required
  - RF grounding less critical
  - Better RF performance, smaller, lighter phones
  - LVDS extends battery life

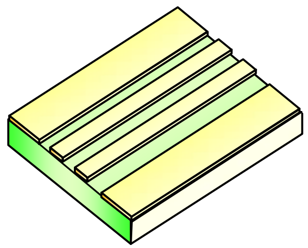
- Signal Integrity
  - Verify waveform quality of high speed digital signals
  - Engineers primarily interested in time-domain analysis

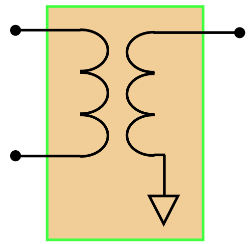
Target Devices

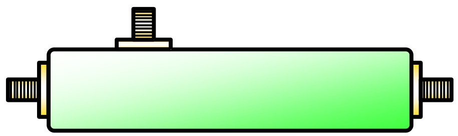
RF/Microwave Components

- Balanced filters
- Differential/push-pull amplifiers
- Baluns
- Balanced transmission lines
- Cable connectors
- Couplers*, circulators*, splitters/combiners*







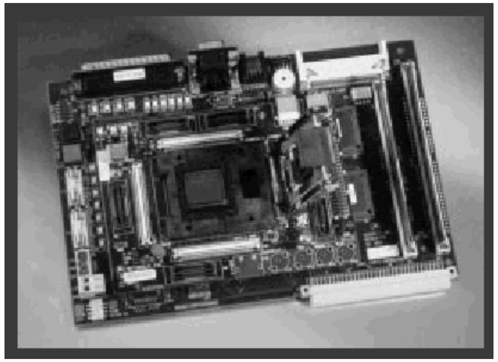


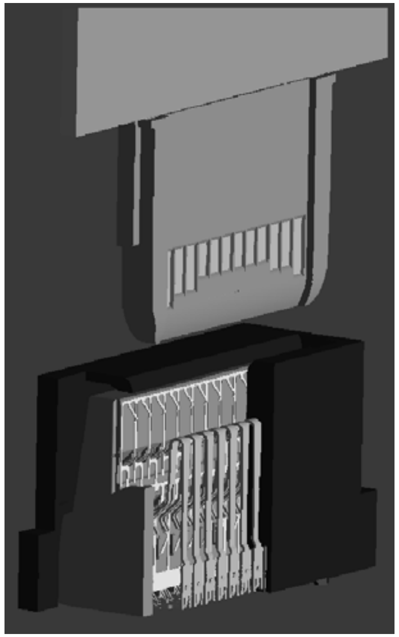
*** single-ended devices that need 4-port error correction***

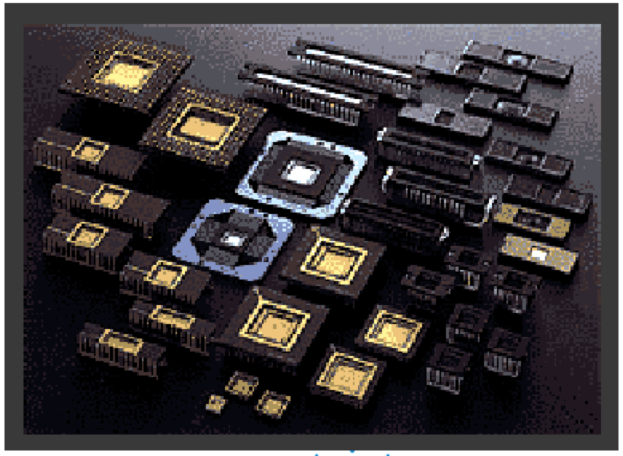
Target Devices

Digital Design

- PCB backplanes
- PCB interconnects
- Sockets, packages
- High-speed serial interconnects
  (Ethernet, Firewire, Infiniband, USB ...)







