IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 6, Number 1, February 2014

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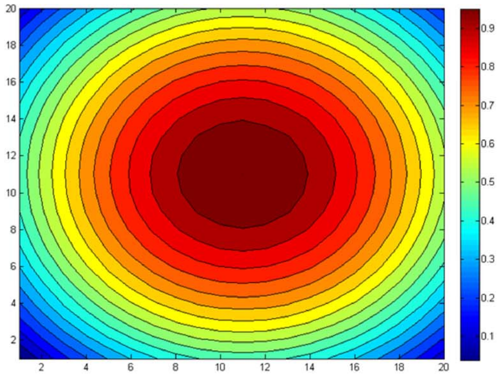

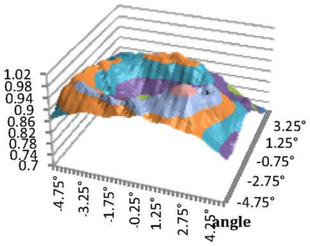

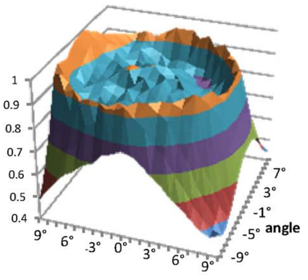

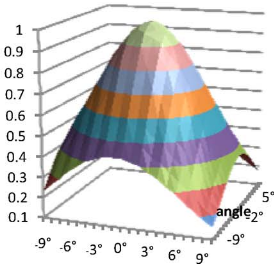

DOI: 10.1109/JPHOT.2013.2295458

Impact of Detector Spatial Uniformity on the Measurement of Averaged LED Intensity

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DOI: 10.1109/JPHOT.2013.2295458

Manuscript received October 27, 2013; revised December 10, 2013; accepted December 10, 2013. Date of publication December 20, 2013; date of current version December 30, 2013. Corresponding author: B. Zhang (e-mail: zhangbzh@bnu.edu.cn).

Abstract: Photometers are widely used for the measurement of the average LED intensity as defined by CIE 127, under the circumstance that LEDs have many kinds of intensity spatial distributions. Significant measurement errors can be resulted due to the following facts: 1) a photometer with a diffuser generally has a spatial response that is stronger in the center of the detector; and 2) LED angular distributions of intensity often have a sidelobe about the central axis rather than a central peak. A special measuring facility for illuminance intensity distribution of LEDs and spatial response distribution of photometers has been designed. An evaluation factor "*c*" has been introduced to describe the spatial response distribution uniformity of photometers. Three kinds of photometers with different spatial response distribution were used to measure the averaged LED intensity individually. Experiment shows that the photometer with a diffuser has a response distribution of a cosine function, and the illuminance intensity distribution of LEDs generally presents a sine, trapezoidal, or cosine function with the 6.5° field of view for CIE Condition B. The results show that the measurement errors could be more than -5.10% when using the photometer with a diffuser to measure the average intensity of LEDs with a narrow beam angle. It is very important that the uniformity of spatial response distribution of the photometer should be considered when calibrating Averaged LED Intensity as it can introduce a significant error.

Index Terms: Metrology, uniformity of spatial response, light-emitting diode (LED), glass diffuser, photometer.

1. Introduction

Light emitting diodes (LEDs) offer a number of advantages over conventional light sources, including reduced power consumption, better spectral purity, and longer life time and lower cost [1]. With the rapid development of LED industry during the past decades, LEDs have become popular in an increasing amount of applications and are considered as key replacements for conventional light sources.

The measurements for LED are usually carried out using photometers. Typically a photometer is consisted of a silicon photodiode array, a $V(\lambda)$ filter and a diffuser. The optical radiation of a LED is generated from a semiconductor chip packaged in a certain form. The spectral and spatial distribution of the radiant power, emitted from the chip is frequently changed by the packaging components, such as built-in reflectors, lenses, scattering material, colored filters, or fluorescent layers [2]–[5]. Compared with the traditional light sources, many LEDs have narrow beam angles or irregular intensity distributions [6]. When the spatial response of the detector across the entrance aperture is non- uniform and illuminance intensity distribution of the LED within the aperture is also non-uniform, significant amount of errors can be resulted in Averaged LED Intensity measurement [7].

