Optical characterization of diffuser-input standard irradiance meters

George Eppeldauer[a], Miklós Rácz[b], and Thomas Larason[a]

[a]Optical Technology Division of the National Institute of Standards and Technology
Gaithersburg, MD 20899, USA

[b]Guest Researcher at National Institute of Standards and Technology from the Hungarian Academy of Sciences Research Institute for Technical Physics and Materials Science
P.O. Box 49, Budapest-114, Hungary 1525

ABSTRACT

Standards quality irradiance meters have been developed at the National Institute of Standards and Technology (NIST) to realize a detector based spectral irradiance scale. The design criteria and the optical and radiometric characterization of diffuser-input irradiance meters are discussed. The input geometry optimization is described for a broad-band InGaAs irradiance meter when measuring a 2856 K incandescent light source. The directional responsivity of the fabricated InGaAs and Si irradiance meters matches the cosine function with a maximum deviation of 0.15 % within a 12° field-of-view (FOV). Irradiance from sources of different sizes (incident beams with different *f*/numbers) can be measured over a wavelength range of 350 nm to 1800 nm.

Keywords: aperture, cosine function, directional responsivity, detector, diffuser, irradiance, photodiode, radiometer, spectral responsivity, working standard.

1. INTRODUCTION

The detector spectral responsivity scale of NIST is based on an electrical substitution High Accuracy Cryogenic Radiometer (HACR)[1]. The HACR measures the radiant power of intensity stabilized laser lines with a relative standard uncertainty of 0.021 %. After a scale derivation procedure[2], large-area, single-element Si[3] and Ge[4,5] photodiode working standards are calibrated for spectral power responsivity. The uncertainty of the spectral power responsivity is wavelength dependent. The relative standard uncertainty is about 0.1 % in the visible, 1 % in the UV, and 2.5 % in the near-infrared range when the responsivity is transferred to test detectors[2].

In order to extend the detector based spectral power responsivity calibrations to irradiance responsivity, standards quality irradiance meters had to be developed. The beam geometry at calibration and the different applications varies from parallel (collimated) to 12° full angle (6° incidence angle). In order to achieve high measurement accuracy, the directional characteristics of the detectors have to follow the cosine law in this angular range. The directional characteristics were controlled up to a 10° incidence angle to assure the proper cosine response of the detectors within the desired angular range. The design and optical characterization of these meters are discussed for an InGaAs irradiance meter. The described optimization procedure was utilized for a Si irradiance meter as well.

2. SPECTRAL CHARACTERISTICS

The spectral characteristics of the irradiance meters are determined by the photodiode and the flashed opal glass diffuser used in the meter. In Fig. 1 the spectral responsivities of the Si and InGaAs photodiodes and the irradiance meters can be seen. The magnitudes of the irradiance responsivities are similar for the two meters because the larger aperture (8.0 mm diameter) of the Si meter produces higher irradiance responsivity than the smaller aperture (6.4 mm diameter) of the InGaAs meter. Sources with either monochromatic or known (e.g., Planckian) spectral power distributions can be measured with these broadband irradiance meters.

