PHOTONICS POINTERS

Getting the most out of photonics

Avoiding Errors in UV Radiation Measurements

by Thomas C. Larason

The variety of applications of ultraviolet light and the consequent need for accurate UV measurements have increased. In some cases, the UV radiation from a source is of interest. At other times, the action or chemical reaction initiated by UV irradiation of a system is of interest. Also, because UV radiation has a cumulative harmful effect on biological systems, its accurate measurement is required for health and safety.

The typical broadband UV meter or radiometer comprises a number of simple optical elements (Figure 1). The signal i from such a radiometer is the photosensitive area of the meter, A, multiplied by the integral of the product of the instrument responsivity, S(λ), and the irradiance distribution of the source, E(λ):[1]

$$i = A \cdot \int_{\lambda} E(\lambda) \cdot S(\lambda) \cdot d\lambda$$

The instrument responsivity is a function of the responsivity of the detector and the transmittance of the diffuser and optical filter.

To fully understand the accuracy of a UV meter, we must know the optical properties of its components, its spectral responsivity and the relative spectral distribution of the source. Most UV meters are calibrated at a specific wavelength, and only a nominal wavelength band is specified. In addition, the spectral distribution of the source being measured is often unknown.

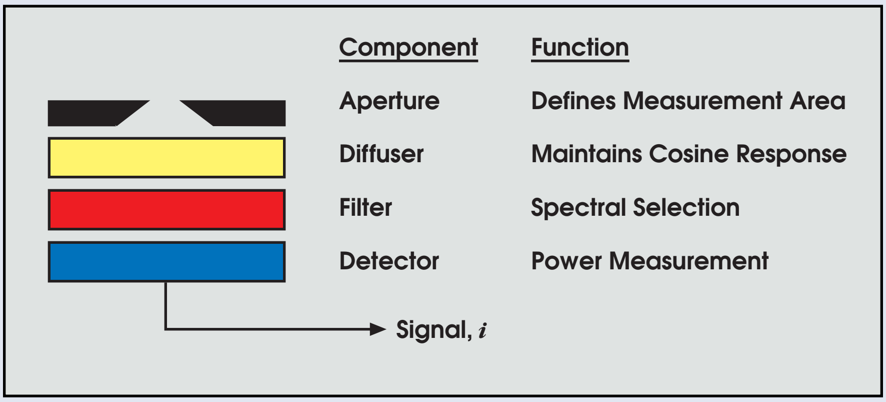

Figure 1. *A UV radiometer comprises a number of relatively simple optical elements.*

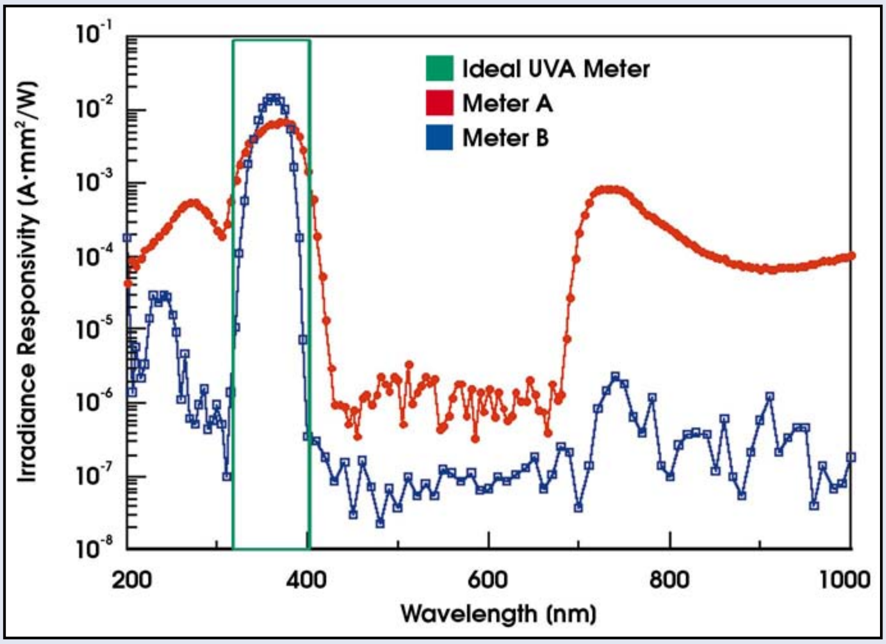

Figure 2. *The spectral responsivity differs between two broadband UV meters used in semiconductor photolithography to determine the total exposure of a photoresist to 365-nm radiation from a filtered mercury source.[5] The graph also points out the spectral responsivity of an "ideal" UVA meter.*

Measurement requirements

It is important to define at the outset the physical quantity that is to be measured and the level of uncertainty needed to achieve the measurement goals. The measurement requirements can be very different: spectrally integrated irradiance (watts per square centimeter) in the UVA (315 to 400 nm) or UVB (280 to 315 nm) regions, as in the case of solar irradiation; a single wavelength dose or exposure (joules per square centimeter), as in the case of semiconductor photolithography; or an effective or weighted dose (effective joules per square centimeter), as in the case of biological action spectra.