2. Method

The mathematical method of calibration has been introduced to analyze the source of measurement error and improve the measurement accuracy of Averaged LED Intensity.

The non-uniformity is usually evaluated using the following formula:

$$\text{Nonuniformity} = \frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}} \times 100\%. \tag{1}$$

The illuminance intensity distribution of a LED in a fixed plane is measured at the entrance aperture of photometer. The relative illuminance distribution E_{ij}can be expressed by

$$E_{ij} = \frac{e_{ij}}{e_a} \qquad i,j = 1,2,3\ldots \tag{2}$$

where e_{ij} is the illuminance intensity measured in a series of positions and e_a is the average value of e_{ij}.

Similarly, the relative spatial response of the detector R_{ij} can be expressed as

$$R_{ij} = \frac{r_{ij}}{r_a} \qquad i,j = 1,2,3\ldots \tag{3}$$

where r_{ij} is the detector response measured in a series of positions and r_a is the average value of r_{ij}.

So the partial luminous flux in the fixed plane $(\emptyset)$ can be expressed by

$$\emptyset \propto \sum\sum E_{ij} R_{ij} \Delta S = \Delta S \times \sum\sum E_{ij} R_{ij} \tag{4}$$

where ΔS is the detector sampling area of the entrance aperture, which is a constant and can be placed in front of the summation symbol.

For an ideal point light source, the illuminance intensity distribution is uniform and $E_{ij} = 1$; Similarly, if the detector has an ideal uniform spatial response distribution, then $R_{ij} = 1$. However, in actual measurement for the uniformity of distribution, $E_{ij} \neq 1$ and $R_{ij} \neq 1$. In order to analyse the impact the of detector spatial response on the measurement results, two detectors with different spatial response distribution have been chosen to measure the illuminance intensity. One detector is a standard detector with a ideal spatial response distribution of R_{ij}^s, and the other is a test detector with a spatial response distribution of R_{ij}^t. If a light source is measured by the two detectors independently, the partial luminous flux can be expressed as

$$\emptyset_{ts} \propto \Delta S \times \sum\sum E_{ij}^t R_{ij}^s \tag{5}$$

and

$$\emptyset_{tt} \propto \Delta S \times \sum\sum E_{ij}^t R_{ij}^t \tag{6}$$

where $\emptyset_{ts}$ is the partial luminous flux from the standard detector, and $\emptyset_{tt}$ is from test detector.

Here we define a mismatch factor c to represent the difference of measurement results using detectors with different spatial response distribution [8]

$$c = \frac{\Delta S \times \sum\sum E_{ij}^t R_{ij}^t}{\Delta S \times \sum\sum E_{ij}^t R_{ij}^s} = \frac{\sum\sum E_{ij}^t R_{ij}^t}{\sum\sum E_{ij}^t R_{ij}^s}. \tag{7}$$

If the test detector has the same spatial response distribution as the standard detector, then $c = 1$; otherwise it is necessary to correct the measurement result using the mismatch factor c. When the light sources used to calibrate the two detectors are different, it becomes more complex.

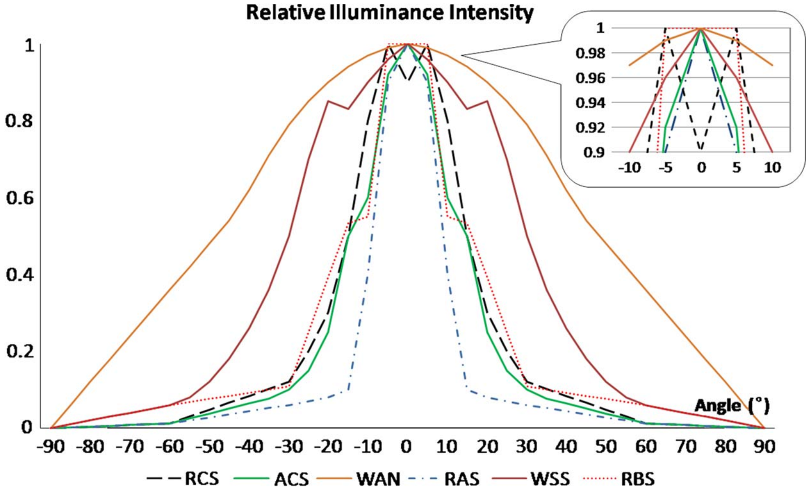


Fig. 1. Measured relative illuminance intensity distribution of different types of LEDs.

