Angular color uniformity enhancement of white light-emitting diodes integrated with freeform lenses

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We demonstrate a freeform lens to enhance the angular color uniformity (ACU) of white light-emitting diodes (LEDs) whose phosphor layers were coated by freely dispersed coating processes. Monte Carlo ray tracing simulation results indicated that the ACU of the modified LED integrated with the freeform lens significantly increased from 0.334 to 0.957, compared with the traditional LED. Enhancement of ACU reached as high as 186.5%. Moreover, the ACU of the modified LED was not only at a high level, but also stable when the shape of the phosphor layer changed. The freeform lens provided an effective way to achieve white LEDs with high ACU at low cost.

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Light-emitting diodes (LEDs), with increasing luminous efficiency in recent years, have greater applications in daily life, such as road lighting, backlighting for LCD display, headlamps of automobiles, and interior and exterior lighting [1–3]. Besides efficiency, the major challenge for general lighting is the quality of white light in terms of angular color uniformity (ACU), especially for phosphor-conversion white LEDs [4,5]. The widely adopted phosphor coating process in terms of a freely dispersed coating is easy to operate and at low cost, but it would result in yellow rings in the radiation pattern [5,6], which reduces ACU. This problem can be overcome by phosphor conformal coating, including electrophoresis [7], slurry, settling [8], evaporating solvent [9], and wafer level coating [10]. Besides conformal coating, phosphor layers with convex shapes [5] and transparent refractive-index-matched microparticle (TRIMM)-doped diffusers [11] can also enhance ACU significantly. Although these methods are effective to achieve high ACU, most of them are complicated and costly. In this Letter, we demonstrate a freeform lens to enhance the ACU of white LEDs whose phosphor layers were freely dispersed coated. Simulation results show that ACU was enhanced dramatically by the freeform lens. Also, effects of various shapes of phosphor layers on ACU are studied.

Figure 1(a) shows the traditional LED mainly consists of a board, an LED chip, a phosphor layer, and a hemisphere silicone lens. The phosphor is freely dispersed on the chip. As shown in Fig. 1(a), light within radiation angles of 0°–90° will exit through the hemispherical surface of the lens and not overlap. Therefore, as shown in Fig. 2(a), optical power of P_0 at the center of far field consists of B_0 and Y_0, which represent optical power of blue light (380–490 nm) and yellow light (490–780 nm) emitted from the chip and the phosphor, respectively, at the direction of 90°. Similarly, optical power of P_1 at the edge of far field consists of B_1 and Y_1. In this analysis, we introduce a yellow–blue ratio (YBR) to illustrate the variation of correlated color temperature (CCT) [5]. ACU is the ratio of minimum YBR to maximum YBR in the range of 0°–180°. However, in the traditional LED, a YBR of $P_1(Y_1/B_1)$ is much larger than that of $P_0(Y_0/B_0)$ owing to phosphor freely dispersed coating [5,6], which results in yellow rings.

In this Letter, we try to eliminate yellow rings by overlapping light with different radiation angles. Figure 1(b) shows a modified LED integrated with a freeform lens, which has two discontinuous surfaces, the side and the top surface. Light within radiation angles of 0°–θ exits from the LED through the side surface and covers the emergence angles of 0°–90°. Also, light within 0°–90° exits through the top surface and covers the same range of emergence angles of 0°–90°. Therefore, as shown in Fig. 1(b), the far field of the modified LED consists of two parts, part I and part II. Light in these two parts overlaps each other. Optical power of P_0 in Fig. 2(b) includes B_0, Y_0, B_2, and Y_2, while optical power of P_2 includes B_1, Y_1, B_3, and Y_3. Because $Y_2/B_2 > Y_0/B_0$ and $Y_3/B_3 < Y_1/B_1$ [5,6], we can obtain following formulas:

$$\frac{Y_0}{B_0} < \frac{Y_0 + Y_2}{B_0 + B_2}, \tag{1}$$

$$\frac{Y_1 + Y_3}{B_1 + B_3} < \frac{Y_1}{B_1}, \tag{2}$$

which means the difference of the YBR between the central point and the edge point of far field becomes smaller after adopting the freeform lens, which enhances the ACU. Furthermore, it is theoretically possible to make the YBR at different points of the far field equal, leading to perfect color distribution of the LED [see Eq. (3)]. The ACU could reach as high as 1:

