Near-/Mid-Field Effect of Color Mixing for Single Phosphor-Converted Light-Emitting Diode Package

Run Hu, Shan Yu, Yong Zou, Huai Zheng, Fei Wang, Sheng Liu, and Xiaobing Luo

***Abstract*—In this letter, it is found through both experiments and Monte Carlo ray-tracing simulations that the working distances would influence the correlated color temperature (CCT) and the angular color uniformity (ACU) of single phosphor-converted light-emitting diode (pc-LED) package. When the working distance decreases, the CCT decreases and the ACU deteriorates. The deterioration caused by short distance is regarded as the near-/mid-field effect of color mixing of pc-LED. This discovery of the near-/mid-field effect may help to find some specific packaging methods to control color mixing and improve white light quality for some applications where the working distance was short.**

***Index Terms*—Color mixing, light-emitting diode (LED), near-/mid-field effect, phosphor.**

I. Introduction

WHITE light LEDs have been widely used in our daily life for their extraordinary features [1]–[6]. Currently, there are three methods to produce white light based on LEDs, i.e. 1) a blue LED chip with yellow phosphors; 2) an ultraviolet LED chip with blue and yellow phosphors (or red, green and blue phosphors); 3) a device combined with red, green and blue LEDs together. Among these methods, the former two methods are involved with phosphor materials, which can be stimulated by short-wavelength light from the LED chips and emit long-wavelength light. As shown in Fig. 1, the white light of phosphor-converted LEDs (pc-LEDs) can be obtained by mixing the blue light from the LED chips and fluorescent light from the phosphor layers. The white light in the third method was obtained by mixing the trichromatic light from red LED, green LED, and blue LED. Therefore, all the white light of the existing LEDs was obtained by color mixing.

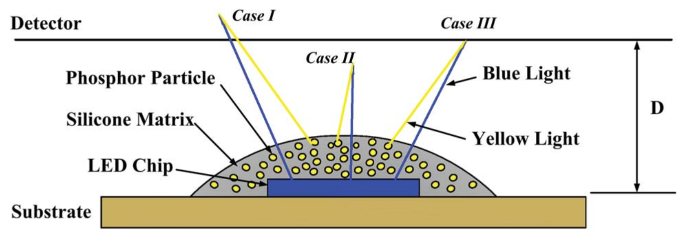

Fig. 1. Schematic of white light generated by color mixing.

In fact, color mixing has been applied in a lot of applications, such as down lighting, spot lighting, floodlighting, and show lighting, etc. Therefore, color mixing plays a significant role in determining the final optical performance, including the illumination uniformity (IU), angular color uniformity (ACU), correlated color temperature (CCT), etc. Researchers have conducted a lot of studies on color mixing. Dong *et al.* [7] studied the color mixing of RGB LED array for machine vision inspection by considering the color distribution, CCT, and color uniformity. Tu *et al.* [8] investigated the effect on color mixing properties of the near- field light distribution due to different high power RGB LED-chips array. The near-/mid-field effect on LED array was modeled and discussed [9]–[11]. From these studies, we may notice that all the color mixing in these studies fall into the category of multiple LEDs including the array LEDs or RGB LEDs, but no studies referred to single pc-LED as far as we know. Whether the near-/mid-field effect of color mixing exists in single pc-LED is still unknown.

The color mixing for single pc-LED is illustrated in Fig. 1. For a certain distance D between the LED module and the detector, some joints of blue light and yellow light are beyond the detector (like *Case I*), some joints are within the detector (like *Case II*), and some joints are exactly on the detector (like *Case III*). It is seen that the distance D determines which case the joints of the blue light and yellow light belong to. Therefore the distance will influence the color mixing of single pc-LED. When the distance is short, it falls into the near-/mid- field category. To figure out the existence of near-/mid-field effect in single pc-LED will help us to control the color mixing and improve the white light quality of single pc-LED. This is the exact motivation behind this letter.

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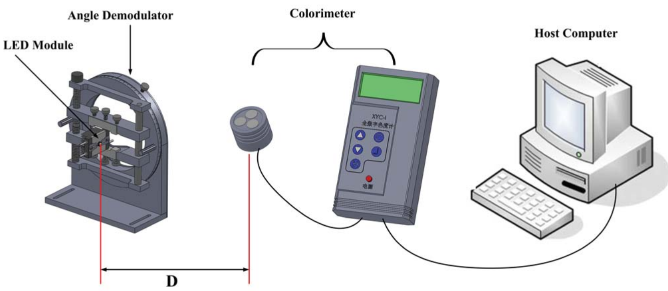

Fig. 2. Configuration of experimental apparatus.

