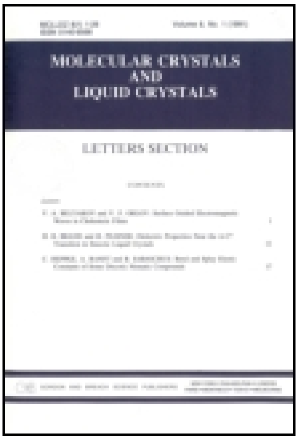

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Separation Distance Dependence of Luminous Efficiency in Phosphor-Converted White-Light-Emitting Diodes Fabricated Using Open Remote Method

Sang-Chul Park [a] , Hongsub Bae [a] , Ilsu Rhee [a] , Sungwook Hong [b] , Jong-Youl Kim [c] , Hong Jun Bark [c] & Junho Jeong [d]

[a] Department of Physics , Kyungpook National University , Daegu , 702-701 , Korea

[b] Division of Science Education , Daegu University , Gyeongsan , 712-714 , Korea

[c] Department of Optometry , Yangsan University , Yangsan , 626-740 , Korea

[d] Department of Materials Physics , Dong-A University , Busan , 604-714 , Korea

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Separation Distance Dependence of Luminous Efficiency in Phosphor-Converted White-Light-Emitting Diodes Fabricated Using Open Remote Method

SANG-CHUL PARK,[1] HONGSUB BAE,[1] ILSU RHEE,[1,*] SUNGWOOK HONG,[2] JONG-YOUL KIM,[3] HONG JUN BARK,[3] AND JUNHO JEONG[4,*]

[1]Department of Physics, Kyungpook National University, Daegu 702-701, Korea
[2]Division of Science Education, Daegu University, Gyeongsan 712-714, Korea
[3]Department of Optometry, Yangsan University, Yangsan 626-740, Korea
[4]Department of Materials Physics, Dong-A University, Busan 604-714, Korea

Phosphor-converted white-light-emitting diodes (WLEDs) were fabricated using the open remote method. The separation distance between the blue LED chip and phosphor layer was varied to examine the effects of blue lights penetrating through the annular gaps between the phosphor layer edge and reflector cup walls on the luminous efficiency of the WLED. The WLEDs with a separation distance of 0.55 mm showed the highest luminous efficiency which was close to that of the slurry sample, while the amount of phosphors used was less than 25% of the amount used in the slurry sample. These results suggest that the phosphor quantity used for fabricating the WLEDs can be reduced considerably by the open remote method without any significant loss of luminous efficiency.

Keywords Luminous efficiency; open remote method; phosphor-converted WLED

Introduction

White-light-emitting diodes (WLEDs) are expected in the near future to replace the incandescent and fluorescent lamps currently used widely for lighting [1–7] owing to their low electric power consumption, long lifetime, and no use of mercury. Three methods are generally used to fabricate WLEDs [8–11], a combination of green, red and blue LEDs, a combination of ultraviolet LED and phosphors, and a combination of blue LED and phosphors. More than 90% of commercial WLEDs are constructed using a combination of blue LED and phosphors owing to its simplicity for the fabrication and low cost. These WLEDs are called phosphor-converted WLEDs because the phosphors convert some of the blue light from the blue LED to yellow light to give white light. Nevertheless, before WLEDs can be used for general lighting, the power of the constituent LEDs should be comparable

*Address correspondence to Prof. Ilsu Rhee, Department of Physics, Kyungpook National University, 80 Daehak-Ro, Buk-Gu, Daegu 702-701, Korea (ROK), Tel.: (+82)53-950-5324, Fax: (+82)53-952-1839, E-mail: ilrhee@knu.ac.kr; and Prof. Junho Jeong, Department of Materials Physics, Dong-A University, 37 Nakdong-Ro, Saha-Gu, Busan, 604-714, Korea (ROK), Tel.: (+82)200-7221, Fax: (+82)51-200-7232; E-mail: jjheco@dau.ac.kr.

to that of conventional light sources, such as incandescent and fluorescent lamps. These high power requirements can be satisfied using LEDs based on InGaN/GaN quantum wells and flip chip structures [12–15].