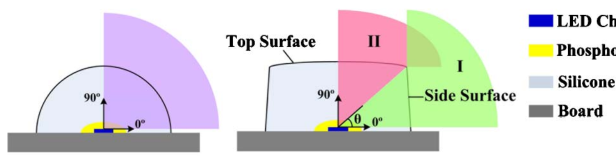

Fig. 1. (Color online) Schematic of light output of (a) the traditional LED and (b) the modified LED.

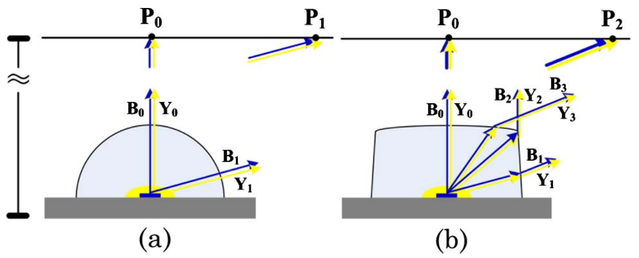

Fig. 2. (Color online) Schematic of optical power of center and edge points in the far field of (a) the traditional LED and (b) the modified LED.

$$\frac{Y_0}{B_0} < \frac{Y_0 + Y_2}{B_0 + B_2} = \frac{Y_1 + Y_3}{B_1 + B_3} < \frac{Y_1}{B_1}. \tag{3}$$

The side and top surfaces of the freeform lens were designed according to a practical and precise nonimaging optical design method [12]. Light exited from both the side and the top surfaces of the lens will uniformly irradiate on the target plane. Figure 3(b) shows the freeform lens.

First, two optical models of the traditional and the modified white LEDs were built as shown in Figs. 3(a) and 3(b). The size of the chip is 1 mm × 1 mm. The thicknesses of the layers are N-GaN 4 μm, MQW 100 nm, P-GaN 300 nm, and Si 100 μm. The absorption coefficients and refractive indices for N-GaN, MQW, and P-GaN are 5, 8, and 5 mm^{-1} and 2.42, 2.54, and 2.45, respectively [13]. The shape of the phosphor layer is a spherical cap with a height of 0.4 mm and a radius at the base of 1.5 mm, which is formed by a freely dispersed coating. The phosphor concentration is 0.35 g/cm^3. Based on the Mie scattering model, the absorption and scattering coefficients of phosphor are 3.18 and 5.35 mm^{-1} for blue light and 0.06 and 7.44 mm^{-1} for yellow light [14]. The refractive index of silicone is 1.50. The heights are 3 mm for both the hemisphere and freeform silicone lenses, which are easy to manufacture by a molding process.

Next, blue and yellow light were separately calculated by a Monte Carlo ray-tracing method. To simplify the calculation, specific wavelengths of 465 and 555 nm were used in the calculation to represent blue and yellow light, respectively, which had been verified as feasible during a simulation [5]. The phosphor layer first collected the absorbed blue light and then the re-emitted yellow light from the top and bottom surfaces. Optical power from 0° to 180° in the space was collected to analyze the color distribution.

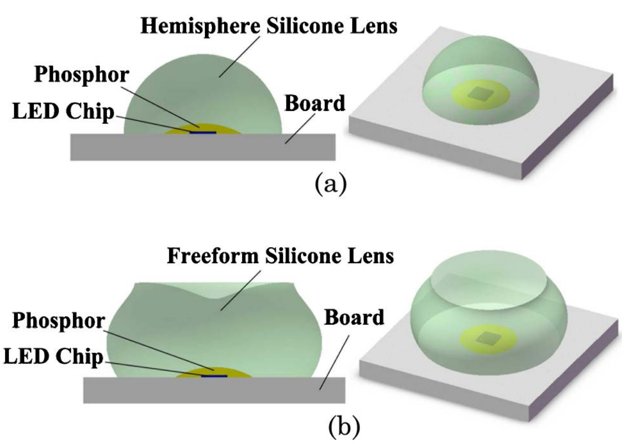

Fig. 3. (Color online) Optical models of (a) the traditional LED and (b) the modified LED.

