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Estimation of the average junction temperature of two phosphors-converted white LED array based on (B + Y + R)/B ratio

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ABSTRACT

The method of non-contact measurement of the junction temperature (Tj) for phosphor-converted white LEDs based on W/B ratio, the ratio of the total radiant energy (W) to the radiant energy of blue emission (B), is verified firstly. It is shown that for two phosphors ($Y_3Al_5O_{12}$:Ce and $CaAlSiN_3$:Eu)-converted white LEDs, an significant uncertainty is introduced into the linearity between Tj and W/B ratio. Then a new approach is proposed which uses (B + Y + R)/B ratio, the ratio of the sum of radiant energies of blue emission (B), yellow emission (Y) and red emission (R) to the radiant energy of blue emission, to establish the correlation with Tj. Result shows that the proposed approach is of a satisfactory linearity between Tj and (B + Y + R)/B ratio, with *R*-square equal to 0.9906 and RMSE equal to 2.27 °C. It is also demonstrated that the proposed method is applicable to actual LED lighting system composed of large number of LEDs.

1. Introduction

Light-emitting diodes (LEDs) are emerging as a new potentially revolutionary technology, owing to their comparative advantages such as higher conversion efficiency, environment friendliness, longer life and good reliability. Especially white LEDs have demonstrated their superiority compared with conventional lighting in certain applications such as indoor or street lighting, display backlight, and automotive headlights. One of the most common methods for producing white LEDs is to utilize a blue LED chip coated with yellow emitting phosphor (like Ce^{3+}-doped yttrium aluminum garnet (YAG:Ce^{3+})) [1], which has already been accepted by LED manufacturers for its stability and efficiency. But the lamps fabricated in this manner give a poor color-rendering index (CRI), because the resulting light is typically deficient in the green and red colors. To achieve excellent CRI, more than one phosphor is used for the light conversion in white LEDs normally [2].

End users of lighting commonly concern the service lifetime of a lighting system as selecting a product for a given application. The reliability or lifetime of LED reduces as its junction temperature (Tj) rises [3,4], and most optical and electrical properties of LED strongly depend on Tj [5,6]. Therefore the accurate measurement of Tj is helpful for designing and building a reliable LED product. The traditional method for Tj estimation is by means of detecting the drop of forward voltage [7,8], which requires access to the lead wires of LED. However once the LEDs are enclosed into a lighting system, it is not easy to gain access to the lead wires without affecting the integrity of the system [9]. Therefore non-contact measurement of Tj especially based on spectral properties is developed. Zhang [10] analyzed the feasibility of Tj measurement for GaN-based LEDs by means of peak wavelength shift. Chen [11] demonstrated the Tj estimation of AlGaInP-based LED array, composed of four individual LEDs, by means of the shift of center wavelength at full width at half maximum (FWHM).

For phosphor-converted white LEDs, Tamura [12] showed that the emission intensities of blue and yellow radiations of white light decreased at different rates with increasing junction temperature, mainly due to the changes in phosphor efficiency at different temperatures. Zhang [13] investigated the temperature-dependent excitation and emission spectra of YAG:Ce^{3+} phosphor, and showed that the emission intensity of YAG reduced by about 54% for 460 nm wavelength excitation as temperature from room temperature up to 573 K. Ye [14,15] separated the efficiency of white LED

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by LED die efficiency and phosphor efficiency, and experimentally demonstrated that the LED die efficiency was a function of temperature and the phosphor efficiency was a function of correlated color temperature (CCT). Masui [16] proposed a mathematical model to describe the intensity ratio of blue light to yellow light (IB/IY). Using this model, You [17] demonstrated that the reduced phosphor conversion efficiency was due to the increased junction heat, leading to an increased ratio of IB/IY.

For LED junction temperature estimation, Gu and Narendran [1] demonstrated that for single phosphor (YAG:Ce)-converted white LED array, composed of six LEDs, Tj could be determined by W/B ratio (W represents the total radiant energy of white light and B represents the radiant energy within the blue emission), and also showed that the W/B ratio changed proportionally with Tj. Chen [18] established a linear function of the ratio of the radiant energy of phosphor emission to the radiant energy of blue emission with respect to the junction temperature. The slope of the linear fitting was experimentally determined to be $-0.00487/°C$ for Sharp 4.4W LED and $-0.00602/°C$ for Sharp 8.0W LED. Narendran [19] investigated the linearity between Tj and W/B for white LEDs converted by more than one phosphor, in which the second sample was of a weak linear correlation between W/B and Tj, with the coefficient of determination of regression (R-square) of 0.8.

The main objective of this study is to investigate the uncertainty in Tj estimation for two phosphors-converted white LEDs by means of W/B ratio, and to propose a new approach of Tj estimation for this type of white LEDs. Additionally, because an actual lighting system is normally composed of a large number of LEDs, and the individual difference in the spectrum power distribution (SPD) among LEDs should be considered, the second objective is to identify whether the proposed method is applicable to actual lighting system with large number of LEDs. As a result the average junction temperature of an LED array is estimated in this paper instead of the Tj of a single LED.

