Optics and Lasers in Engineering 51 (2013) 1179–1184

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Influence of the temperature dependent spectral power distribution of light-emitting Diodes on the illuminance responsivity of a photometer

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ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form
11 March 2013
Accepted 2 April 2013
Available online 15 May 2013

Keywords:
Junction temperature
Light-emitting diode
Photometer
Solid-state lighting
Spectral mismatch correction factor

ABSTRACT

Accurate optical measurements of LEDs are crucial because of the increasing popularity of LEDs. However, a photometer with a V(λ) filter spectrum curve may yield large errors when it is used for photometric measurements of colored LEDs. The junction-dependent light output and spectral distribution of LEDs also introduce measurement errors of the measured photometric characteristics. For the accurate measurements of LEDs, the c(S_t,S_s) factors were used to estimate the possible deviation in the photometric measurement of colored LEDs with various junction temperatures using commercial and industrial grade photometer heads. The spectral measurements of LEDs with specified junction temperature were conducted using a miniature fiber-optic spectrometer, and the relative spectral power distributions of LEDs were used to calculate the spectral mismatch correction c(S_t,S_s) factors of the photometer heads. Therefore, the c(S_t,S_s) factors of colored LEDs were calculated according to the temperature dependent spectral power distributions with various junction temperatures, and these factors were used to estimate the possible deviation in the photometric measurement of colored LEDs. The estimation of the possible deviation in the photometric measurement shows that photometers with excellent relative spectral responsivities must be used for accurate measurement; otherwise, careful calibration must be conducted when using a photometer with inferior relative spectral responsivity of the photopic filter.

1. Introduction

Because of the advancements in light-emitting diode (LED) technology in recent years, solid-state lighting (SSL) may replace conventional lighting technologies, such as incandescent and fluorescent lamps. The primary advantages of solid-state lighting over conventional lighting are its long lifetime, high efficiency, low energy consumption and low cost, and environmental friendliness.

Because of the increasing popularity of LEDs, accurate measurement of their optical properties is required. In photometry, a photometer with spectral responsivity that perfectly matches the standard photopic observer is a crucial device for photometrical measurement. In general, the silicon photodetector in the photometer converts optical radiation into an electrical current, and the magnitude of the electrical signal is proportional to the amount of optical radiation received by the photodetector. Filters that scale the silicon response curve to the luminous efficiency function are used in the photometer to match the spectral responsivity of the device to that of the eye, as determined from the luminous efficiency curve of the eye. However, a mismatch between the luminous efficiency function for photopic vision CIE-V(λ) and the filter spectrum is common in the blue and red portions of the spectrum because of the available filter materials. A mismatch between the spectral responsivity of photometer and the V(λ) function can result in deviations in the measured photometric quantities. The typical calibration of a photometer used to measure standard incandescent sources results in large errors when this type of photometer is used to measure the characteristics of colored LEDs. A problem occurs when the relative spectral power distributions (RSPD) of the LEDs differs considerably from that of the broadband light-source (typically CIE Illuminant A), which is used to calibrate the photometer. The narrow bandwidth of the LEDs allow only a narrow region of the filter spectrum in the photometric measurement, rather than accurate as an average over a broad range of wavelengths range. Therefore, the relatively inferior matching of the photometer to CIE-V(λ) can result in large deviations in the photometric measurements of blue and red LEDs. The possible photometric measurement error of LEDs using photometers has been addressed in related literature [1–4].

Another requirement for the accurate photometric measurement of LEDs is the ability to operate them under electrical and thermal conditions to ensure that the light output of LEDs is stable and reproducible. Prior studies have indicated that substantial errors occur in the measurement of luminous intensity and luminous flux because of the temperature sensitivity property of LEDs

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http://dx.doi.org/10.1016/j.optlaseng.2013.04.002

[2,5,6]. The optical and electrical characteristics of LEDs strongly depend on the junction temperature (Tj). Previous researchers have found that the spectral power distribution of LED changes with junction temperature [7,8]. An increase in junction temperature shifts the spectra at constant current to longer wavelength. Moreover, the peak wavelength shift is proportional to the change in the junction temperature. The high correlation of the trend lines generated from the experimental data of LEDs validates that the observed relationship is linear [9–11]. To predict the optical characteristics of LEDs, a spectrum model based on the spectral power distribution of commercial color LED at several junction temperatures has also been constructed [12–14]. The skewness variation, peak frequency shift and peak value change in the spectrum with junction temperature can be predicted. At the mean time, the change in junction temperature leads to changes in light output, wavelength and spectral width. These all influence the color quality of RGB-LED, such as the chromaticity and color rendering. It is observed that the chromaticity point shifts, color temperature increases and luminous efficacy decreases as junction temperature increases [15,16]. The effects of drive current and junction temperature variations on the chromaticity changes of phosphor-converted white LEDs were also discussed [17].

However, in the mass production of LEDs, the luminous flux figures cited by LED manufacturers are measured under instantaneous operation in integrating spheres or open air using photometers with a V(λ) filter. The LEDs are tested during manufacturing under conditions that differ from those of actual operation in a fixture or system, and the junction temperature is higher when operated under constant current in a fixture or system. In that period, the unstable Tj affects the relative spectral power distributions of the LEDs and may induce another photometric error other than the measurement error caused by the mismatch between the spectral responsivity of the photometer and the V(λ) function. Therefore, the dependence of deviations in photometric measurements with junction temperature must be determined if a photometer is used to measure the luminous flux or luminous intensity. The estimation of possible deviations with various junction temperatures in photometric measurements using a photometer is useful for the calibration of automatic photometric measurements of LEDs.