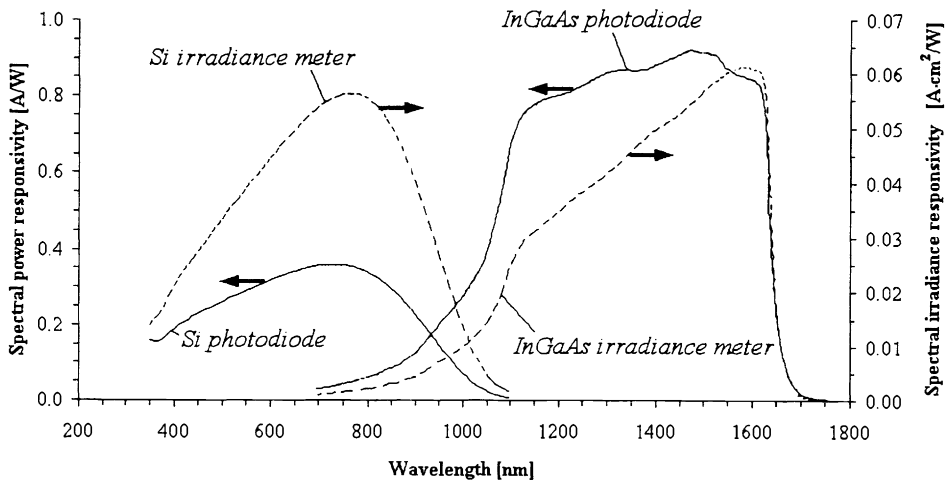

Fig. 1. Spectral responsivities of the Si and InGaAs photodiodes and the corresponding irradiance meters.

3. DIRECTIONAL CHARACTERISTICS

The directional responsivity measurements were performed on the NIST photometry bench. Several tungsten incandescent lamps were used as non-calibrated radiation sources. The color temperature of the lamps was set to 2856 K or lower. The irradiance meters to be measured were mounted on a rotational stage and the input apertures were positioned on the rotation axis. The distance between the lamps and the rotation axis was about 3.25 m. The quality of the directional responsivity data was characterized with the Commission Internationale de L'Éclairage (CIE) directional error $f_2(\varepsilon,\phi)$:

$$f_2(\varepsilon,\phi) = \frac{E_{\text{reading}}(\varepsilon,\phi)}{E_{\text{reading}}(\varepsilon = 0°)\cdot\cos\varepsilon} - 1 \tag{1}$$

where $E_{\text{reading}}(\varepsilon,\phi)$ and $E_{\text{reading}}(\varepsilon = 0°)$ are the readings for an irradiance, E, arriving at the angles of incidence ε and 0° respectively. ϕ is the azimuth angle. Because the irradiance meters are circularly symmetrical, they were only tested at two perpendicular ϕ values.

Drawings of the NIST developed diffuser-input irradiance meters can be seen in Fig. 2. The FOV limiters reject optical radiation outside the FOV. The input apertures determine the reference plane and the active area of the irradiance meters. The diffusers dominate the directional responsivity of the meters. The detectors are temperature controlled by thermoelectric coolers and are electrically shielded. The temperature of the InGaAs and Si photodiodes are controlled to -30 °C and +25 °C respectively.

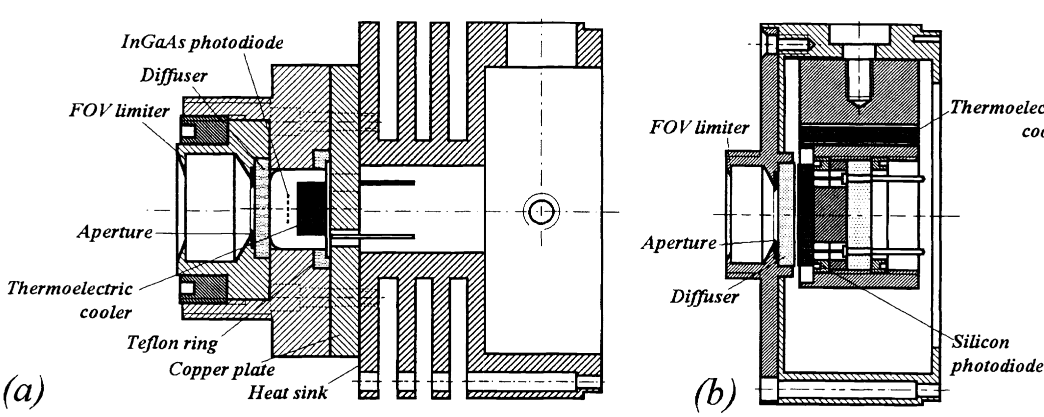

Fig. 2. Input optics cross-section of the InGaAs (a) and Si (b) irradiance meters.