For example, we usually firstly calibrate a detector using a standard lamp which has a ideal uniform illuminance distribution, then use the detector to measure a test lamp. If the detector has a uniform spatial response distribution, there is no error introduced in measurement, otherwise the mismatch factor c should be considered when the test lamp is entirely different from the standard lamp. This often appears in measurement of LEDs with various intensity distributions. In order to characterize the measurement error when using a detector with non-uniform spatial response distribution and the test lamp has different intensity distribution from the standard lamp at the same time, we can calculate the relative deviation of mismatch factor c between the standard lamp and test lamp. The relative deviation is expressed in the form of

$$\Delta = \frac{c_S - c_t}{c_S} \times 100\% \tag{8}$$

where c_s is the mismatch factor using the standard lamp which is calculated with equation (7) and c_t the mismatch factor using the test lamp.

3. Measurement

Three detectors with different spatial response distributions were used to measure the Averaged LED Intensity. Detector A is a Hamamatsu S1337 type photodiode array, which has linear response over several decades of input radiant flux and nearly negligible temperature dependence of spatial response in the visible region [8], [9]. Detector B consists of a Hamamatsu S1337 and a $V(\lambda)$ filter. Detector C is same as detector B but with an extra diffuser. The spectral transmission of the filter and the diffuser appears a good no-selective transmission from 380 nm to 780 nm according to our experiment.

Six LEDs with a variety of beam geometries from CREE are measured, and the brief summary [10] of distributions of the LEDs is illustrated in Fig. 1. The test LEDs have great different half-value angles and distributions of relative illuminance intensity. They are some typical distributions from -5° to 5°, which are corresponding to the equivalent full plane angle 6.5° for CIE Condition B.

Each LED was mounted on a LED holder to keep the LED stable. This enabled immovable conditions during the measurements and better repeatability of the results. All the LEDs were operated in constant current mode of 20 mA, with stability of the current setting better than 0.02%.

The illuminance intensity distribution measurement was performed on optical bench with a two-dimensional automated scanning device. The schematic is shown in Fig. 2(a). The measuring detector fix a small entrance aperture with diameter of 0.5 mm, and it has a thin opal glass to assure a good cosine response. The illuminance intensity distributions were measured with a step of 0.5 mm

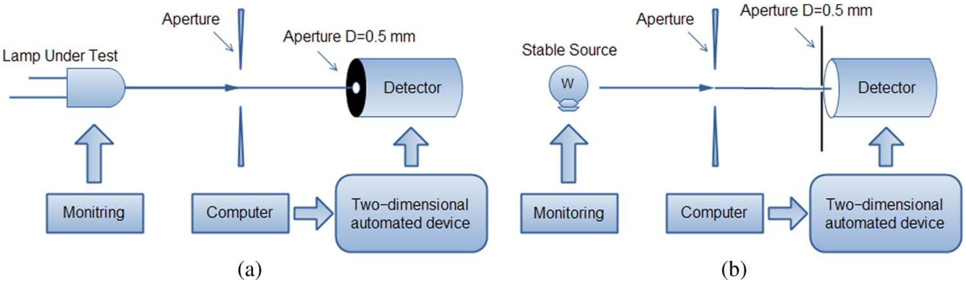


Fig. 2. The measurement schemes for illuminance intensity distribution and detector spatial response distribution.