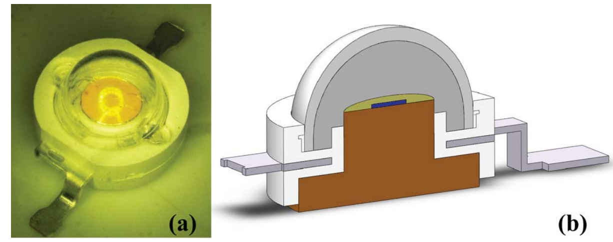

Fig. 3. (a) Picture of typical LED module and (b) its corresponding model.

In this letter, we studied the color uniformity of cerium (III)-doped yttrium aluminium garnet (YAG) pc-LED and found the near-/mid-field phenomenon of color mixing both by experiments and Monte Carlo ray-tracing simulations. In the experiments, the CCT of pc-LED in the whole radiation angle was measured by a colorimeter when the distance between the LED and the colorimeter was changed. While in the simulations, we built a corresponding model of pc-LED and simulated the variation of ACU by adjusting the distance. The results were reported and analyzed in detail.

II. Experiments and Simulation

As shown in Fig. 2, the experimental apparatuses mainly include LED module, angle demodulator, and colorimeter. The LED module in this experiment was a typical leadframe LED, in which the phosphor silicone matrix was freely dispersed to coat the LED chip. The chip dimension is 1 mm × 1 mm. The phosphor layer is convex, and the height is 0.3 mm in the center region. The LED module was mounted onto an aluminium heat sink for heat dissipation and convenience of fixing to the angle demodulator. The XYC-I all digital colorimeter, whose sensitivity is 1 K and the accuracy is ± 20 K, has three digital sensors to record the (X, Y, Z) color coordinates (CIE 1931). The diameter of each sensor is 10 mm. The colorimeter was linked to a host computer, thus the real-time CCT data could be recorded. We rotated the angle demodulator to record the CCT data in the whole radiation angle, and adjusted the distance between the LED module and the colorimeter in order to observe the CCT variation versus the distance. In this experiment, due to the size confinement of angle demodulator, the distance in the experiments was only changed from 14 cm to 100 cm. As shown in Eq. (1), the ACU in the experiments can be calculated as Eq. (1) [12], [13].

$$ACU = CCT_{\min}/CCT_{\max} \tag{1}$$

To verify the near-/mid-field effect of color mixing in pc-LED, we also conducted Monte Carlo ray-tracing simulations. The building of a precise model of pc-LED chip is necessary. In the simulations, a 1 × 1 mm^2 conventional blue GaN LED chip was modeled. The luminescencent Multi-Quantum Well (MQW) was sandwiched by an n-GaN layer and a heterostructure of p-GaN layer and p-AlGaN layer. A current spreading layer fabricated by Indium Tin Oxide (ITO) and a sapphire substrate were also taken into consideration. The top and bottom surfaces of the MQW were set as luminescent surfaces with Lambertian light distribution. The absorption coefficients and refractive indices for p-GaN, MQW, and n-GaN were 5, 8 and 5 mm^{-1} and 2.45, 2.54, and 2.42, respectively [12], [13]. The surface reflection coefficient of the reflecting layer (Ag) was set as 0.95. By setting the absorption coefficients and refractive indices of the materials, the precise model of conventional GaN blue LED chip could be achieved.

In the simulations, we built a corresponding 3D model to the experimental LED module, as shown in Fig. 3. The LED chip was mounted on a copper slug for thermal dissipation and the phosphor silicone matrix was dispersed freely to coat on the chip. The silicone was filled into the interspace between the phosphor and the polycarbonate hemispherical lens for encapsulation. The surface reflection coefficient of the copper slug was set as 0.9. In the simulations, the quantum efficiency of the phosphor was assumed as 80%, which means 0.8 photons of the converted yellow light could be re-emitted from the phosphor particle when one blue photon was absorbed by one phosphor particle [14]. The detailed phosphor parameters, especially the absorption coefficients and scattering coefficients, were calculated from the Lorenz-Mie theory [15]. The wavelength-dependent refractive indices, absorption and scattering coefficients, which varied with the phosphor concentration, were essential to determine the optical performance of the LED packages. In this letter, to make the simulation closer to the real packaging process, the phosphor concentration was set as 0.16 g/cm^3. The necessary parameters in the simulations can be referred in our previous works [1]–[3], [15], [16]. For modeling the light conversion process, the rays of blue and yellow light were simulated separately by Monte Carlo ray-tracing method. In the simulation, two wavelengths were ray-traced separately, i.e. 465 nm and 555 nm, which could represent the blue LED light and the phosphor-converted yellow light, respectively. The blue light was emanated from the top surface of the chip and the yellow light was emitted from the volume of phosphor silicone matrix according to the distribution of phosphor particle inside the silicone matrix.