To precisely calculate the relationship between photometric quantities and the Tj of an LED, the spectral responsivity of the photometer head and the relative spectral power distributions of LEDs with various junction temperatures must be determined. Standard photometer heads are typically calibrated against an incandescent reference lamp (a CIE standard illuminant A operated at a color temperature of 2856 K). The deviation occurs when the spectral power distribution of the LEDs differs from that of the lamp used to calibrate the photometer. The spectral error can be corrected by applying the spectral mismatch correction factor c(S_t, S_s) [3,4,18], as follows:

$$c(S_t, S_s) = \frac{\int_\lambda S_t(\lambda)V(\lambda)d\lambda \int_\lambda S_s(\lambda)S_{rel}(\lambda)d\lambda}{\int_\lambda S_t(\lambda)S_{rel}(\lambda)d\lambda \int_\lambda S_s(\lambda)V(\lambda)d\lambda} \quad (1)$$

where St(λ) is the relative spectral power distribution of LEDs with various junction temperatures, Ss(λ) represents the relative spectral power distribution of the standard light source, Srel(λ) is the relative spectral responsivity of a photometer head, and V(λ) is the luminous efficiency function for photopic vision. The photometer head signal is multiplied by this factor to eliminate the spectral mismatch errors.

This paper presents calculations of the c(S_t,S_s) factors of commercial photometer heads for colored LEDs with various junction temperatures. The junction temperature of an LED is determined using a temperature-controlled heat sink, a pulse current source, and a fast voltage meter to measure the forward voltage of the LED on the pulse [19]. LEDs can be set to any specified junction temperature, and the spectral measurements of LEDs can be conducted at a specified current to calculate their c(S_t,S_s) factors.

2. Experimental setup

To verify the c(S_t,S_s) factors of the relative spectral power distributions of LEDs with various junction temperature values using commercial photometer heads, the junction temperature values must first be determined, and the spectral measurements of the LEDs at specified junction temperatures and currents must be performed. The required experimental apparatus consists of three parts: the temperature-controllable system, the pulsed diode test system, and the optical measurement system. Fig. 1 shows the experimental setup that used in this study. The LED package attached on the temperature-controllable heat sink was placed in the input port of a 30 cm integrating sphere. A thermoelectric cooler (TEC) controller CDS30012RRA from Wise Life Technology was used to set the temperature of the heat sink to the desired temperature Tc, and we waited for the LED to stabilize thermally. After thermal stabilization, the junction temperature Tj(0) of the LED was equal to the desired temperature Tc of the heat sink, and the subsequent processes for the determination of the LED junction temperature were conducted. Fig. 2 shows the determination of the LED junction temperature. Multiple short pulses of a specified current were applied to the LED and the corresponding voltage $V_F(0)$ at desired Tj(0) was measured repeatedly using a Keithley 2520 pulsed laser diode test system [19]. To minimize the increase in Tj associated with the specified current, the pulse-width of the short pulse applied to the LED was set to 1 ms. The subsequent voltage measurements indicated that the increase in junction temperature during these pulses was negligible. The LED was then operated at the specified DC current using the Keithley 2520, and the LED chip was heated to a higher junction temperature with a lower $V_F(t)$ because of the DC operation. Therefore, the temperature of the heat sink was required to generate the des-ired junction temperature Tj(0) when the corresponding $V_F(t)$measured using the Keithley 2520 was $V_F(0)$. The junction temperature of the LED chip operated at a specified DC current reached the desired value, which was used in subsequent spectral measurements. The TEC controller and Keithley 2520 were controlled using LabVIEW software. The relative spectral power distributions of the LEDs with the desired Tj were measured using a miniature fiber-optic spectrometer (HR4000, Ocean Optics), which was equipped with the 30 cm integrating sphere, as shown in Fig. 1. The relative spectral power distributions of the LEDs measured using the HR4000 in the range from 380 to 830 nm in steps of 1 nm were used to obtain the spectral mismatch correction of c(S_t,S_s) factors.

Commercial high-power light-emitting diodes of various colors manufactured by OSRAM were used to determine the possible deviation in the photometric measurements using a photometer. The colored LEDs, based on the family of Golden Dragon Plus, were deep-blue (LD-W5AM), blue (LB-W5AM), verde green (LV-W5AM), true green (LT-W5AM), amber (LA-W5AM), red (LR-W5AM), and hyper red (LH-W5AM), and the corresponding peak wavelengths of the colored LEDs at Tj=30 °C were 459 nm, 480 nm, 510 nm, 530 nm, 590 nm, 631 nm and 656 nm, respectively. Fig. 3 shows the relative spectral power distributions of the colored LEDs at 350 mA with various values of Tj. The figure shows data of only few relative spectral power distributions for clarity. The spectra of various colored LEDs shifted, and their breadth varied with junction temperature.

One commercial photometer head (International Light Inc., SED (SEL)033/Y/W) and two industrial grade photometers with