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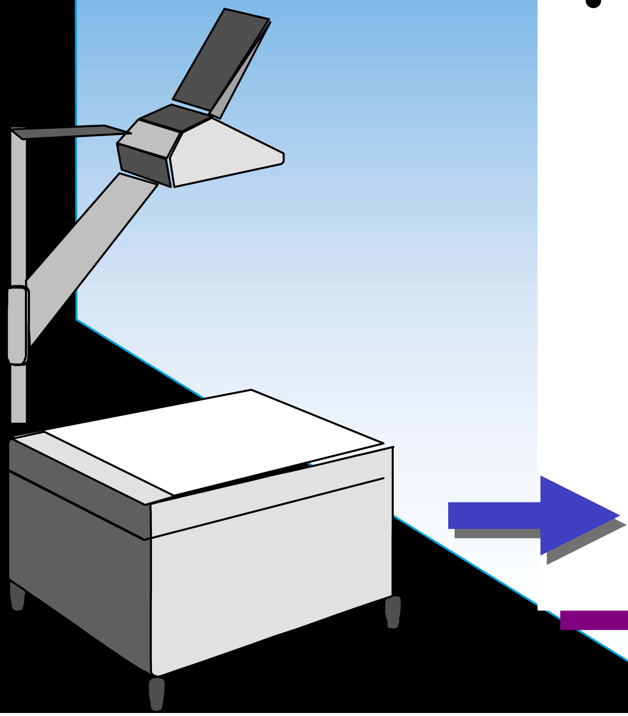
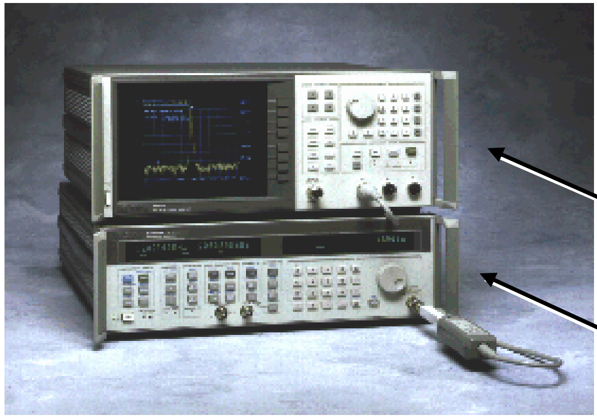
Agenda



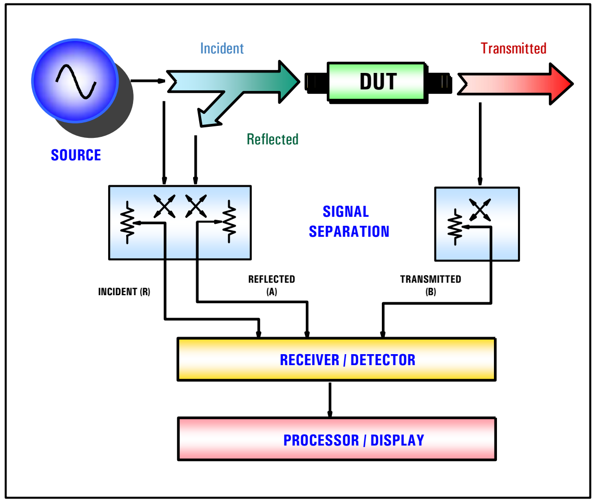
- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix
  - Advanced Topics
    - time domain
    - frequency-translating devices
    - high-power amplifiers
    - extended dynamic range
    - multiport devices
    - in-fixture measurements
    - crystal resonators
    - balanced/differential
  - Inside the network analyzer
  - Challenge quiz!

Traditional Scalar Analyzer



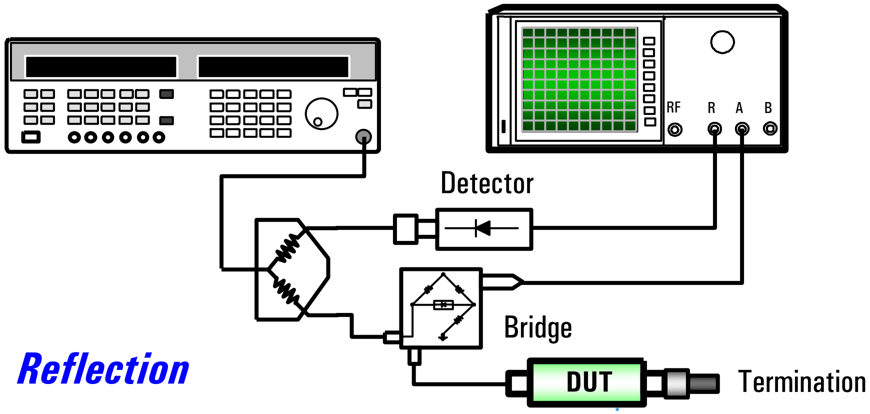
processor/display

source

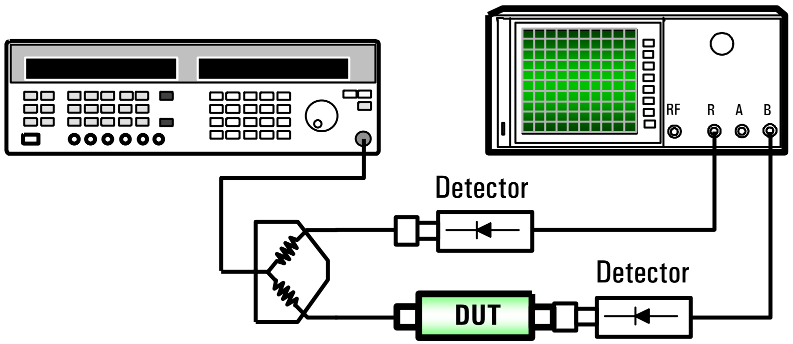


Example: **8757D**

- requires external detectors, couplers, bridges, splitters
- good for low-cost microwave scalar applications