The geometry of the input optics of the irradiance meters was optimized experimentally. Several flashed opal glass diffusers were tested with a Cary 4a spectroradiometer in the 400 nm to 1700 nm wavelength range because their visual appearance was not the same. The diffusers were separated into four groups according to their diffuse reflectances of about 27 %, 31 %, 35 %, and 40 % at 1400 nm. As can be seen in Fig. 3, the diffuse reflectance of the samples decreases with increasing wavelength.

Four sizes of apertures were also tested. Their diameters were approximately 3.5 mm, 6.4 mm, 8.0 mm, and 11.5 mm. The optimal aperture-diffuser pair was chosen experimentally. Every possible combination was measured for angular response and the CIE $f_2(\varepsilon)$ error functions were evaluated. Fig. 4 shows the $f_2(\varepsilon)$ functions for the 0° to 10° incidence angle range at a given ϕ value. The $f_2(\varepsilon)$ functions can be seen for combinations with the 6.4 mm aperture and the four different diffusers in Fig. 4a. Whereas Fig. 4b shows the $f_2(\varepsilon)$ functions for combinations built with a 40 % reflectance diffuser and the four different apertures.

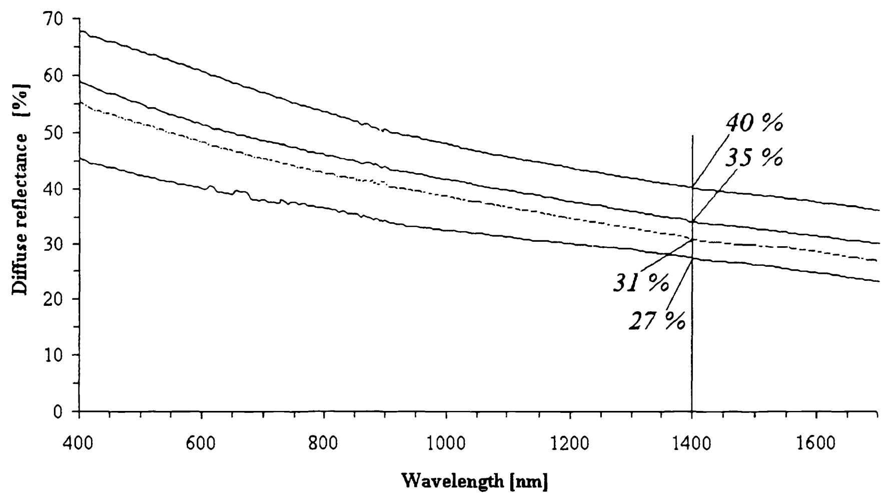

Fig. 3. Diffuse spectral reflectance of the flashed opal glass diffusers. The vertical line shows the wavelength of the diffuser selection.