In fabricating phosphor-converted WLED using the slurry method, the reflector cup is filled with a mixture of phosphor and silicon resin, and thermally cured it. Most commercial WLEDs are fabricated using the slurry method owing to its simplicity. On the other hand, in this phosphor distribution, the light converted by phosphors can be backscattered directly into the chip, which can increase the temperature of the chip, resulting in a decrease in the efficiency and life span of WLEDs. To reduce the backscattered light, a remote phosphor distribution was developed [16–21]. In this configuration, the phosphor layer is formed at a certain position above the LED chip. The separation distance between the phosphor layer and chip means that the light converted by phosphors has less chance of being backscattered directly into the chip.

Phosphor-converted WLEDs were fabricated using the open remote method. In this method, a phosphor layer is formed with annular gaps between the phosphor layer edge and reflector cup walls. Therefore, some of the light reflected from the chip can pass through these annular gaps to reduce the multiple reflections between the chip and phosphor layer. The separation distance between the chip and phosphor layer was varied from 0.47 to 0.74 mm to examine how blue light penetrating the annular gaps affects the luminous efficiency of the WLEDs. The WLED with a separation distance of 0.55 mm showed the highest luminous efficiency.

Experimental

Bridgelux LED chips were used as the blue light source. The area and thickness of the LED were 1,143+30/−10 μm × 1,143+30/−10 μm and 150 ± 10 μm, respectively. The peak output wavelength of the blue LED was 450 - 455 nm with a FWHM (full width at half maximum) of approximately 27 nm. The LED chip was located at the center of the bottom of the reflector cup, whose shape was a truncated cone, as shown in Fig. 1. The phosphor-converted WLED was constructed by filling the reflector cup with silicone resin and phosphor. The amount of silicone resin required to completely fill the reflector cup was 33 mg. $Y_3Al_5O_{12}$:Ce phosphor (Model DLP-1217WG) with a mean particle size of 7 μm was used as the phosphor converter. The nominal refractive index of the silicone resin (DOW Corning, OE-6635) used was 1.53.

In fabricating the WLEDs using the open remote method, the reflector cup was filled partially with silicone resin. In this process, 8, 10 and 15 mg of silicone resin was used to obtain samples with different distances between the phosphor layer and LED chip. The phosphor layer for the sample containing 15 mg silicone resin was separated farthest from the LED chip. The distances between the chip and phosphor layer for the 8-, 10- and 15-mg samples were estimated to be 0.47, 0.55 and 0.74 mm, respectively. The silicone resin was dried at 60°C for 30 min. Subsequently, 8 mg mixture of the silicone resin and phosphor (8 wt%) was dropped on the dried silicone resin and cured to form annular gaps (approximately 1.5 mm) between the phosphor layer and reflector cup walls, as shown in Fig. 1(a). This mixture was cured at 60°C for 30 min. The reflector cup was then filled completely with silicone resin. Final curing was performed for 110 min at 75°C followed by additional curing for 60 min at 170°C. The silicone resin and mixture was dispersed using an accurate dispenser (AD 300D, Yujin Tech), which controls the amount of dispensing liquid by the pressure and dispensing time. Silicone resin and phosphor were mixed using a mixer