Reflection



Transmission

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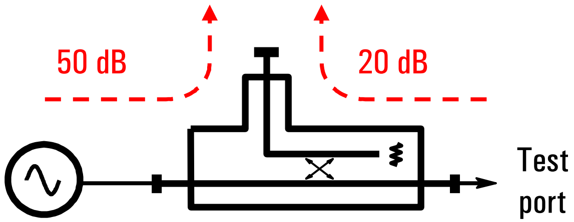
Directional Coupler *Directivity*

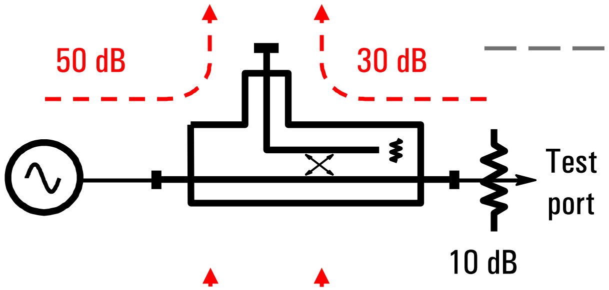
$$\text{Directivity} = \frac{\text{Coupling Factor}_{\text{(fwd)}} \times \text{Loss}_{\text{(through arm)}}}{\text{Isolation}_{\text{(rev)}}}$$

Directivity (dB) = Isolation (dB) - Coupling Factor (dB) - Loss (dB)

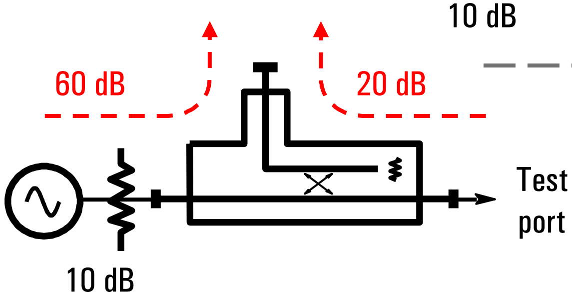
Examples:



Directivity = 50 dB - 20 dB = 30 dB

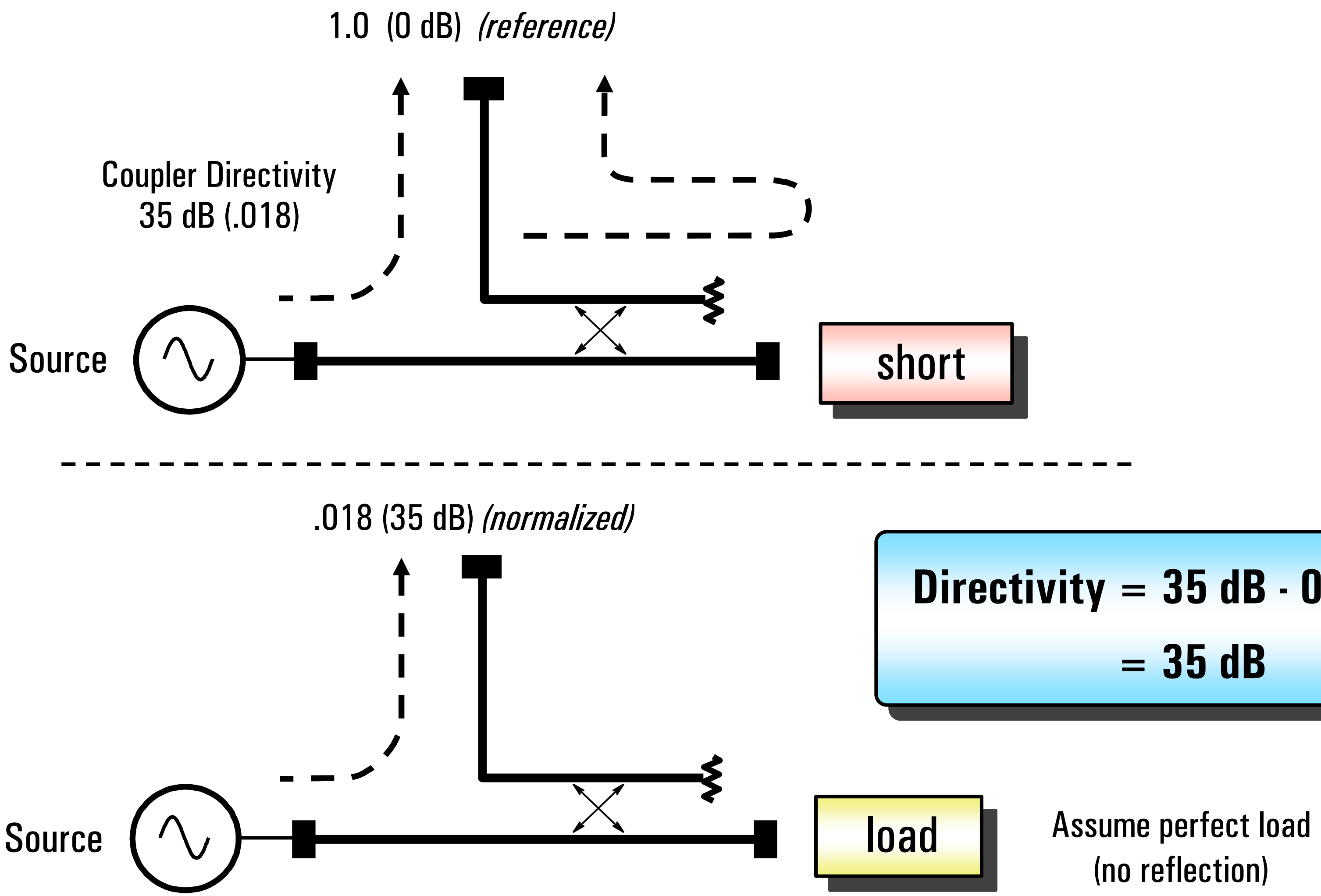


Directivity = 50 dB - 30 dB - 10 dB = 10 dB



Directivity = 60 dB - 20 dB - 10 dB = 30 dB

One Method of Measuring Coupler Directivity



Directivity = 35 dB - 0 dB

= 35 dB

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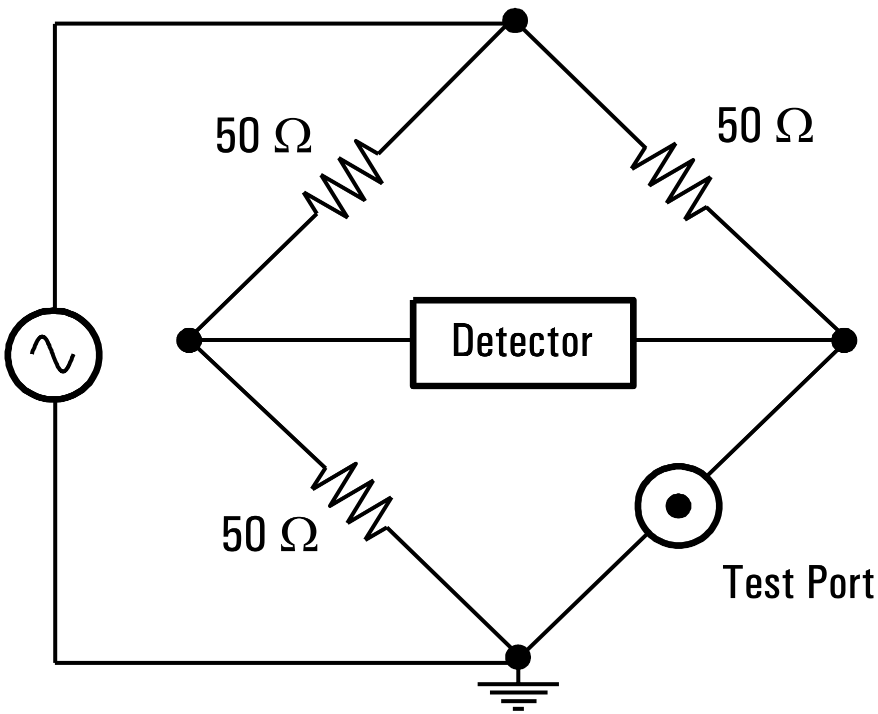
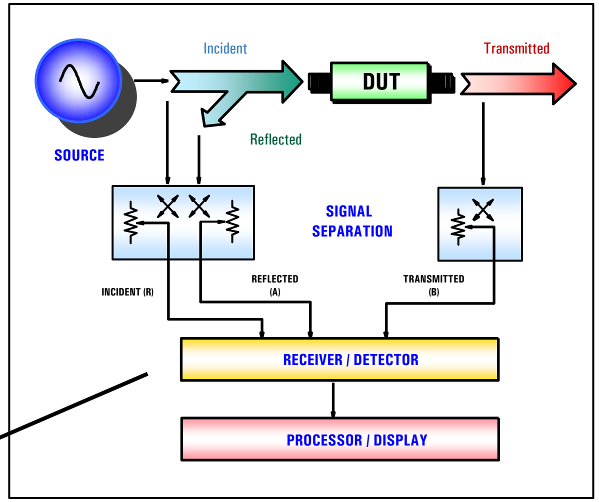
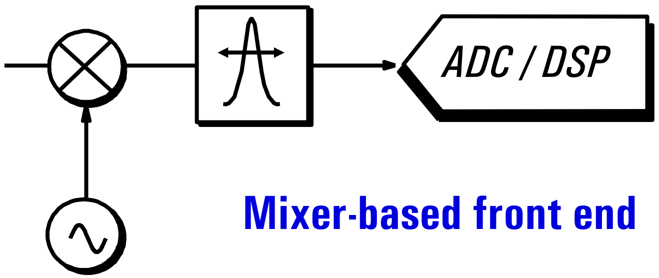
Directional Bridge



