Preprint: Paper to be published in Proc.,
CIE Expert Symposium on LED Light Sources, June 2004, Tokyo

MEASUREMENT OF TOTAL RADIANT FLUX OF UV LEDS

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ABSTRACT

We have developed a source-based method and a detector-based method for total radiant flux measurement for deep-blue and UV LEDs, using a 2.5 m integrating sphere. Several UV LEDs with peak wavelengths of 375 nm and 390 nm were measured using both the source-based method and the detector-based method with a relative expanded uncertainty (k=2) of ~6 % and ~5 %, respectively. The results of the two methods agreed within 2 %.

Keywords: integrating sphere; LED; total radiant flux.

1. INTRODUCTION

There is an increasing need for accurate measurement of the total radiant flux (W) and efficiency of LEDs in the deep-blue to UV region. NIST has already established a calibration facility for the total luminous flux (lm) of LEDs using our 2.5 m integrating sphere [1]. The current absolute integrating sphere calibration method cannot be used for radiant flux measurement in the UV region or even the deep blue region because the photometer signal is very low and the uncertainty is too high. Total radiant flux measurements, in general, can be realized by radiometric measurements with a goniophotometer or by measurements of total spectral radiant flux (W/nm) with a spectro-goniophotometer. However, these facilities are yet to be established at NIST. To accommodate the urgent need of industry for calibration of UV and deep-blue LEDs, we have established two calibration methods using our 2.5 m integrating sphere facility.

2. MEASUREMENT METHODS

Two independent methods have been developed for the measurement of the total radiant flux of deep-blue and UV LEDs. One is a source-based method using a spectral irradiance standard lamp. The other is a detector-based method using a spectral irradiance responsivity reference detector.

2.1 The source-based method

Figure 1 depicts this source-based method. It employs a spectroradiometer and a spectral irradiance standard FEL lamp as an external calibration source. The same principles as the Absolute Integrating Sphere method [2] for the luminous flux measure-ment at NIST is used but applied spectrally. Since the flux from an LED is relatively low and the sphere throughput is low (due in part to the large size), we need an instrument with a very high sensitivity. We used an array spectroradiometer employing a back-thinned CCD array, which gives sufficient signal-to-noise ratio for the LEDs measured. The total sphere system (spectroradiometer and the integrating sphere) is calibrated against the spectral radiant flux of the beam introduced from the external spectral irradiance standard FEL lamp, which was calibrated at the NIST Facility for Automated Spectro-radiometric Calibrations, in the direction of its optical axis at a distance of 0.5 m.

The external beam and the LED emission have very different spatial profiles and illuminate different parts of the sphere; thus, a uniform sphere responsivity is critical to reduce the error from the spatial dissimilarity. In order to achieve a uniform sphere responsivity, the cosine-response of the fiber probe of the spectroradiometer on the sphere wall is extremely important. We use the same diffuser, a surface-ground opal glass, as was used for total luminous flux calibrations [2]. The surface-ground

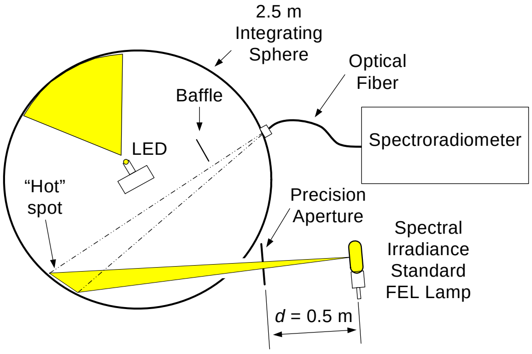

Figure 1. Source-based method

opal glass is a good diffuser in the UV and visible regions. The diffusion property of the opal glass has very little dependence on wavelength, significantly reducing the characterization work of the sphere with respect to various wavelengths. The problem with the opal glass is the low transmission in the UV (it drops quickly at < 400 nm).

We tested several other UV diffusers at 380 nm: a surface-ground quartz plate, a surface-ground quartz dome, and a teflon dome diffuser. These diffusers had unacceptable cosine response or the diffusion property is strongly wavelength dependent.

The spectral flux of the external reference beam, $\Phi_{ext}(\lambda)$, is determined by

$$\Phi_{ext}(\lambda) = A \cdot E_{ext}(\lambda) \qquad (1)$$

where $E_{ext}(\lambda)$ is the spectral irradiance of the FEL lamp at the aperture plane, and A is the area of the aperture. The total radiant flux of the LED, Φ_{LED}, is obtained by

$$\Phi_{LED} = k_{corr} \int_{\lambda} \Phi_{ext}(\lambda) \frac{i_{LED}(\lambda)}{i_{ext}(\lambda)} \mathrm{d}\lambda \qquad (2)$$

where $i_{LED}(\lambda)$ is the spectroradiometer signal for the test LED, $i_{ext}(\lambda)$ is the spectroradiometer signal for the external beam from the FEL lamp, and k_{corr} is the overall correction factor that is determined by

$$k_{corr} = k_E \cdot k_{angle} \cdot k_{spatial} \qquad (3)$$

where k_E is irradiance nonuniformity correction factor at the precision aperture, which is the ratio of the average irradiance within the aperture to the irradiance at the center of the aperture; k_{angle} is the correction factor of incident angle dependence, which is the ratio of the sphere response at the angle of incidence of the external beam to that at normal incidence; $k_{spatial}$ is the spatial nonuniformity correction factor of the sphere responsivity due to the geometrical differences between the external beam and the LED emission illluminating inside the sphere.

