corrected, although placing the intensity monitor as close to the test device as possible can minimize these effects. A spatially nonuniform light source presents a measurement challenge of determining the average illumination level for a cell or the illumination level of the current-limiting cell in a module [126, 137]. The efficiency will always be reduced for nonuniform illumination compared to uniform illumination at the cell [138, 139] or module [140] level.

There are three types of illumination sources typically used for solar simulators: continuous arc, pulsed arc, and filament lamps. The merits and problems of these different simulators have been compared [28, 141–143]. If the distance between the test plane and the nearest optical surface is short, the possibility for reflection-related artifacts may exist [141]. These reflection-related artifacts occur because the field of view of the reference cell and test device are not identical and can occur from reflections off simulator optics, reference cell packages, probe fixtures, the test station enclosure, and the region underneath the test device. Light reflecting from the region under the test device is especially important for bifacial cells and superstrate structures.

With proprietary filters, commercial continuous Xe-arc lamp solar simulators have an excellent spectral match to the AM0 or terrestrial spectrum, and their point source (small arc volume) with integrating optics achieves a ± 1 to $\pm 3\%$ variation in spatial uniformity. The spectrum of these lamps shifts slightly from the blue to the red during the bulb life, with most of the spectral shift occurring in the first 100 h of operation [141]. The intensity of continuous arc lamps is controlled by changing the distance from the lamp to the test plane or by changing the current. Pulsed simulators are especially useful for characterizing concentrator cells and for large-area modules. The intensity of pulsed Xe-arc light sources is adjusted by changing the distance from the lamp to the test plane, by adjusting an aperture near the flash lamp, or by changing the voltage at which the lamp flashes. The spectrum of pulsed lamps shifts from the blue to the red less with the number of flashes of the lamp and is difficult to quantify because of the difficulty in measuring the spectral irradiance of pulsed light sources. The spectral match of unfiltered arc lamps in the UV and visible region is excellent but poor in the red (>700 nm) because of the numerous Xe emission lines. Custom filters reduce the magnitude of these lines to manageable levels. These emission lines are reduced for pulsed-Xe lamps.

The least expensive small-area light source is a tungsten-halogen lamp with a dichroic filter. These lamps are ideal for quantum efficiency measurements because of their irradiance temporal stability. The lamp spectrum depends strongly on the operating voltage or current [138]. A shift in the spectrum with bulb age has been attributed to tungsten-halogen lamps, but a careful study revealed that although the intensity drops with bulb age at a constant current, the shift with bulb age is less than the variation from bulb to bulb out of the same case [141]. To minimize spectral shifts of filament light sources with bulb age, they should be run at the same current throughout their life. The distance between the bulb and test plane should be varied to maintain the proper light level. There are a wide variety of tungsten-halogen bulbs with different wattage, lifetime, and voltage ratings. The choice of the most appropriate bulb is a compromise; for example, the ELH bulb has one of the highest wattages, but operates at 120 V and has a short lifetime of 35 h. Low-voltage bulbs such as the HLX, ELC, or HMM operate below 40 V, eliminating the safety hazard of higher voltage bulbs, and they have a longer life but a lower wattage. As with continuous arc lamps, the lamp lifetime is reduced by