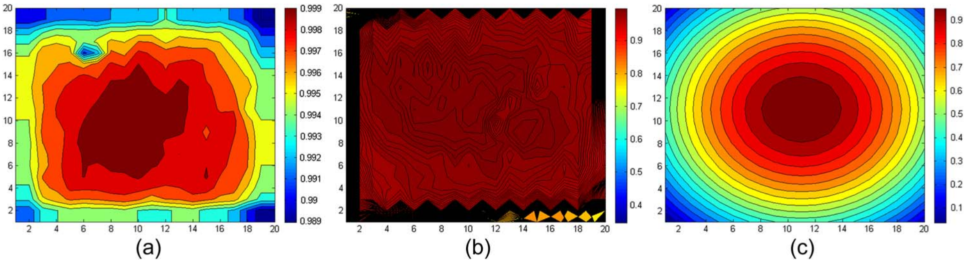


Fig. 3. The measured spatial response distributions of three different types of detectors.

by the control of stepper motor. A digital voltmeter was connected to a measurement computer via the RS-232 bus to monitor the stability of light source. And the illuminance distribution was measured in the area of 10 mm × 10 mm which is approximately the window size of the photometer.

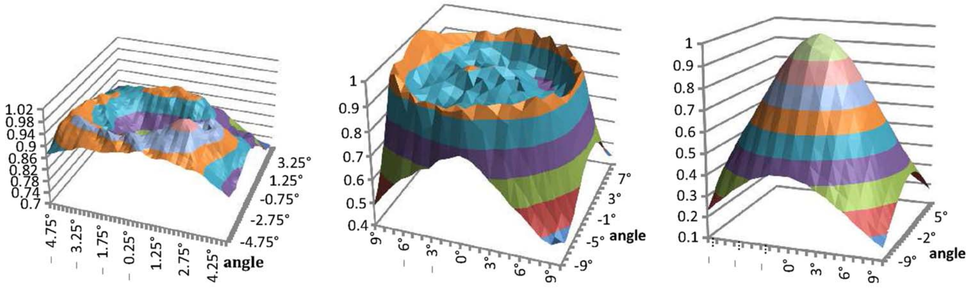
The detector spatial response distribution was measured in a similar way, as illustrated in Fig. 2(b). The small entrance aperture with diameter of 0.5mm did not fix with the detector. It combines with the small entrance aperture together to provide a stable collimated light source for the measurement of detector spatial response distribution. The data acquisition and analysis were carried out by LabVIEW software and the spatial response distribution of the detector was saved automatically.

Measurement results of three detector spatial response distributions are presented in Fig. 3. Fig. 3(a) is the spatial response distribution of Detector A, the spatial response differs by 0.1% between the adjacent gray. Detector A has a perfect spatial response distribution as the nonuniformity is less than 0.6%. Fig. 3(b) and (c) are the spatial response distribution of Detector B and Detector C respectively.

The $V(\lambda)$filter makes the uniformity of spatial response become worse, the spatial response differs by 0.2% between the adjacent gray and the nonuniformity reaches 2.0% on the whole surface of detector. The Detector C has the worst uniformity distribution because of the extra diffuser. Its spatial response distribution presents a good cosine law. The spatial response differs by 5.0% between the adjacent gray, and the nonuniformity reach to a shocking 50.0% on the whole surface of detector. The spatial response distribution of Detector C is similar to the cosine function.

The measurement results of the relative illuminance intensity distributions of LEDs are presented in Fig 4. The LEDs were measured by the same detector at the field angle, which clearly distinguishes the illuminance intensity distributions from -5° to 5°.

Fig. 4(a) shows the actual relative illuminance intensity distribution of LED named CREE 503B-RCS. It is a typical distribution with the lower illuminance intensity on optical axis than around area. It presents a roughly symmetrical distribution, the nonuniformity is close to 20.0% from the minimum illuminance intensity of the center to the maximum of around area. Fig. 4(b) is the typical distribution of CREE 503B-RBS. It has a relatively flat illuminance intensity distribution with a certain field angle, its nonuniformity is less than 5.0% in this area. Fig. 4(c) introduces the most common illuminance



(a) (b) (c)

Fig. 4. The measured relative illuminance intensity distributions of LEDs.