2. Theoretical analysis

For single yellow-phosphor-converted white LEDs, the intensity ratio of yellow light (Y) to blue light (B), Y/B can be expressed as follow [16]:

$$\frac{\mathrm{Y}}{\mathrm{B}} = \eta_{\mathrm{Y}} S_{\mathrm{Y}} \frac{e^{2\alpha_{\mathrm{B1}}(B_0)x} - 1}{e^{2\alpha_{\mathrm{Y1}}x}} \tag{1}$$

where B_0 is the initial intensity without the presence of phosphor material, α_{B1} and α_{Y1} are the absorption coefficient of phosphor mixture for the photon energy of blue and yellow light respectively, x is the width of the phosphor mixture layer, η_Y is the quantum efficiency of yellow phosphor, and S_Y stands for the Stokes shift. Moreover, the relationship between Y/B ratio and junction temperature (Tj) is experimentally determined which follows a linear rule [18]:

$$\mathrm{Y/B} = a_1 \mathrm{Tj} + b_1 \tag{2}$$

where a_1 and b_1 are constants. As a result, (B + Y)/B ratio over Tj also follows a linear rule. The (B + Y) stands for the total radiant energy of LED white LEDs (W), and thereby the W/B ratio is used for establishing the linear correlation [1,19]:

$$\mathrm{W/B} = a_1 \mathrm{Tj} + (b_1 + 1) \tag{3}$$

Similarly for single red-phosphor-converted white LEDs, we have the following expressions:

$$\frac{\mathrm{R}}{\mathrm{B}} = \eta_{\mathrm{R}} S_{\mathrm{R}} \frac{e^{2\alpha_{\mathrm{B2}}(B_0)x} - 1}{e^{2\alpha_{\mathrm{R1}}x}} \tag{4}$$

$$\mathrm{W/B} = a_2 \mathrm{Tj} + (b_2 + 1) \tag{5}$$

where α_{B2}, α_{R1}, η_R, S_R, a_2 and b_2 are the parameters of red-phosphor-converted white LEDs similar to that of yellow-phosphor-converted white LEDs.

For white LEDs converted by these two phosphors, we have similar expressions:

$$\frac{\mathrm{Y+R}}{\mathrm{B}} = \eta_{\mathrm{Y}} S_{\mathrm{Y}} \frac{e^{2\alpha_{\mathrm{B3}}(B_0)x} - 1}{e^{2\alpha_{\mathrm{Y2}}x}} + \eta_{\mathrm{R}} S_{\mathrm{R}} \frac{e^{2\alpha_{\mathrm{B3}}(B_0)x} - 1}{e^{2\alpha_{\mathrm{R2}}x}} \tag{6}$$

$$(\mathrm{B+Y+R})/\mathrm{B} = a_0 \mathrm{Tj} + b_0 \tag{7}$$

where α_{B3}, α_{Y2} and α_{R2} is respectively the absorption coefficient of phosphor mixture for blue, yellow and red light in the two phosphors-converted white LEDs. In this case, the phosphor photoluminescence spectrum is distorted by phosphor sedimentation [20], the mixing of phosphors [21] and the interaction absorption between two phosphors. Therefore (B + Y + R) is different from the total radiant energy of the white LEDs of W, and Y, R cannot be simply acquired from the total spectrum power distribution.

We propose a method to obtain the value of B, Y and R, which requires the SPD of single yellow phosphor-converted white LEDs and the SPD of single red phosphor-converted white LEDs. The procedures are as follows.

A cut-off wavelength is experimentally determined which is the position of the lowest radiant energy between LED chip emission and phosphor emission. B is then calculated by integrating the SPD of the white LEDs, from starting wavelength to this cut-off wavelength. A matching point less than the starting wavelength of the emission of the red phosphor is chosen for scaling the SPD of single yellow phosphor-converted white LEDs, and Y is then obtained according to the scaled SPD. Another matching point within the emission band of the red phosphor is chosen for scaling the SPD of single red phosphor-converted white LEDs, and R is then obtained according to the scaled SPD. The (B + Y + R)/B ratio is then used to establish the linear correlation with respect to Tj for the two phosphors-converted white LEDs.

3. Experiment and results

3.1. Measurement of Tj and correspondent spectrum

As shown in Fig. 1, three kinds of customized white LED arrays are tested.

3.1.1. Single phosphor-converted white LED arrays

LED array 1 (composed of thirty 0.15-W, GaN-based white LEDs converted by $Y_3Al_5O_{12}$:Ce (10 wt% relative to epoxy)). LED array 2 (composed of thirty 0.15-W, GaN-based white LEDs converted by $CaAlSiN_3$:Eu (1 wt%)).

3.1.2. Two phosphors-converted white LED arrays

LED array 3 (composed of thirty 0.15-W, GaN-based white LEDs converted by $Y_3Al_5O_{12}$:Ce (10 wt%) and $CaAlSiN_3$:Eu (1 wt%)).

The electrical configuration of the arrays is as follows. Thirty LEDs are divided into three groups connected in parallel, with each group consisting of 10 LEDs connected in series. The rated current of single LED is 45 mA, and the rated current of the LED arrays is therefore approximately 135 mA which is taken as the drive current in this research. In testing procedure, the Tj of samples is prevented from reaching an excessive level by a well-designed heat sink with thermal grease attached, as shown in Fig. 1.

The rationale for using the above three types of LED arrays is that $Y_3Al_5O_{12}$:Ce (yellow) and $CaAlSiN_3$:Eu (red) are two phosphors widely used in white LEDs presently, and the LED array 3 are with a significantly improved CRI (89) by doping $CaAlSiN_3$:Eu (1 wt%) into $Y_3Al_5O_{12}$:Ce (10 wt%), compared to the CRI (72) of LED array 1 and