Some recent publications[2,3] and a few technical organizations[4] have

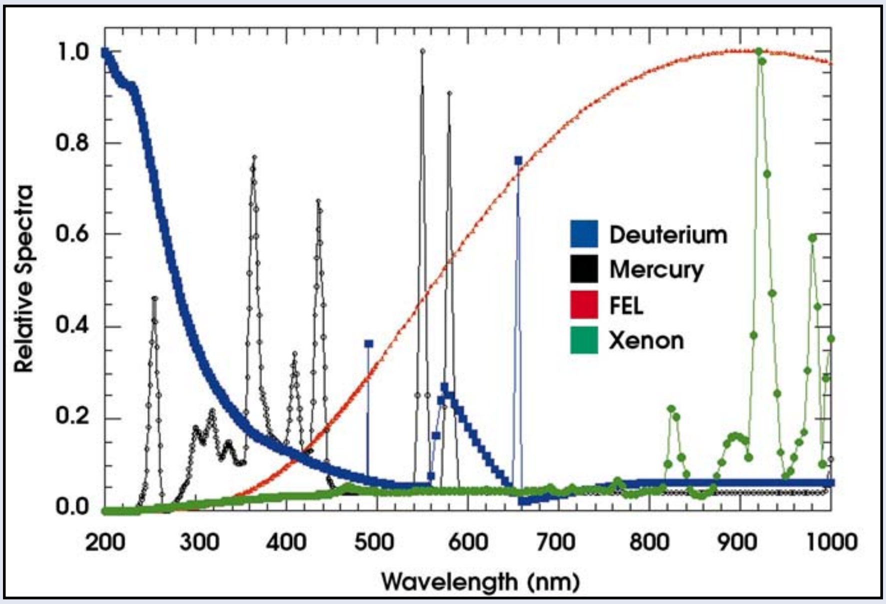

Figure 3. *Two UV meters' responses to a mercury arc lamp, an FEL lamp (a quartz-halogen lamp used for calibration purposes), a deuterium lamp and a xenon arc lamp illustrate the differences in their out-of-band response. Their ratios of out-of-band signal to in-band signal differ dramatically.*

specifically addressed UV meter calibration and characterization.

Several potential sources of error exist in UV radiation measurements, including out-of-band contributions to the signal, nonideal geometric properties (nonideal cosine response in the meters) and poor matching to a defined action spectrum. Other sources of error include environmental factors such as temperature and humidity. UV radiation also induces aging of the optical elements in meters. Optical detectors used in UV meters have a limited range over which they are linear. These sources of error in optical radiation measurements are not new and, in addition to measurement techniques and procedures, are well-documented in the field of photometry.

Out-of-band responsivity

An ideal meter would have a well-defined responsivity within a specific spectral region and zero responsivity outside of this region. For example, an ideal UVA meter would have a constant responsivity from 315 to 400 nm and no response outside of this region.

In practice, real meter responsivity is not ideal (Figure 2).[5] In the figure, two instruments can make measurements of monochrome radiation near 365 nm with little error because out-of-band response is not important. But they demonstrate significantly different increases in responsivity in the near-infrared, with Meter A's responsivity two to three orders of magnitude larger than Meter B's from 700 to 1000 nm. The responsivity increases because the glass filters transmit more in the IR and because silicon photodiodes have their peak response in the near-IR. The

TABLE 1.
Expected error when measuring differing test and calibration sources for Meter A.

Calibration Source	Test source			
	FEL	Mercury	Deuterium	Xenon
FEL	0.0 %	−74.8 %	−74.7 %	−64.9 %
Mercury	297.0 %	0.0 %	0.3 %	39.5 %
Deuterium	296.0 %	−0.3 %	0.0 %	39.2 %
Xenon	184.6 %	−28.3 %	−28.1 %	0.0 %

TABLE 2.
Expected error when measuring differing test and calibration sources for Meter B.

