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Determining Two-Dimensional Phosphor Surface Temperature Distribution of Phosphor-Coated LEDs Based on Hyper-Spectral Imaging

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ABSTRACT We present a high-resolution non-contact method for the measurement of two-dimensional (2D) phosphor surface temperature distribution (PSTD) of phosphor-coated light-emitting diodes (pc-LEDs) based on advanced hyper-spectral imaging technology. The studied pc-LEDs with a surface-mounted device structure are mainly consisted of blue InGaN/GaN-based LED chips (with a spectral emission at about 456 nm), red $(Sr,Ca)AlSiN_3 : Eu^{2+}$ phosphors (with a spectral emission at around 623 nm), and transparent silicone gels. Experimental temperature results are compared with those of micro-thermocouple (μ-TC) and infrared thermal imaging (TI), and fairly good agreements can be noticed. However, the spatial resolution of this proposed method is more than one order of magnitude higher than that of TI method, and the proposed method provides more detailed surface temperature information of phosphors than the latter. Therefore, we believe that this proposed method can serve as useful tools for the non-contact measurement of PSTD in pc-LEDs with or without optics lens.

INDEX TERMS Light-emitting diodes, non-contact, measurement, two-dimensional, phosphor surface temperature distribution.

I. INTRODUCTION

The phosphor-coated light-emitting diodes (pc-LEDs) have been greatly applied in the general lighting, automobile lighting, and back-lighting of displays. The conventional fabrication of pc-LEDs lies in that phosphor powder and silicone gel (phosphor/silicone mixtures) are mixed together with a certain mass ratio, and are uniformly spin-coated on the surface of LED chips. Generally, to protect phosphor/silicone mixtures from air and water vapor and to enhance the light extraction efficiency, irregular and transparent optics lens are covered on LED chips and phosphor/silicone mixtures.

The phosphor temperature or its spatial distribution is important for evaluating performances of pc-LEDs [1], because high temperature of phosphors or phosphor/silicone mixtures would affect both reliability and efficiency of pc-LEDs [2], [3]. Therefore, the thermal management in pc-LEDs including both LED chips and phosphors becomes very crucial [4], [5]. Phosphor thickness, phosphor concentration, and phosphor particle size of phosphor/silicone mixtures are three key factors for affecting phosphor temperatures in pc-LEDs. Accordingly, what the phosphor temperature and its spatial distribution of pc-LEDs with various phosphor parameters behave becomes a focus of attention of both industry and academia in the lighting and display fields.

The current useful methods for the detection of phosphor surface temperature distribution (PSTD) of pc-LEDs may mainly include micro-thermocouple (μ-TC) and infrared thermal imaging (TI) [6], [7]. As a direct-contact method, the μ-TC method is generally used for measurement of surface temperature in electric devices. However, it is unable to measure the surface temperature distribution of phosphors, especially for pc-LEDs with optics lens, for the reason that it is impossible to directly touch the surface of phosphor/silicone mixtures inside pc-LEDs when they are covered by optical lens. At the same time, it physically contacts the surface of pc-LEDs and may damage tested samples. Thermal imaging is capable of detecting temperature distribution of pc-LEDs, but the emissivity of materials is hard to be determined, especially for phosphor/silicone mixtures with various mass ratios, and the inaccurate emissivity would affect final experimental results. In addition, the spatial resolution of TI is not high enough, too. Other methods, such as thermal simulation, would only demonstrate ideal temperature values strongly depending on adopted thermal conduction coefficients and thermal convection coefficients of materials, and simulated temperature values can not precisely reflect real temperatures during the operation of pc-LEDs.

Based on advanced hyper-spectral imaging technology [8], we put forward a non-contact method for precisely determining two-dimensional (2D) phosphor surface temperature distribution of pc-LEDs, increasing the spatial resolution of measured temperature distribution up to more than one order of magnitude higher than the conventional thermal imaging approach. Previously, our research groups have conducted the measurement of 2D temperature distributions for GaN-based LEDs by the hyper-spectral imaging method [6], [7], and also obtain the averaged phosphor temperature of pc-LEDs based on divisional normalized emission power of phosphors' emissions [9]. With these progresses, we can readily achieve high-resolution 2D phosphor surface temperature distribution of pc-LEDs. Finally, the calculated temperature results by proposed methods are compared with those of μ-TC method and TI method.