TABLE 1

The measurement results of partial luminous flux using three different types of detectors

	half-value angle (º)	nonuniformity (≤)	S1337 (Detector A)	S1337 and filter (Detector B)	S1337 add filter and diffuser (Detector C)
BZ5 Standard Lamp	/	0.30%	400.000 XΔS	400.001 XΔS	400.002 XΔS
LED1	10	28.80%	400.138 XΔS	400.641 XΔS	420.390 XΔS
LED2	15	14.00%	400.063 XΔS	400.292 XΔS	409.206 XΔS
LED3	30	3.70%	400.016 XΔS	400.073 XΔS	400.303 XΔS
LED4	60	0.90%	400.004 XΔS	400.018 XΔS	400.556 XΔS
LED5	105	0.30%	400.001 XΔS	400.005 XΔS	400.161 XΔS
LED6	/	16.90%	399.969 XΔS	399.876 XΔS	395.347 XΔS

intensity distribution. The LED has an angular illuminance intensity distribution [11] as $\cos^{n}(\theta)$. It is the measurement of the relative illuminance intensity distributions of CREE-503B-ACS. The rest of LEDs listed in Fig. 1 have the similar relative illuminance intensity distributions as the CREE-503B-ACS under Condition B. The difference is the different half-value angle has the different *n* in cosine function.

In fact, the Condition B correspond to solid angles of view of 0.01 sr, in other words, it has approximately 6.5° field angle. Most of relative illuminance intensity distributions have changed to the regular ones. The distributions showed in Fig. 4 can be simulated by sine, trapezoid and cosine function, respectively.

We don't consider the cosine-fourth law of the LED here. We know $E_\theta = \cos^4\theta \cdot E_o$ in the plane according to the cosine-fourth law, there θ the angle from optical axis to the test position in the plane, then E_θ is the illuminance of the θ position and E_o is the illumiance of the position of optical axis crossing on the plane. The field angle is 6.5°, and $\theta = 3.25°$, then $E_\theta = 0.99358 E_o$. The result shows that the non-uniformity of relative illuminance intensity distribution caused by the cosine-fourth law is only 0.64%, and this impact is much less than that from LED's package.

4. Analysis

The illuminance intensity measurements were performed on optical rail at Condition B. According to the measuring results mentioned in Section 2, the illuminance intensity distribution of LEDs mainly expresses as a single peak map at Condition B. The distinction of LED's distribution is the different half-value angles.

We simulated the measurement results of the LEDs of different relative illuminance intensity distribution with different detectors by proportional expression (4). It is listed in Table 1. The BZ5 Standard Lamp is a reliable tungsten lamp with color temperature of 2353K, and it has a near-ideal uniform intensity distribution in the measured area. Its nonuniformity is less than 0.30%. LED1 $\sim$

TABLE 2

The mismatch factor and measurement error of three different types of detectors

	S1337		S1337 and filter		S1337 add filter and diffuser	
	mismatch factor c	error	mismatch factor c	error	mismatch factor c	error
LED1	1.0003	-0.03%	1.0016	-0.16%	1.0510	-5.10%
LED2	1.0002	-0.02%	1.0007	-0.07%	1.0230	-2.30%
LED3	1.0000	-0.00%	1.0002	-0.02%	1.0058	-0.58%
LED4	1.0000	-0.00%	1.0000	-0.00%	1.0014	-0.14%
LED5	1.0000	-0.00%	1.0000	-0.00%	1.0004	-0.04%
LED6	0.9999	0.01%	0.9997	0.03%	0.9884	1.16%

LED5 present a single peak sine distribution with different half-value angle. Their nonuniformities deteriorate rapidly when the half-value angle becomes more and more narrow. LED6 has a typical double peak distribution like CREE 503B-RCS in Fig. 4(a). But it presents a sine law under Condition B for being limited by field angle of 6.5°. The nonuniformity is 16.90% from the edge to the center of measured surface.

The last three columns of Table 1 are results calculated from measured data. The numerical value before ΔS is the sum of the relative illuminance intensity and relative spatial response's product in every ΔS As the table shows, LED1, LED2, and LED6 are very different from other LEDs, especially when measured by Detector C.

If the spatial response of every detector was calibrated by the same uniform light source, the nonuniformity of spatial response of detector cannot introduce obvious errors except there is a strong spectral mismatch between the measured source and calibration source. Here three detectors were calibrated by BZ5 Standard Lamp, which has an ideal uniform illuminance intensity distribution. Then we calculate the mismatch factor according to equation (7). The results of calculation are showed in Table 2.