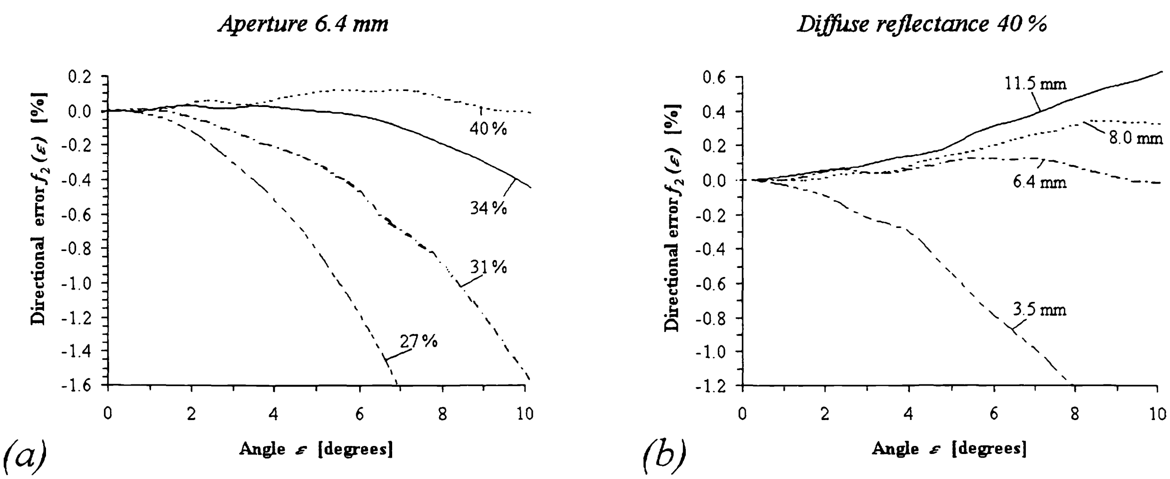

Fig. 4. Directional error of different aperture-diffuser pairs for a circular InGaAs photodiode with a diameter of 5.0 mm. Figure 4a shows the measurement results for four different diffusers with the 6.4 mm aperture. Figure 4b shows the results for four different apertures with a diffuser reflectance of 40 %.

As can be seen, the angular responsivity depends upon the diameter of the aperture and the quality of the diffuser. Two pairs of aperture-diffuser were found to have adequate directional characteristics, the 6.4 mm aperture with a 40 % diffuser and the 8 mm aperture with a 35 % diffuser. The 6.4 mm aperture and 40 % diffuser pair had better spatial responsivity characteristics and was selected for the InGaAs irradiance meter. The selected diffuser pair had an effective area 11.0 % smaller than the geometrically measured area. For the other pair, the effective area was 18.4 % smaller than the geometrically measured area because of the larger spatial nonuniformity.

It follows from Figs. 3 and 4a that the optimum cosine response depends on the wavelength. Consequently, the input geometry has to be optimized for the wavelength (or the spectral distribution) of the source to be measured.

4. RESPONSIVITY CALIBRATION AND SPATIAL CHARACTERISTICS

An x-y scanning procedure was used to determine the integrated irradiance responsivity and the effective aperture area of irradiance and illuminance meters[6]. This irradiance calibration method uses only detector standards instead of conventional standard sources. The procedure where a small beam overscans the input aperture of the meter, also provides information on the spatial responsivity uniformity of the detector. The output signal of the detector was measured as a function of the position of the beam. The wavelength was selected for the sensitivity range of the photodiode, 780 nm for Si and 1500 nm for InGaAs. Fig. 5 shows the spatial responsivity of the InGaAs meter with the 6.4 mm aperture and the 40 % diffuser. The diameter of the beam was 1.1 mm. Each distance step of the scan was 0.5 mm. The position of the beam relative to the center of the aperture is measured on the horizontal axes, while the output signal of the irradiance meter is drawn on the vertical axis. The irradiance meter output signal is normalized to the signal measured in the central position. In Fig. 5a the response uniformity of the active area is shown and in Fig. 5b the radiation scattered from the area surrounding the aperture can be seen.