II. EXPERIMENTAL

A. EXPERIMENT SETUP AND TESTED SAMPLES

Firstly, we introduce the experimental setup and tested samples. The experimental setup for measuring 2D surface temperature distribution of pc-LEDs is schematically illustrated in Fig. 1, including following components as: hyper-spectral imager with charge-coupled device (CCD) detector, high-accuracy optical microscope, tested pc-LEDs (heatsink, aluminum substrate, blue LED, phosphor/silicone mixture), electrical source meters (Keithley 2400), and temperature-controlling systems (Whtalent TLTP-TEC). Incident light provides enough brightness for capturing the real image of pc-LEDs samples when LEDs are not lit up. The infrared

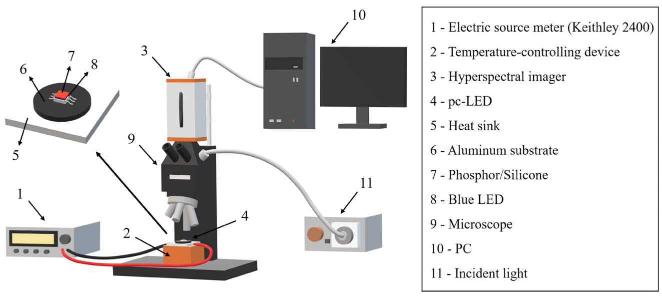

FIGURE 1. The schematic measurement setup.

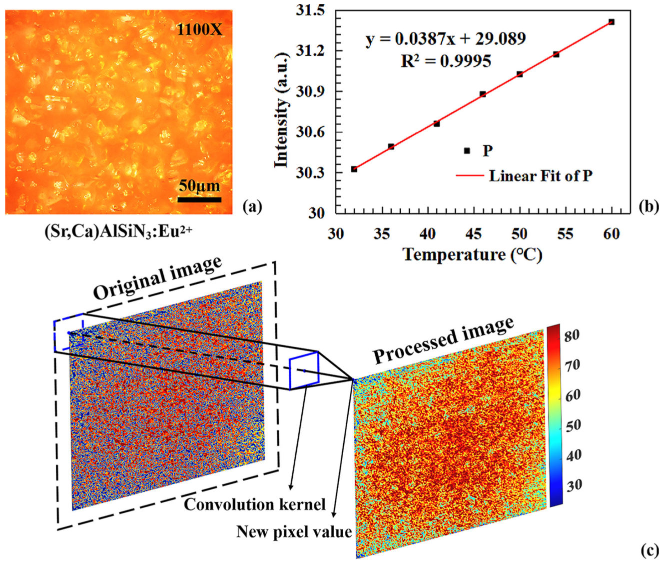

FIGURE 2. (a) The microscopic image of (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphor/silicone mixture captured by three-dimensional laser confocal microscope, (b) for a random pixel, a perfectly linear relationship between the normalized optical power of phosphors (*P*) and the temperature (*T*) at 10 mA electrical current (with a slope, *K*, of 0.0387 and the coefficient of determination of R^2 of 0.9995), and (c) the convolution kernel for processing the original image from the micro-hyperspectral imager.

thermo-grapher (Research-N2) is adopted for detecting the 2D temperature distribution of pc-LEDs for comparison.

The studied pc-LEDs are mainly consisted of blue InGaN/GaN-based LED chips, red (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphors, and silicone gels. InGaN/GaN-based LED chips own multiple quantum well (MQW) structures, and their spectral emissions are peaked at about 456 nm. Red (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphor powders have an average particle size of about 14 μm. Red phosphors and silicone gels are mixed together with a mass ratio of 1:10, corresponding to a phosphor concentration of 9.1 wt%. The red emission from (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphors after excited by InGaN/GaN-based blue LEDs is peaked at about 623 nm. As can be seen, phosphor particles are well-distributed in silicone gels (seen in Fig. 2(a), captured by the three-dimensional laser confocal microscope (OLS5000, OLYMPUS Corp.) with a magnification of 1100X). In addition, the structure of pc-LEDs belongs to surface-mounted device (SMD).

B. CALIBRATION AND MEASUREMENT

Prior to following 2D phosphor surface temperature distribution measurement, we need to carry out a calibration first. Previously, we have reported the averaged surface temperature measurement of phosphors in pc-LEDs while employing divisional normalized emission power (DNEP) of red emissions from (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphors as the temperature-sensitive parameter (TSP) [9]. Thus, we still use this DNEP parameter for conducting the calibration in this work.