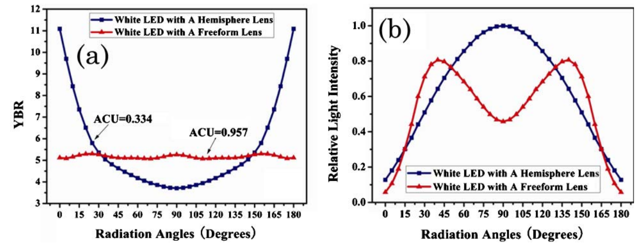

Fig. 4. (Color online) (a) ACU and (b) LIDs of the traditional LED and the modified LED.

Simulation results are shown in Fig. 4(a). We can find that the YBR of the traditional LED is 3.71 at the center, while it rapidly reaches as high as 11.09 at the edge, resulting in a low ACU of only 0.334. After adopting the freeform lens, the YBR of the modified LED increases from 3.71 to 5.26 at the center and decreases from 11.09 to 5.12 at the edge compared with the traditional LED. There is a shift toward yellow (lower CCT) for the light emitted between 40° and 140° and a shift toward blue (higher CCT) out of this region. Therefore, the difference between the YBR of the center and the edge becomes quite small in the modified LED. The ACU increases significantly from 0.334 to 0.957, and the enhancement reaches as high as 186.5%. Besides good ACU performance, the light extraction efficiency of the modified LED reaches as high as 99.5% of that of the traditional LED, whose light extraction efficiency is defined as a reference of 100%. Moreover, light intensity distributions (LIDs) of LEDs are very important for researchers when designing optical systems of LED fixtures. As shown in Fig. 4(b), the LID of the traditional LED is close to Lambertian, while the modified LED's is of the batwing type, which is suitable for some applications that require large view angles, such as backlighting and road lighting.

The effects of various shapes of phosphor layers on the ACU were also studied, including changes of height (h) and radius (a) of the base of the spherical caplike phosphor layer. Figure 5(a) depicts that when the height is 0.4 mm and the radius increases from 0.9 to 1.9 mm, the ACU of the traditional LED decreases from 0.633 to 0.272. However, in the same circumstances, the ACU of the modified LED is still at a high level of around 0.8. Effects of the heights of phosphor layers on ACU are shown in Fig. 5(b). We can find that when the radius is 1.5 mm and the height increases from 0.2 to 1.0 mm, the ACU of the

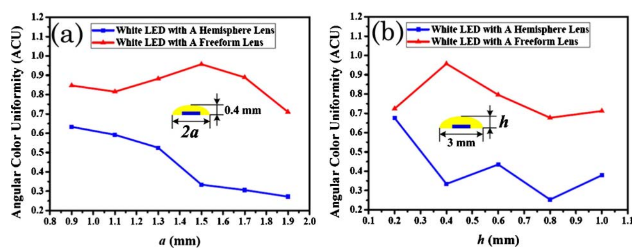

Fig. 5. (Color online) Effects of (a) radii and (b) heights of phosphor layers on the ACU of LEDs.

traditional LED decreases from 0.676 to 0.379, while most ACUs of the modified LED keep at around 0.7. Therefore, the ACU of the modified LED is not only at a high level but also stable when the shape of the phosphor layer changes.

In summary, an effective method was presented to achieve a high ACU of white LEDs when adopting phosphor a freely dispersed coating process. According to this method, we created a modified white LED that was integrated with a freeform lens and could achieve a high ACU up to 0.957. Compared with the traditional LED, enhancement of ACU reached as high as 186.5%. Moreover, the ACU of the modified LED was not only at a high level but also stable when the shape of the phosphor layer changed. The simulation results indicated that the freeform lens provided an effective way to achieve white LEDs with high ACU at low costs.

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