- 50-ohm load at test port balances the bridge -- detector reads zero
- Non-50-ohm load imbalances bridge
- Measuring magnitude and phase of imbalance gives complex impedance
- "Directivity" is difference between maximum and minimum balance

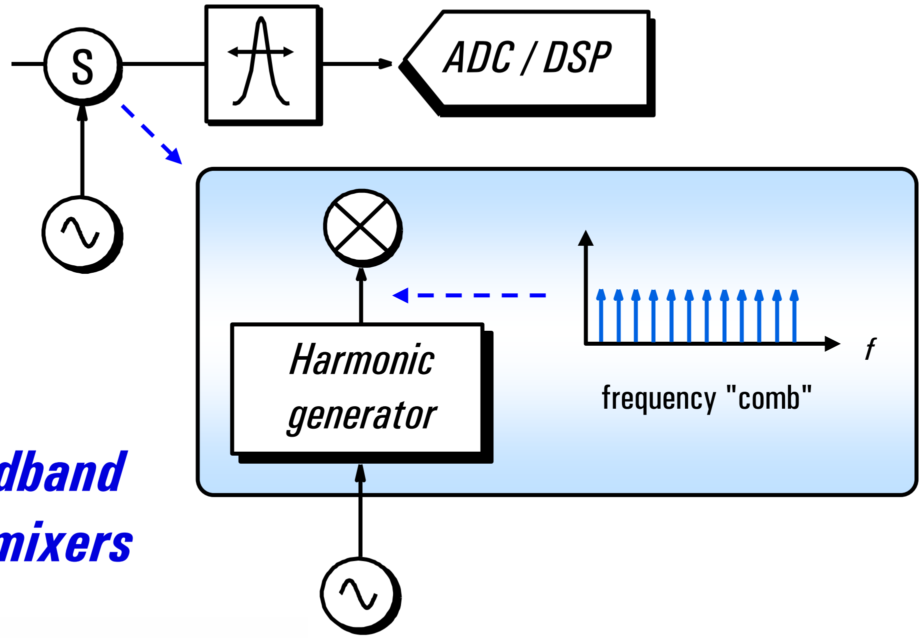
NA Hardware: Front Ends, Mixers Versus Samplers