During the calibration, a small driven electrical current (DC) as 10 mA is employed to drive pc-LEDs to avoid the self-heating effects. The temperature of pc-LEDs is set as 30 °C, 35 °C, 40 °C, 45 °C, 50 °C, 55 °C, and 60 °C, respectively, by the aforementioned temperature-controlling system. Under this condition, the real temperature on the surface of pc-LEDs acquired by the μ-TC is 32 °C, 36 °C, 41 °C, 46 °C, 50 °C, 54 °C, and 60 °C, respectively. At one pixel, a linear relationship (with a slope, K, of 0.0387 and the coefficient of determination of R^2 of 0.9995) between the normalized optical power (P) of phosphors and temperature (T) can be observed in Fig. 2(b). Thus, for each pixel (m, n), we can obtain the slope of $K(m, n)$.

Therefore, based on this linear relationship at each pixel (m, n), via a coefficient $K(m,n)$, we can transfer the measured normalized optical power at each pixel, $P(m,n)$, as

$$P(m,n) = K(m,n) \times T(m,n) + b(m,n), \quad (1)$$

at a certain condition to the temperature of $T(m,n)$ at each pixel, formulated by (2),

$$T(m,n) = (P(m,n) - b(m,n))/K(m,n). \quad (2)$$

During the measurement, the set temperature for tested samples in Whtalent TLTP-TEC is fixed at 30 °C, and the driven electrical current (DC) applied to pc-LEDs is set as 100 mA, 200 mA, 300 mA, 400 mA, and 500 mA, respectively (five electrical currents).

III. ANALYSES AND DISCUSSION

In practical, pc-LEDs with SMD structure have uneven surface in phosphor/silicone mixtures and the particle in the mixture is not uniformly distributed, too. This phenomenon along with 1) poor signal-to-noice (S/N) caused by hardware conditions and 2) multiple photon scattering and absorption by materials leads to that the normalized spectral emission of red (Sr,Ca)AlSiN$_3$: Eu^{2+} phosphor particles at each pixel looks similarly but not exactly the same to each other. Therefore, not all pixels exhibit a perfect linear relationship with the R^2 coefficient in excess of 0.99. Through conducting the experiment, we have observed that 70.4% data among all hyper-spectral data have shown a R^2 larger than 0.9. However, about 29.6% data left have exhibited a poor linear relationship. We have compared the spectrum of pixels for good fitting and poor fitting, there is not big difference between them. The primary causes of the difference of pixels for good fitting and bad fitting lie in the unsatisfied uneven particles distributed on samples affecting the focus of camera especially for high temperatures. Therefore, we only calculate the 70.4% hyper-spectral imaging data to obtain related temperature values. At the same time, the left data in the original image are compensated by introducing a convolution kernel, as shown in Fig. 2(c).

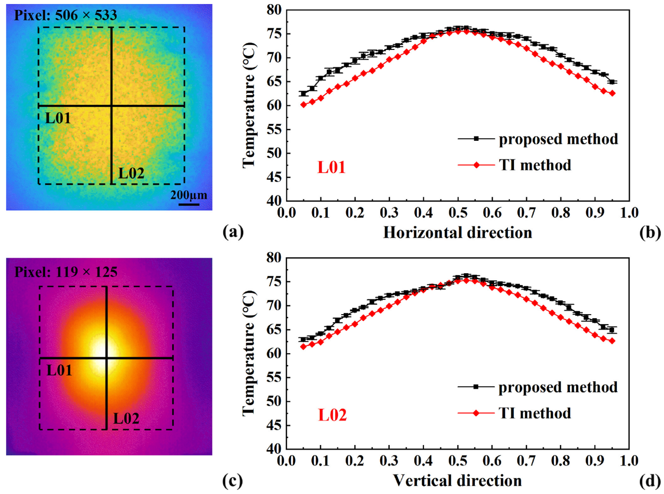

FIGURE 3. (a) The hyper-spectral imaging of the surface of the phosphor/silicone mixture, (b) the temperature distribution for the horizontal line (L01) by the proposed method and the TI method, (c) the thermal imaging of the surface of the phosphor/silicone mixture captured by infrared thermo-grapher, (d) the temperature distribution along the vertical line (L02) by the proposed method and the TI method.

TABLE 1. The averaged temperature results of proposed method and μ-TC method, for pc-LEDs with 9.1 wt% phosphor concentration at the electrical current of 100 mA, 200 mA, 300 mA, 400 mA, and 500 mA, respectively.