Calibration Source	Test source			
	FEL	Mercury	Deuterium	Xenon
FEL	0.0 %	50.8 %	−6.7 %	2.7 %
Mercury	−33.7 %	0.0 %	−38.2 %	−31.9 %
Deuterium	7.2 %	61.7 %	0.0 %	10.1 %
Xenon	−2.7 %	46.8 %	−9.2 %	0.0 %

increased responsivity at wavelengths shorter than 300 nm is from fluorescence of the diffuser, which then re-emits longer-wavelength radiation that passes through the filter to the photodiode.

Although these UV meters were designed to measure monochromatic radiation, they are very similar to UV meters designed and used to measure broadband UV radiation. If the source to be measured emits flux at wavelengths below 300 nm or above 680 nm, the 365-nm radiation could be overestimated, and measurements between instruments would disagree.

To illustrate these errors, we compared signals from the two UV meters using four sources with different spectral power distributions (Figure 3). Using our first equation, we can compare the integrated in-band irradiance signal with the out-of-band signal.[6]

Calibrating a meter with one type of source and subsequently measuring a different type can lead to large and undefined errors (Tables 1 and 2).[6] The errors are large for Meter B, even though it has low out-of-band response, because the in-band response does not closely match the ideal UVA response function.

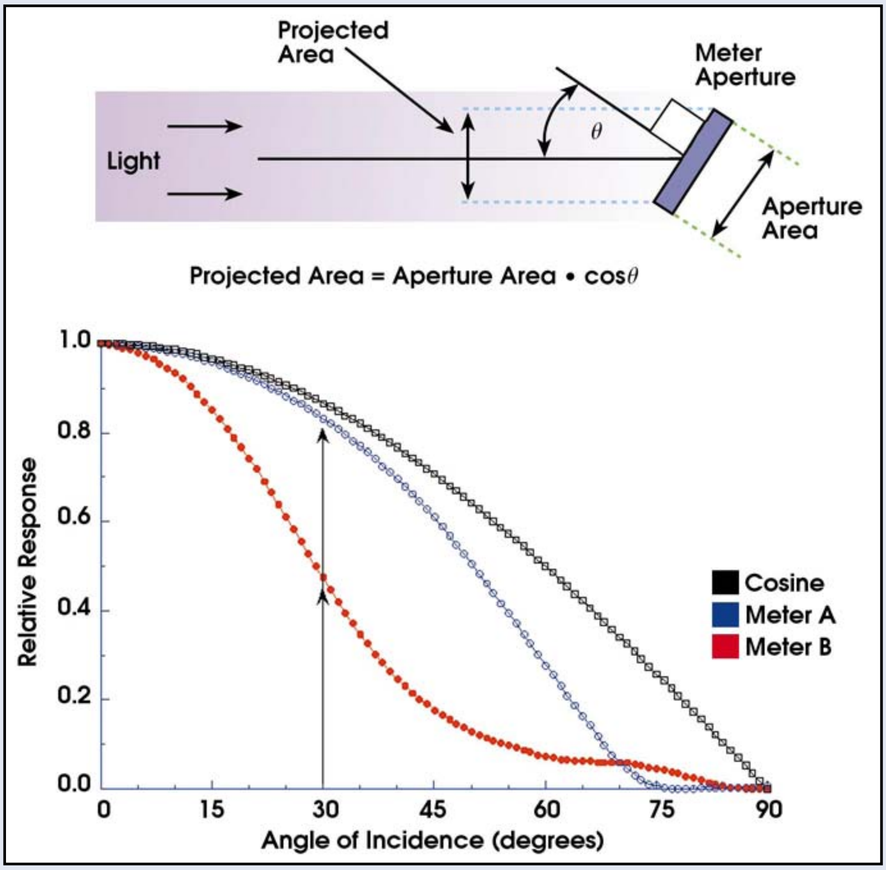

Figure 4. *Two UV meters' angular responses differ not only from each other, but also from an ideal cosine response. Meter A's responsivity to light 30° from normal was 3.5 percent less than ideal, and Meter B's was 45 percent less. The inset shows the geometry illustrating how angle affects the signal measured by a meter.*

Cosine response

For an ideal meter, we can calibrate responsivity with an incident beam of any solid angle and use the meter to correctly measure light entering its aperture over any angular distribution. The reality is that a meter's responsivity decreases with angle faster than the expected cosine function. This nonideal cosine response can lead to large errors.