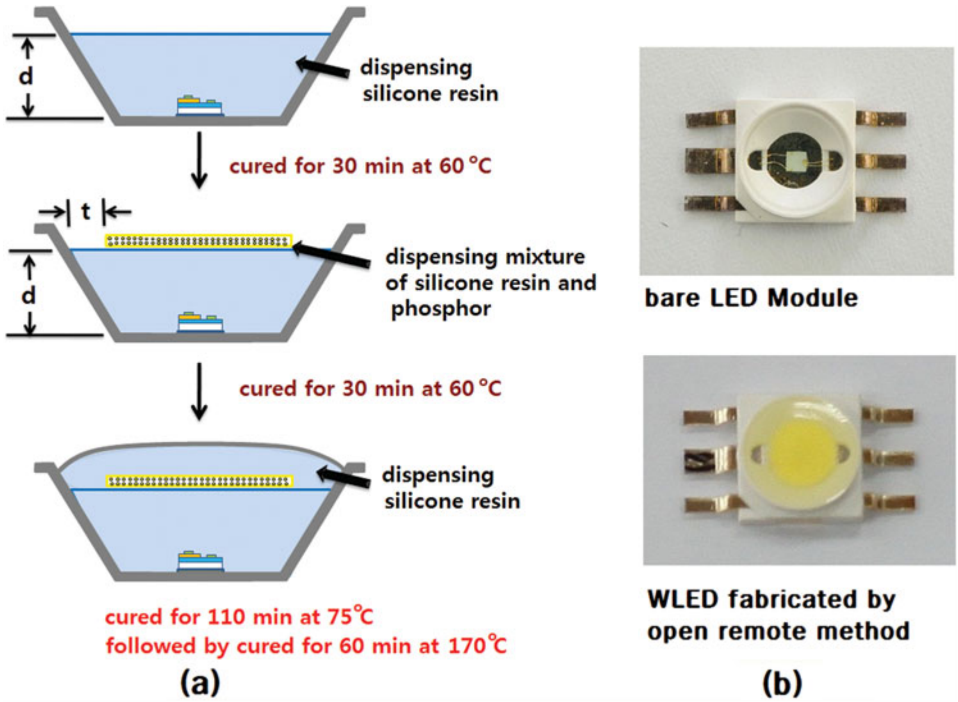

Figure 1. (a) Procedures for fabricating the WLED using the open remote method. (b) Photos for the bare LED module and constructed WLED.

(KK50s, Kurabo) for 3 min at 1,000 rpm before dispensing. WLEDs were also prepared by the slurry method for comparison with the WLEDs fabricated by the open remote method. In the slurry sample, the reflector cup was completely filled with the mixture of the silicone resin and phosphor (8wt%) and cured.

The optical and electrical properties of the fabricated WLEDs were analyzed using an integrating sphere (Model OPI-100, Withlight) installed with a set of spectrophotometers (WLSP-SI-NOR, Hamamatsu). The standard light source of A 2856 K (incandescent, Rs 100V/60W) was used to determine the color rendering index.

Results and Discussion

Figure 2 shows the current-dependent luminous efficiency of the WLEDs fabricated using the open remote method. The efficiency of the WLED fabricated using the slurry method is also shown for reference. The efficiency of the WLED samples generally decreased with increasing current due to joule heating caused by an increase in electrical resistance of the LED chip, resulting in a decrease in luminous efficiency.

Figure 2 also shows that the luminous efficiencies of the 0.47- and 0.55-mm samples were very close to that of the slurry sample. The ratios of the luminous efficiency of the 0.47- and 0.55-mm samples to that of the slurry sample at 350 mA were 0.94 and 0.96, respectively. However, this ratio for the 0.74-mm sample was just 0.81. The luminous efficiency decreased abruptly as the separation distance was increased from 0.55 to 0.74 mm. These results suggest that there is a high possibility to have the optimum separation distance for the highest luminous efficiency near 0.55 mm. The amount of phosphor used for the