Methods (°C)	100 mA	200 mA	300 mA	400 mA	500 mA
T_c	36.9	46.1	56.2	64.7	74.5
T_p	39.4	43.2	54.3	61.4	71.8
ΔT	-2.5	2.9	1.9	3.3	2.7

The processed data in the proposed method are compared with those of the TI method, as shown in Figs. 3(b) and 3(d). For a comparison, the same data points of two methods are adopted. As can be observed, variation trends of two methods are in satisfied coincidence with each other. However, the spatial resolution of the proposed method (506 pixels × 533 pixels for the rectangular dashed box) is more than one order of magnitude better than that of TI method (119 pixels × 125 pixels for the same box), shown in Figs. 3(a) and 3(c). Table 1 gives averaged temperature results of the proposed method (T_p) and μ-TC (T_c), for pc-LEDs with a 9.1 wt% phosphor concentration at five electrical currents of 100 mA, 200 mA, 300 mA, 400 mA, and 500 mA, respectively. From calculated ΔT (by (3)), we can see that the temperature difference between two methods is within 4 °C for all five electrical currents, proving that the proposed method is in well coincidence with μ-TC. The main reason for this temperature difference is that the micro-thermocouple would absorb parts of light from LED, and the measured temperature would slightly vary from the real one. The

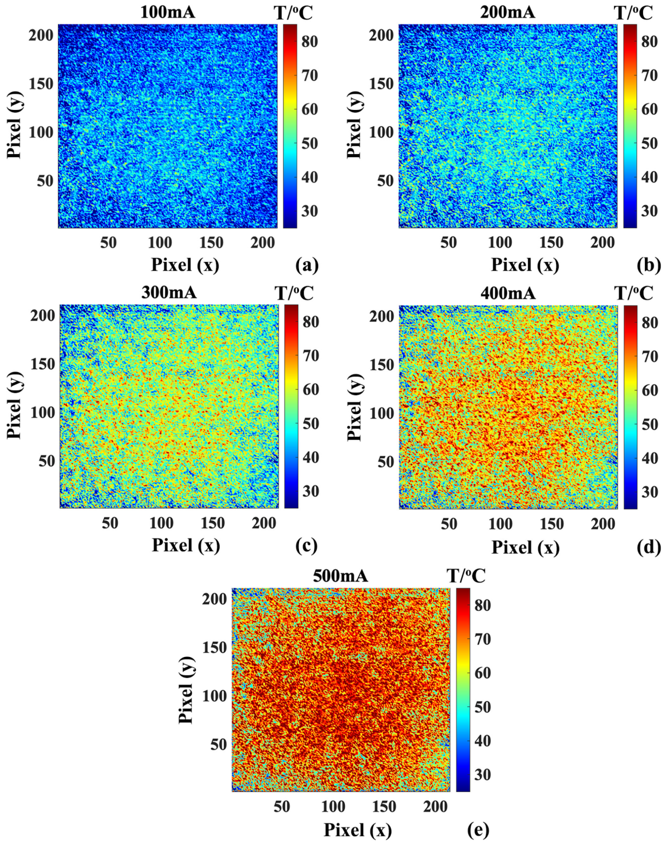

FIGURE 4. Measured by the proposed method, the 2D phosphor surface temperature distribution of pc-LEDs at five electrical currents (100 mA, 200 mA, 300 mA, 400 mA, and 500 mA, respectively).

other reason is that the linear fitting is not exactly perfect and causes some measurement errors from the reference results. In addition, we have also done experiments on samples with other phosphor concentrations. Most of samples have the similar and good results with the studied one, except for samples with extremely low phosphor concentration, because of bad signal-to-noise ratio will be discovered from them which leads to bad linear fitting during the calibration.

Figure 4 depicts the 2D phosphor surface temperature distribution at five electrical currents (100 mA, 200 mA, 300 mA, 400 mA, 500 mA, respectively) after the data processing. As can be noticed, the surface temperature is the highest in the center, and increases as the electrical current increases. The high temperature in the center is attributed to the Lambert distribution of blue LED die.

IV. CONCLUSION

In summary, we have presented a non-contact method for achieving the 2D phosphor surface temperature distribution in pc-LEDs. The experimental results are compared with those of infrared thermal imaging and micro-thermocouple, showing fairly good agreements among them. However, the spatial resolution of this proposed method is more than one order of magnitude higher than that of infrared thermal imaging. During hyper-spectral data processing, the convolution processing is done for obtaining the real temperature, especially for bad points in the 2D hyper-spectral image with poor fitting (R^2 is lower than 0.9). We believe that the proposed method (the combination of DNEP as the TSP, the hyper-spectral imaging, and the convolution processing) has great application values of precisely determining the 2D microscopic phosphor surface temperature distribution of pc-LEDs with lens or without lens.

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