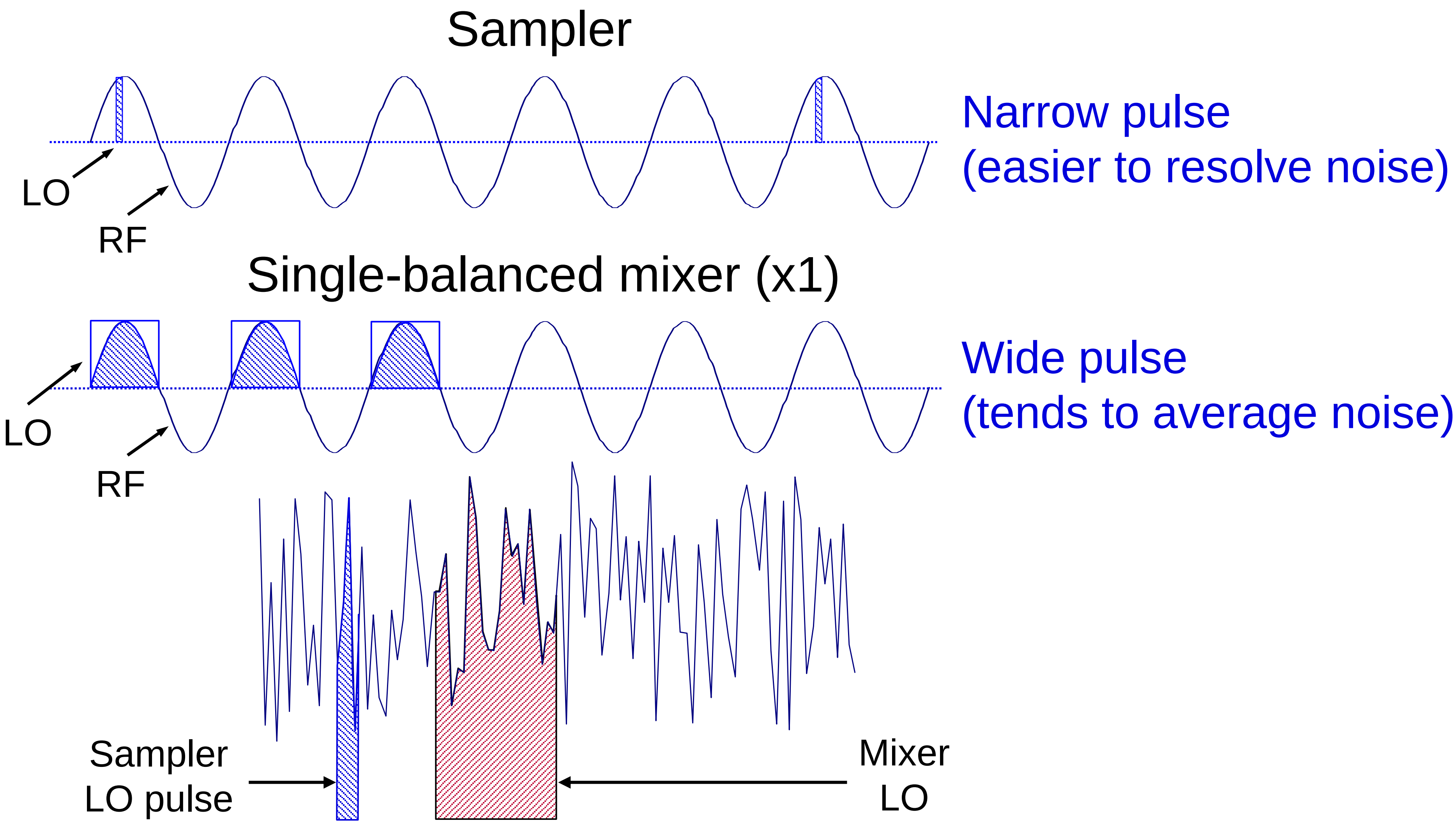
Mixer-based front end

Sampler-based front end



It is cheaper and easier to make broadband front ends using samplers instead of mixers

Mixers Versus Samplers: Time Domain



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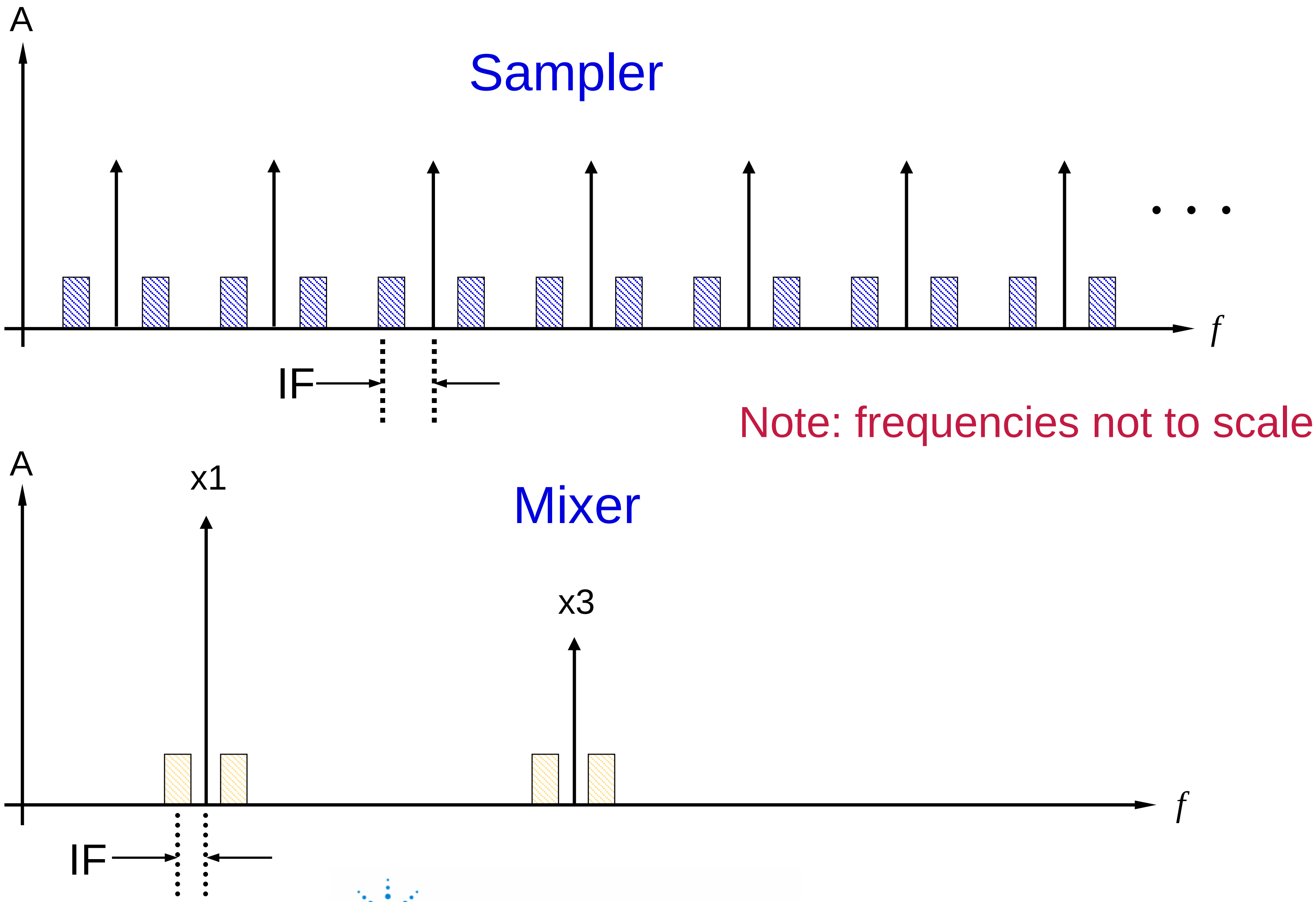
Mixers Versus Samplers: Frequency Domain