To illustrate this, we tested Meters A and B by precisely rotating each one around an axis at the aperture while irradiating it with a narrow light beam (Figure 4).[5] If we assume that the irradiation from a particular source is uniform over the solid angle containing the radiation, we can calculate the difference between the response of an ideal meter and Meters A and B. For example, for a solid angle of 30°, Meter A's response would be low by 2 percent and Meter B's by 23 percent.[5] A large deviation from cosine response leads to greater uncertainty in irradiance determinations. However, for small solid angles, both meters can make measurements with little error.

Commercial photolithography instruments often use a large solid angle. Because it's not feasible to accurately determine the spatial characteristics of the incoming light in a stepper, the meter whose angular response is closest to ideal will provide the most accurate results.

Error also occurs when the calibration source offers an incident irradiation geometry different from the measured source.

Recall from the previous section that Meter A had poorer out-of-band response than Meter B, but superior cosine response. The application would determine which is the better choice.

Action spectra

Roberson-Burger-type meters measure the erythemal effectiveness of sunlight. A comparison of two UV meters (Figure 5)[8] shows that large uncertainties result from calibrating these meters with the quartz-halogen FEL lamps if the ultimate use is to measure solar radiation or UV lamps.

However, note that UV broadband measurements can use the common photometric spectral mismatch correction technique in which a particular UV action spectrum replaces the photopic V(λ) function. In this case, the erythema function replaces V(λ). The spectral mismatch correction factors have been calculated as 0.48 for Meter 1 and 0.19 for Meter 2.[8]

You can minimize the errors if you know both the calibration source and the source to be measured and apply the spectral mismatch function to the measurement result. If the calibration source is different from the source to be measured, you will need correction factors for each type.

Best practices

For UV measurements with the lowest uncertainties: Analyze the measurement problem; match the radiometer to the application; match the calibration source to the application measurement; and characterize the radiometer for its spectral and geometric responses.

If the application involves measuring a monochromatic source, a simple broadband UV meter calibrated at that wavelength is usually sufficient. If the application involves measuring a broadband or extended source, choose a UV meter that has the closest match to the desired measurement function (such as UVA or erythema). If not, calculate a correction factor for each source to be measured — but measure the absolute spectral responsivity of the UV meter and know the source's relative spectral distribution. Alternatively, calibrate the meter with a source that has a spectral distribution similar to that of the source being measured. □

	Ratio of Out-of-Band to In-Band Response			
	FEL	Mercury	Deuterium	Xenon
Meter A	363.8%	7.4%	35.2%	68.1%
Meter B	0.8%	0.0%	1.9%	0.2%

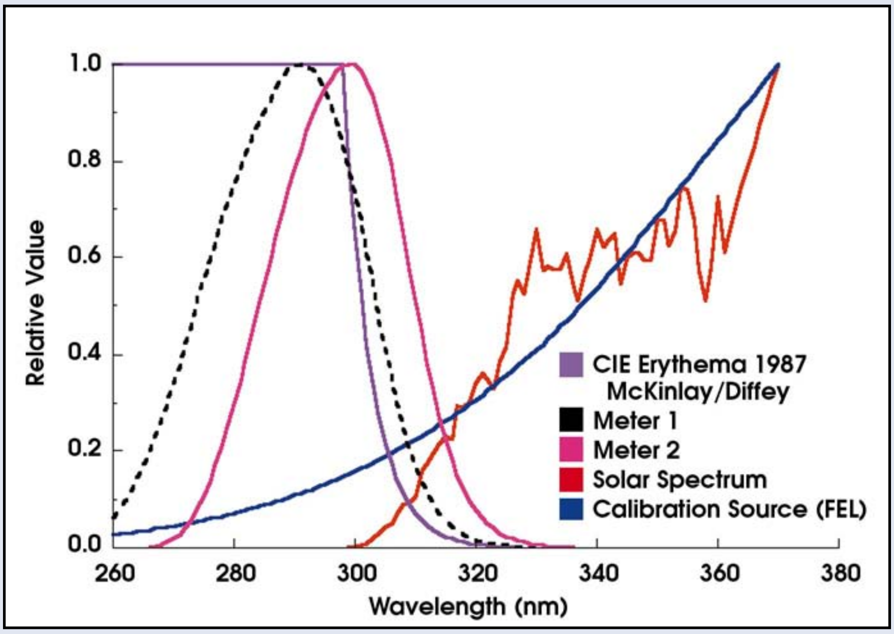

Figure 5. *Two UV radiometers exhibit a mismatch to the CIE 1987 erythema function.[7] This shows the uncertainties that can arise when the calibration source differs from the measurement source.*

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