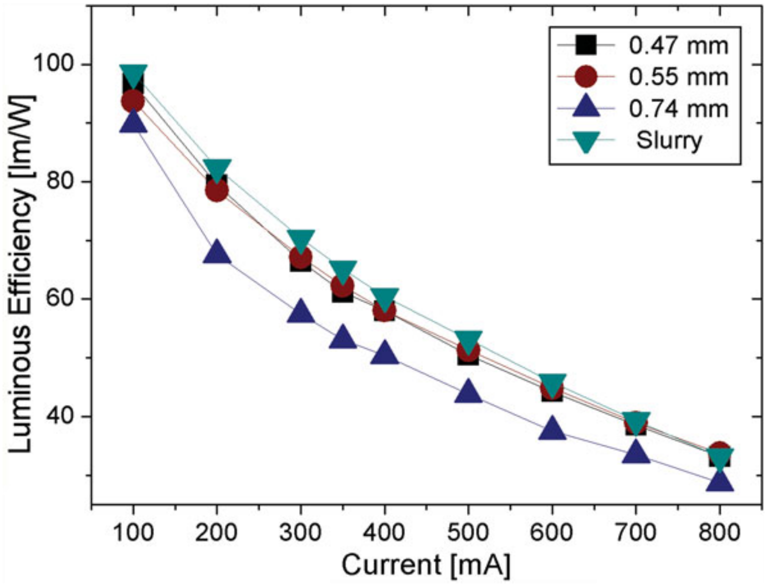

Figure 2. Current dependent luminous efficiency for the WLED samples fabricated using the open remote method. The luminous efficiency for the slurry sample is also shown.

slurry sample was 2.64 mg, whereas the amount of the phosphor used for the open remote samples was 0.64 mg. Therefore, the amount of the phosphor used for the open remote samples was less than 25% of the phosphor used for the slurry sample [19]. Despite this, the luminous efficiency of the 0.55-mm sample was as similar to that of the slurry sample.

Figure 3 presents examples of the emission spectra for the open remote samples. Two distinct peaks corresponding to the blue LED and phosphors were observed. The spectra shown in Fig. 3(a) are for the 0.55-mm sample. Figure 3(b) shows the change in the spectra at 350 mA as a function of the separation distance. The emission spectrum of the slurry sample is also shown for reference. The area under the curve of the spectrum

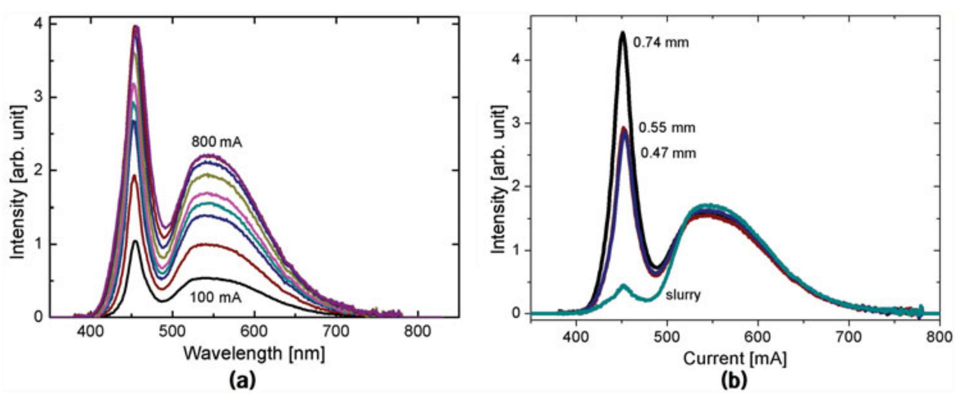

Figure 3. (a) Current dependent emission spectra of the 0.55-mm sample. (b) Change in the emission spectra at 350 mA as a function of the separation distance. The emission spectrum of the slurry sample is also shown for comparison.

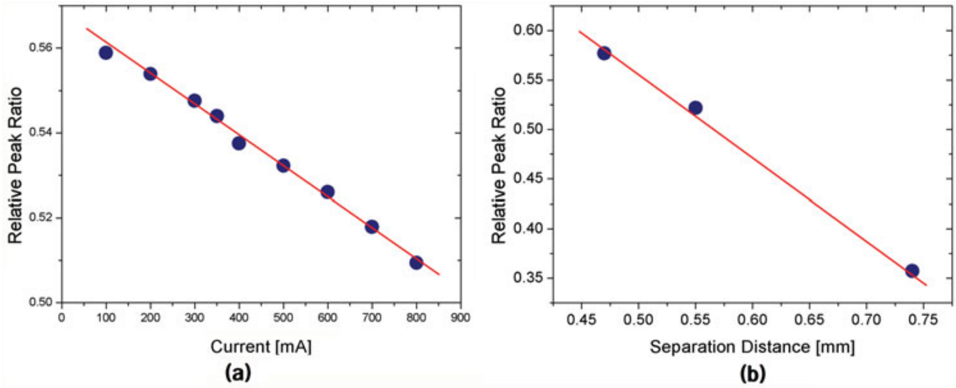

Figure 4. (a) Ratio of the intensity of the yellow peak to blue peak for the 0.55-mm sample at 350 mA. (b) Ratio of the intensity of the yellow peak to blue peak at 350 mA is shown as a function of the separation distance. The lines in the figure are used as a guide for the eyes.