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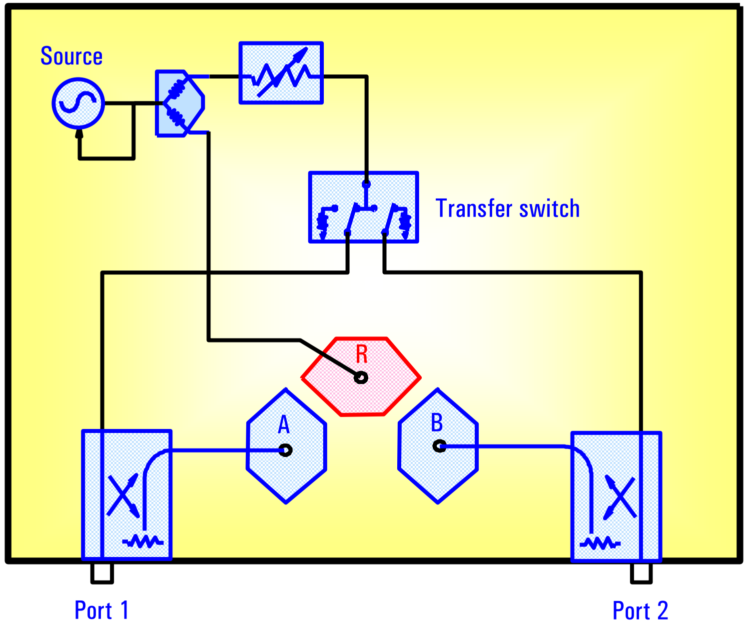
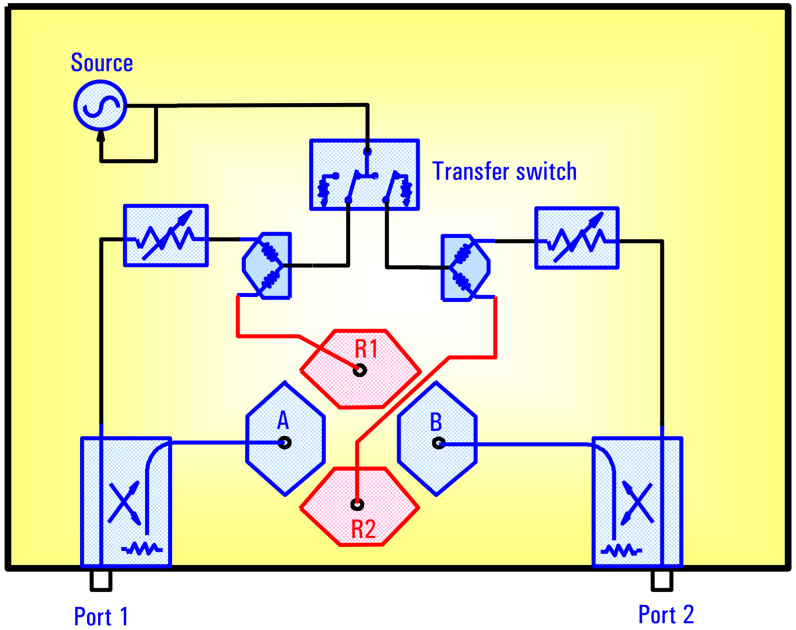
Three Versus Four-Receiver Analyzers





3 receivers

- more economical
- TRL*, LRM* cals only
- includes:
  - 8753ES
  - 8720ES (standard)