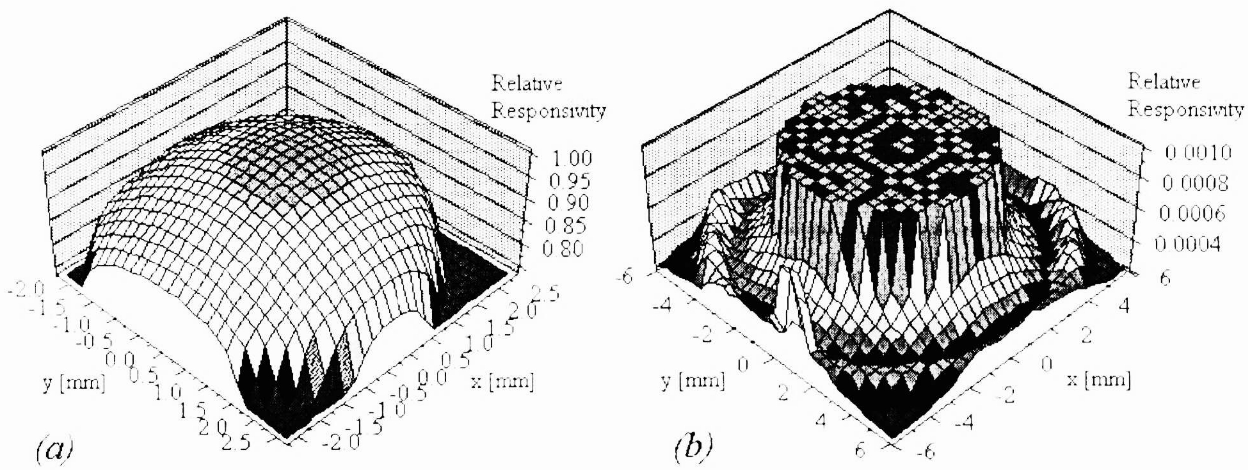

Fig. 5. Spatial responsivity distribution plots of the diffuser-input InGaAs irradiance meter with a 6.4 mm aperture and a 40 % diffuser. Figure 5a shows the uniformity of the sensitive area, while Fig. 5b shows the stray radiation.

The effective area of an irradiance meter can be calculated as the ratio of the integrated irradiance responsivity to the radiant power responsivity in the center of the aperture. The effective area is utilized in flux transfers when the measured irradiance (in the meter's aperture plane) is transferred to another device, e.g., the exit port of a radiance source[7]. In such cases, geometrical aperture area measurements are not needed. When a diffuser is used between the aperture and the photodiode to maintain the cosine response of an irradiance meter, a side effect is the decreased responsivity toward the edges of the photodiode. Because of this side effect, the effective area can be significantly different from the geometrically measured area of the aperture. The measured effective area of the InGaAs irradiance meter with the 6.4 mm aperture was 28.6 mm^2 ± 0.5 %, while the geometrical area is 32.08 mm^2 ± 0.075 %. The effective area of the Si meter was measured at two different wavelengths of 563 nm and 815 nm. The area change was 0.29 %, well within the uncertainty of the radiometric effective area measurement.

5. UNCERTAINTIES

The uncertainty components in addition to the uncertainty of the spectral power responsivity calibrations[2] originate from several sources. The uncertainty of the integrated irradiance measurement method is estimated to be 0.5 %, the directional error of 0.15 % for the optimized meters, and the integrated stray radiation of 0.1 %. The relative combined standard uncertainty of an irradiance measurement with the Si meter is 1.6 % at 350 nm. The standard uncertainty decreases to 0.94 % at 400 nm and is almost constant at 0.54 % in the visible to 925 nm. From 925 nm to 1800 nm the where InGaAs irradiance meter is used the estimated standard uncertainty is about 1.2 % from 925 nm to 1345 nm and increases to about 2.6 % between 1350 nm and 1800 nm.

6. CONCLUSION

Diffuser-input irradiance meters have been developed with InGaAs and Si photodiodes as working standards. The wavelength range of the two irradiance meters covers the 350 nm to 1800 nm wavelength region. The irradiance meters were calibrated against the NIST detector spectral power responsivity scale. The flashed opal glass diffusers were measured and grouped according to their diffuse reflectance. A range of apertures was tested with the different diffusers. Diffuser and aperture pairs were selected for optimum cosine response and minimum spatial responsivity nonuniformity. The CIE directional error was $f_2(\varepsilon) = 0.15$ % or less for the irradiance meters in the 0° to 10° incidence angle range. The total irradiance responsivity of the meters was determined from spatial responsivity integrals over the aperture area during a scanning procedure. The standard irradiance meters can measure spectral irradiance with an estimated combined standard uncertainty of 0.54 % in the visible range.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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