increased with increasing current (Fig. 3(a)). This appears to contradict the result that the luminous efficiency decreases with increasing current, as shown in Figure 2. However, this is reasonable considering that the luminous efficiency is determined by multiplying the intensity with the color matching function, and dividing the result with the input power (input voltage times input current).

Figure 4 shows the ratio of the intensity of the yellow peak to blue peak in the spectra. This ratio decreased linearly with increasing current (Fig. 4(a)). Figure 4(b) shows that with increasing separation distance, more blue light passes through the annular gaps without being converted to yellow light. Consequently, the relative peak ratio decreases with increasing separation distance.

Figure 5 shows the correlated color temperature (CCT) of the samples as a function of the current. The CCT for the 0.47- and 0.55-mm samples showed only a slight current dependence, whereas the CCT for the 0.74-mm sample shows a relatively strong current dependence. Figure 5 shows that the CCT increases with increasing separation distance. As shown in Fig. 4(b), with increasing distance, more blue light from the chip pass through the annular spacing without being converted to yellow light. This blue light enhances the CCT.

The CCT of natural sunlight is in the range of 5,000-6,000 K, whereas the CCTs for the 0.47- , 0.55- and 0.74-mm samples were 7,500, 8,200 K and 11,000 K, respectively. Therefore, CCTs for the open remote samples were larger than that of natural sunlight. The color of light emitted from the open remote samples was bluish white. In particular, in the 0.74-mm sample, more blue light from the chip passes through the annular gaps without being converted to yellow light, which resulted in the largest CCT for this sample. The CCT for the slurry sample was much smaller (∼4,400 K, yellowish white) than that of the open remote samples.

Figure 6 shows the current dependent color rendering index (CRI) of the samples. The CRI is a measure of the degree of color shift of an object when illuminated by a light source (in this case, WLED) compared to that when illuminated by a standard light source of the comparable color temperature. In determining the CRI, A 2856K light (incandescent, Rs 100V/60W) was used as the standard light source. Figure 6 shows that the CRI for the samples has a slight current dependence. The CRI for the open remote samples ranged from

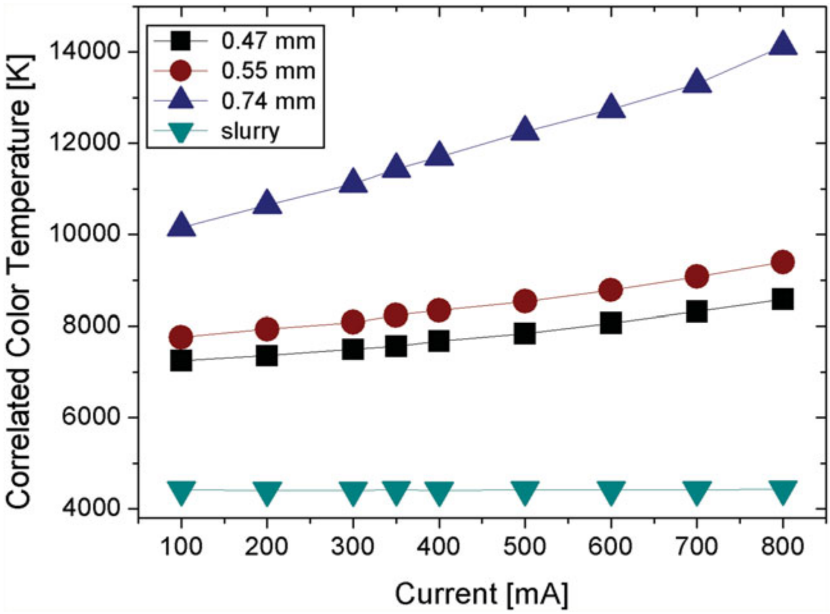

Figure 5. Current dependent correlated color temperature (CCT) for the samples. The CCT for the 0.47- and 0.55-mm samples showed a slight current dependence, whereas the CCT for the 0.74-mm sample showed a larger current dependence. The CCT increased with increasing separation distance.