4 receivers

- more expensive
- true TRL, LRM cals
- includes:
  - PNA Series
  - 8720ES (option 400)
  - 8510C

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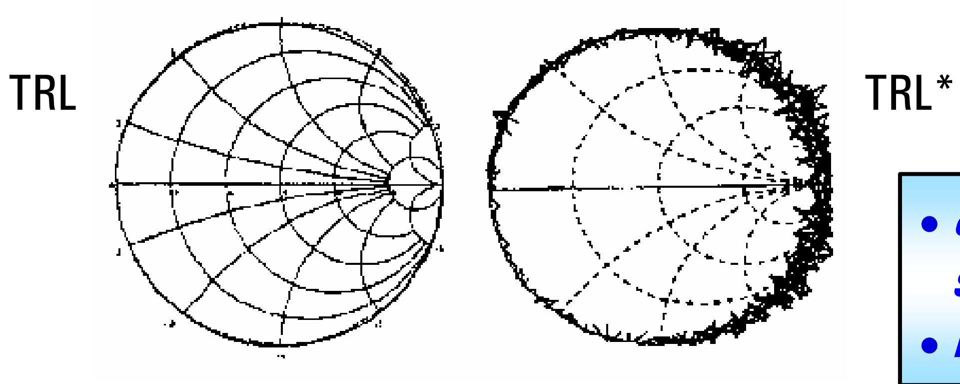
Why Are Four Receivers Better Than Three?



- *8720ES Option 400 adds fourth sampler, allowing full TRL calibration*
- *PNA Series has four receivers standard*

- **TRL***
  - assumes the source and load match of a test port are equal (port symmetry between forward and reverse measurements)
  - this is only a fair assumption for three-receiver network analyzers
- **TRL**
  - four receivers are necessary to make the required measurements
  - TRL and TRL* use identical calibration standards
- **In noncoaxial applications,** TRL achieves better source and load match correction than TRL*
- **What about coaxial applications?**
  - SOLT is usually the preferred calibration method
  - coaxial TRL can be more accurate than SOLT, but not commonly used

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Challenge Quiz

1. Can filters cause distortion in communications systems?

A. Yes, due to impairment of phase and magnitude response
B. Yes, due to nonlinear components such as ferrite inductors
C. No, only active devices can cause distortion
D. No, filters only cause linear phase shifts
E. Both A and B above

2. Which statement about transmission lines is false?

A. Useful for efficient transmission of RF power
B. Requires termination in characteristic impedance for low VSWR
C. Envelope voltage of RF signal is independent of position along line
D. Used when wavelength of signal is small compared to length of line
E. Can be realized in a variety of forms such as coaxial, waveguide, microstrip

3. Which statement about narrowband detection is false?

A. Is generally the cheapest way to detect microwave signals
B. Provides much greater dynamic range than diode detection
C. Uses variable-bandwidth IF filters to set analyzer noise floor
D. Provides rejection of harmonic and spurious signals
E. Uses mixers or samplers as downconverters

Challenge Quiz (continued)

4. Maximum dynamic range with narrowband detection is defined as:

A. Maximum receiver input power minus the stopband of the device under test
B. Maximum receiver input power minus the receiver's noise floor
C. Detector 1-dB-compression point minus the harmonic level of the source
D. Receiver damage level plus the maximum source output power
E. Maximum source output power minus the receiver's noise floor

5. With a T/R analyzer, the following error terms can be corrected:

A. Source match, load match, transmission tracking
B. Load match, reflection tracking, transmission tracking
C. Source match, reflection tracking, transmission tracking
D. Directivity, source match, load match
E. Directivity, reflection tracking, load match

6. Calibration(s) can remove which of the following types of measurement error?

A. Systematic and drift
B. Systematic and random
C. Random and drift
D. Repeatability and systematic
E. Repeatability and drift

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Challenge Quiz (continued)

7. Which statement about TRL calibration is false?

A. Is a type of two-port error correction
B. Uses easily fabricated and characterized standards
C. Most commonly used in noncoaxial environments
D. Is not available on the 8720ES family of microwave network analyzers
E. Has a special version for three-sampler network analyzers

8. For which component is it hardest to get accurate transmission and reflection measurements when using a T/R network analyzer?

A. Amplifiers because output power causes receiver compression
B. Cables because load match cannot be corrected
C. Filter stopbands because of lack of dynamic range
D. Mixers because of lack of broadband detectors
E. Attenuators because source match cannot be corrected

9. Power sweeps are good for which measurements?

A. Gain compression
B. AM to PM conversion
C. Saturated output power
D. Power linearity
E. All of the above

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Answers to Challenge Quiz

1. E
2. C
3. A
4. B
5. C
6. A
7. D
8. B
9. E