All corrections necessary for this absolute sphere method are made spectrally for the spatial nonuniformity of sphere response and incident angle dependence of the sphere response [However, the spectral differences of the correction factors were insignificant]. No considerable dependence of incident angle on wavelength was observed. We conducted series of spectral spatial mapping measurements of the sphere by scanning a beam source [2] and using the spectroradiometer, and found that the spatial uniformity of the integrating sphere system has little dependence on the wavelength (< 0.5 %). The UV regions have similar spatial uniformity as the visible region. The reason for this wavelength independence of the sphere uniformity is because the diffusing property of the opal glass is wavelength-independent and also because both the external source and the LED are illuminating the regions of the sphere wall that have theoretically equal responsivity.

The coating of our sphere is based on barium sulfate. We observed considerable fluorescence from the coating when measuring UV LEDs (or even deep-blue LEDs), which caused significant errors. The stray light of the CCD-array spectroradiometer is another problem. Therefore, we developed an algorithm that effectively corrects the fluorescence of the sphere and stray light of the spectroradiometer at the same time by characterizing the measurement system at many wavelengths using a tunable laser. The details of this work are to be published elsewhere.

We also tested the spectroradiometer for wavelength error (± 0.2 nm) and for nonlinearity (1.5 %). These factors are used in the analysis of the measurement uncertainty.

2.2 The detector-based method

Figure 2 shows a schematic of the detector-based measurement system. This method employs a radiometric detector (silicon photodiode) to measure the output of the sphere. In this method, the total spectral radiant flux responsivity of the total integrating sphere system (A/W) is calibrated using monochromatic radiation at many wavelengths produced by a tunable laser directed through a fiber into a small integrating sphere (50 mm diameter) outside the sphere. The small integrating sphere produces near-Lambertian radiation. We used a portable version of the NIST Spectral Irradiance and Radiance Calibration using Uniform Sources (SIRCUS) [3] that covered wavelengths from 360 nm to 480 nm. The irradiance, $E_{laser}(\lambda)$, at the aperture plane is determined by using a reference detector calibrated for spectral irradiance responsivity, $s_{RD}(\lambda)$, using the NIST Spectral Comparator Facility (SCF).

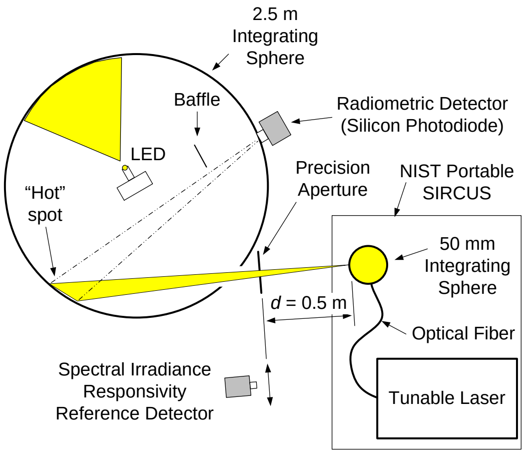

Figure 2. Detector-based method

The total radiant flux of the tunable laser beam, $\Phi_{laser}(\lambda)$, introduced to the sphere for each wavelength is determined by

$$\Phi_{laser}(\lambda) = A \cdot \frac{i_{RD,\,laser}(\lambda)}{s_{RD}(\lambda)} \qquad (4)$$

where $i_{RD,laser}(\lambda)$ is the output signal of the reference detector for laser wavelength λ, and A is the aperture area. The absolute spectral radiant flux responsivity of the sphere system, $s_S(\lambda)$, is given by

$$s_S(\lambda) = \frac{i_{S,\,laser}(\lambda)}{\Phi_{laser}(\lambda)} \qquad (5)$$

where $i_{S,laser}(\lambda)$ is the output signal of the silicon photodiode on the sphere. The absolute responsivity of the sphere system for a test LED, $s_{S,LED}$, is given by

$$s_{S,\,LED} = \frac{\int_\lambda S_{LED}(\lambda)\; s_S(\lambda)\; d\lambda}{\int_\lambda S_{LED}(\lambda)\; d\lambda} \qquad (6)$$

where $S_{LED}(\lambda)$ is the relative spectral power distribution of the test LED. The total radiant flux of the test LED, Φ_{LED}, is obtained by

$$\Phi_{LED} = k_{corr} \cdot \frac{i_{LED}}{s_{S,LED}} \qquad (7)$$

where i_{LED} is the output signal of silicon photodiode on the sphere for the test LED, and k_{corr} is the overall system correction factor, which consists of basically the same corrections as given in Eq. (3). We applied the same correction factors used in the first method for the incident angle dependence of the sphere responsivity, k_{angle}, and the spatial nonuniformity, $k_{spatial}$, because we used the same diffuser as was used in the first method since the cosine correction of the detector for the sphere is just as critical with the first method. k_E is for the laser radiation from the small external sphere, which was determined to be negligible.