Since the distance between the LED module and the detector in the experiment cannot be shorter due to the size confinement of apparatuses, in the simulations, we changed the distance from 100 cm, 10 cm to 1 cm. Both the blue and yellow irradiance distributions were recorded by the same detector. The detector was big enough to receive all the light from the whole radiation angles in the x-y plane of detector. To compare with the experimental results, only the data in the center line (where the x-axis or y-axis vanish) were used to correspond to

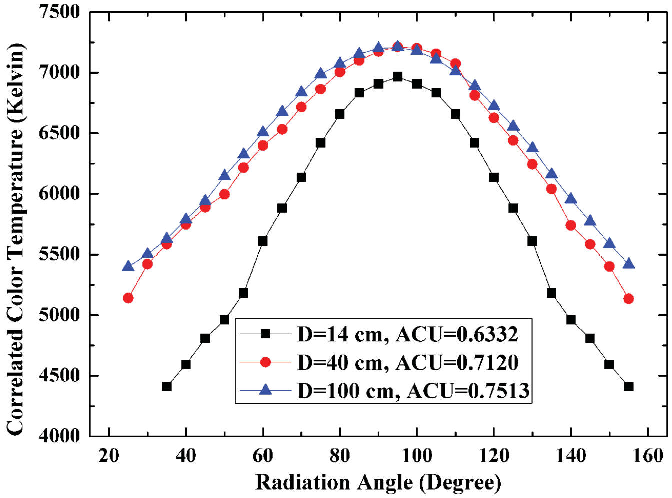

Fig. 4. CCT variation of typical leadframe LED module in the experiments.

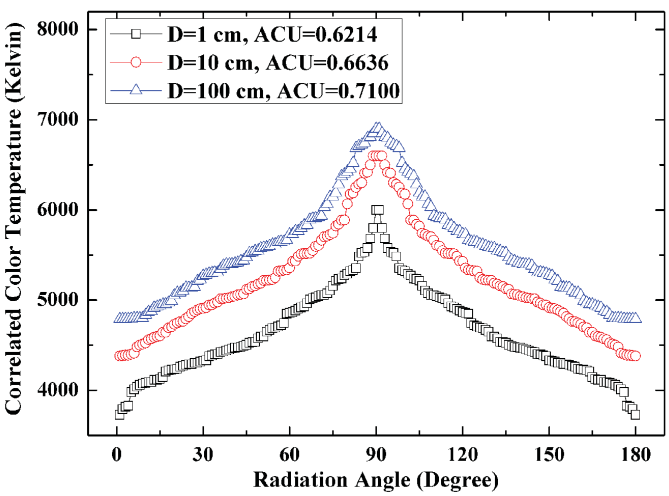

Fig. 5. CCT variation in the whole radiation angle in the simulations.

the experiments. Therefore, the definitions of distance both in experiments and simulations are consistent. The recorded data were converted into the corresponding combined chromaticity coordinates (CIE 1931), and then the CCT can be calculated with the CIE-x and CIE-y coordinates. The ACU was also calculated correspondingly.

III. Results and Discussion

Fig. 4 shows the experimental results. From Fig. 4, we can see that in the center region, the CCT is about 7000 K, while in the edge region, the CCT decreases to about 5000 K. There exists a transparent droop of CCT in the edge region, which is the cause for the yellow ring in the edge of light pattern. When the distance D (between the LED module and the colorimeter) decreases from 100 cm to 14 cm, the ACU decreases from 0.7513 to 0.6332 by 18.65%. The reason for this phenomenon can be explained as follows. When D decreases, more blue light and yellow light fail to mix with each other before reaching the detector (colorimeter) and their joints fall into *Case I* in Fig. 1. Poor performance of color mixing occurs, thus ACU deteriorates. It is seen that the distance may affect the ACU and CCT greatly, which can be regarded as the near-/mid-field effect of color mixing in single pc-LED. Although the distance in our experiments may not be near enough, the effects and the trends are observed.

The simulated CCT was shown in Fig. 5. From this figure, it is noticed that there also exists a transparent droop of CCT in the edge region, which agrees with experimental results in Fig. 4. Moreover, the CCT peaks become obvious when the distance D decreases. When D decreases from 100 cm to 1 cm, the ACU decreases from 0.7100 to 0.6214 by 14.26%. The simulations also prove the existence of the near-/mid-field effect of color mixing in single pc-LED.

From both the experiments and simulations, it is noted that the working distance influences the ACU and color mixing greatly, especially in the edge region. In fact, there are a lot of pc-LED applications, in which the distance between the LED modules and the screen is short and the near-/mid-field effect may exist, such as mobile phone, digital camera, LED backlighting system, personal digital assistant (PDA), etc. For such applications, specific packaging processes or structures may be needed for better performance.

IV. Conclusion

In summary, the near-/mid-field effect of color mixing in single pc-LED was observed by both experiments and Monte Carlo ray-tracing simulations. In the experiments, a typical leadframe LED module with freely dispersed phosphor coating was measured; while in the simulations, the corresponding LED module was modeled. Both in the experiments and simulations, it is found that with the decrease of the working distance between the LED module and the detector, the CCT decreased and the ACU deteriorated. From this letter, it is discovered that the near-/mid-field of color mixing also exists in single pc-LED package.

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