As the Table 2 shows, if the spatial response distribution of a detector is relatively uniform, there is no significant measurement error (According to the result of Detector A and B, the max error is -0.16%). However significant errors appear when a detector has a non-uniform spatial response distribution. Because LED1 and LED2 have a narrower half-value angle than LED3 $\sim$ 5, and the spatial response distribution of Detector C is similar to cosine function, they present a strong positive correlation, which cause a significant measurement error (the error is -5.10% and -2.30% separately). LED3,LED4,LED5 have relative uniform illuminance intensity distribution during the 6.5° field angle as half-value angle increases, and the correlation with spatial response distribution of detector become weaker, so the measurement error lessen. LED6 has a worse uniform distribution than that of LED2, but it presents a sine law, which is a complementation with the sine distribution. Consequently, LED6 has a smaller measurement error. So the conclusion is that the LED with a worse uniformity of illuminance intensity distribution has a stronger mismatch factor *c*, and it can introduce a more significant measurement error.

5. Conclusion

In this paper, a special measuring facility for illuminance intensity distribution of LEDs and spatial response distribution of photometer has been designed. An evaluation factor "c" has been introduced to describe the spatial response distribution uniformity of photometer and it is helpful for the design and selection of photometer. Measurement experiments show that the photometer constructed with photodiode array, filter and diffuser has a spatial response distribution which is similar to cosine function, and the nonuniformity is close to 50.0% from the edge to the center of detector surface. Meanwhile, the LED's illuminance intensity distribution is similar to sine, trapezoid and cosine function during the field angle of 6.5° for CIE Condition B. A diffuser makes the incident beam reflected many times before it leaves the diffuser and transmits into the $V(\lambda)$ filter, the reflection and transmission can dramatically change the uniformity of spatial response distribution of the detector head and make the middle of the detector head of photometer has a significant higher responsibility than the edge of the limit of the aperture. When a photometer with photodiode array, a filter and a diffuser is used to measure a narrow half-value angle LED(such as LED1), the measuring error may reach up to -5.10%, and it will be more significant if the LED has a narrower half-value angle. It should be emphasized that the uniformity of spatial response distribution of photometer need to be considered when calibrating Averaged LED Intensity, as it can introduce a significant error.

References

[1] M. Bürmen, F. Pernuš, and B. Likar, "Automated optical quality inspection of light emitting diodes," *Meas. Sci. Technol.*, vol. 17, no. 6, pp. 1372–1378, Jun. 2006.

[2] Y. Ohno, "Optical metrology for LEDs and solid state lighting," in *Proc. SPIE*, 2006, vol. 6046, p. 604625.

[3] J. Hovila, M. Mustonen, P. Kärhä, and E. Ikonen. (2005, Oct.). Determination of the diffuser reference plane for accurate illuminance spatial response calibrations. *Appl. Opt.* [Online]. vol. 44, no. 28, pp. 5894–5898. Available: http://dx.doi.org/10.1364/AO.44.005894

[4] A. W. Norris, M. Bahadur, and M. Yoshitake, "Novel silicone materials for LED packaging," in *Proc. SPIE*, 2005, vol. 5941, pp. 207–213.

[5] P. Manninen, P. Manninen, J. Hovila, P. Kärhä, and E. Ikonen, "Method for analysing illuminance intensity of light-emitting diodes," *Meas. Sci. Technol.*, vol. 18, no. 1, pp. 223–229, 2007.

[6] T.-m. Chung and S. Dai, "A Study of the spatial intensity distribution of LED for general lighting," *J. Light Vis. Environ.*, vol. 34, no. 3, pp. 170–175, 2010.

[7] Commission Internationale de l'EclairageMeasurement of LEDs, 2007, CIE 127.

[8] F. Manoochehri, P. Kärhä, L. Palva, P. Toivanen, A. Haapalinna, and E. Ikonen, "Characterisation of optical detectors using high-accuracy instruments," *Anal. Chim. Acta*, vol. 380, no. 2/3, pp. 327–337, Feb. 1999.

[9] J. M. Benavides and R. H. Webb, "Optical characterization of ultrabright LEDs," *Appl. Opt.*, vol. 44, no. 19, pp. 4000–4003, Jul. 1, 2005.

[10] "LED product specification of CREE," in *LED product specification of CREE.Cor.*

[11] Sauter G 2001 2nd CIE Expert Symp. on LED Measurement (presentation).