The fluorescence of the sphere is cancelled out using this detector-based method, which is an advantage of this method.

3. MEASUREMENT RESULTS BASED ON THE TWO METHODS

We measured several UV LEDs using both methods. The LED#1, LED#2, and LED#3 produce 200 mW at a peak wavelength of 390 nm, and the LED#4, LED#5, LED#6, and LED#7 produce 20 mW at a peak wavelength of 375 nm. We first measured the test LEDs for relative spectral power distributions, $S_{LED}(\lambda)$, and found that the total emission beyond 450 nm is negligible. Thus, a blue-violet bandpass filter (BG-12, 355 nm to 459 nm) positioned directly in front of the fiber optic was used to block unnecessary spectral radiation of the standard FEL lamp into the CCD-array spectroradiometer in order to increase the dynamic range; to reduce significant stray light at the deep-blue and UV regions; and also to limit system response to sphere fluorescence excited by short wavelength radiation (UV and blue). The blocked light is < 0.2% of the total.

Major uncertainty components (all given in standard uncertainty) with the source-based method are nonlinearity of the spectro-radiometer (1.5 %), random noise in the measurement of the external beam (1.0 %), and system stability (the integrating sphere and spectroradiometer) in the UV (1.5 %). Major uncertainty components for the detector-based method are spectral irradiance responsivity of the reference detector (0.9 %), random noise of the signal in measurement of external laser flux into the sphere (1.0 %), stability of the integrating sphere in the UV (1.0 %), and determination of the relative spectral power distribution of test LED (1.2 %). Including the repro-ducibility of the test LEDs (1.2 %), the overall relative expanded uncertainty (k=2) is 5.8 % for the source-based method, and 5.2 % for the detector-based method.

Figure 3 shows the results of the measure-ments, given as the ratios of total radiant flux using the source-based method and that using the detector-based method. The agreement between the two methods were within 2 %, which is well within the overall relative expanded uncertainty of both methods (The error bars show the expanded uncertainty of the source method, 5.8 %). Errors from common correction factors, such as the incident angle dependence factor, k_{angle} and the spatial nonuniformity factor, $k_{spatial}$ cancel and won't affect the results. However, they are not dominant components of uncertainty. Thus, the comparison results verify that both methods worked well, and either method can be used for the measurement of UV LEDs.

The source-based method is simpler to implement, not requiring tunable lasers except to characterize the sphere fluorescence. It also has an advantage that the total spectral radiant flux (spectral distribution) of the LED is obtained. However, stray light of the spectroradiometer and fluorescence of sphere coating can cause large measurement errors, and should be corrected. The detector-based method does not have these problems. However, it requires a tunable laser covering the wavelength range of the LED emission. Also, the relative spectral power distribution of the test LED must be measured separately.

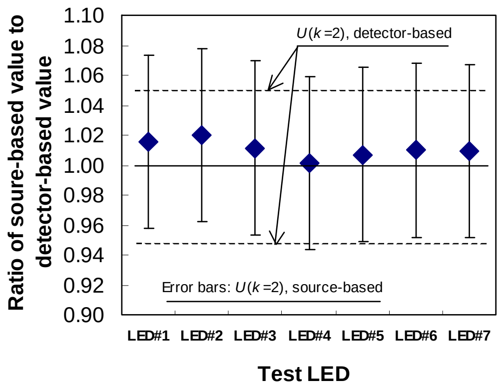

Figure 3. Ratios of results using the two methods

4. CONCLUSION

A source-based and a detector-based method for total radiant flux measurements of UV LEDs were developed with overall relative expanded uncertainties (k=2) of 5.8 % and 5.2 %, respectively. The comparison shows that the two methods worked well within the estimated uncertainty. For the source-based method, the uncertainty can be further reduced by using a diffuser with higher UV transmittance, correcting the nonlinearity of the spectroradiometer, and improving the stability of spectroradimeter in the UV region. For the detector-based method, the uncertainty can be reduced by calibrating the reference detector with our SIRCUS facility, increasing the power of the tunable laser, and use of a diffuser having more spectrally flat transmittance. Further work for such improvements is planned at NIST in order to achieve an overall relative expanded uncertainty (k=2) of 2 %.

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ACKNOWLEDGEMENTS

The authors thank Steve Brown for the Travelling SIRCUS, Thomas Larason for calibration of two silicon photodiode detectors, and Charles Gibson for calibration of two FEL lamps. The authors also thank John Scarangello and Ling Zhou of LumiLEDs Lighting for helpful discussions of UV LEDs.

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