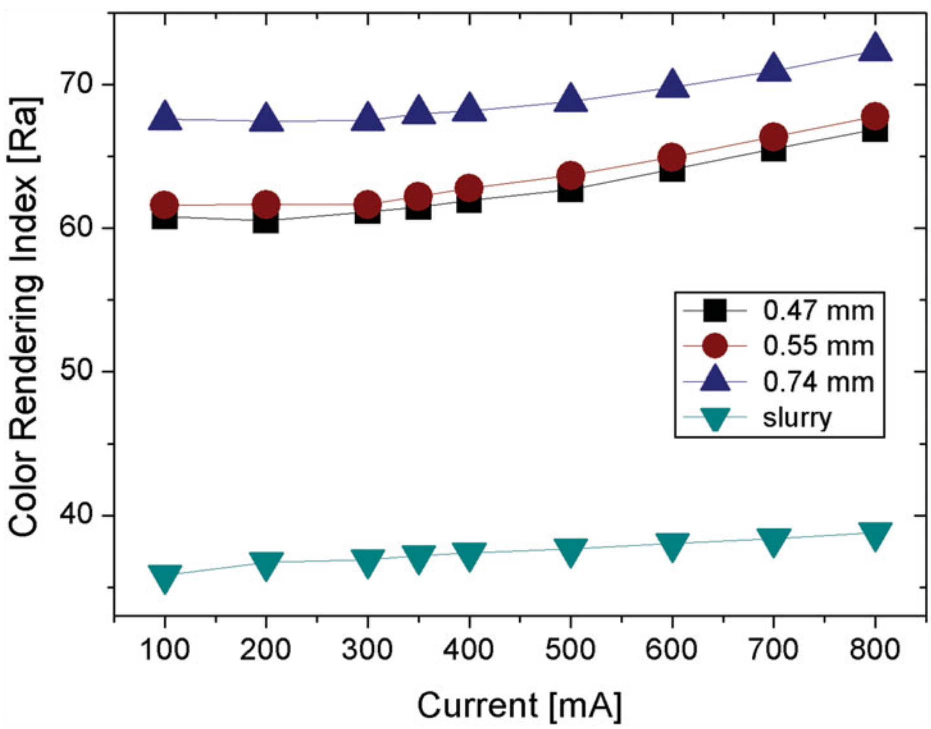

Figure 6. Current dependent color rendering index (CRI) of the samples. The CRI for all samples has a slight current dependence.

Table 1. Phosphor amount, color coordinates, CCT, CRI, and luminous efficiency at 350 mA

Sample	Phosphor amount [mg]	Color coordinates (x, y)	CCT [K]	CRI [Ra]	Luminous efficiency [lm/W]
0.47 mm	0.64	(0.29, 0.32)	7,567	61	61.20
0.55 mm	0.64	(0.29, 0.31)	8,235	62	62.25
0.74 mm	0.64	(0.27, 0.28)	11,436	68	53.03
Slurry	2.64	(0.38, 0.49)	4,416	37	65.12

60 to 75 Ra, whereas it was relatively low for the slurry sample (~37 Ra). Nevertheless, the CRI for the light source involving WLEDs is inappropriate for estimating the color rendering [22]. The CIE Technical Report (177:2007) states that the CIE CRI is generally not applicable to predict the color rendering rank order of a set of light sources when white LED light sources are involved in this set [22,23].

Table 1 summarizes the phosphor amount, color coordinates, CCT, CRI, and luminous efficiency at 350 mA. The luminous efficiency of the 0.55-mm sample was comparable to that of the slurry sample, even though the amount of phosphor used for this sample was less than 25% of the amount used in the slurry sample.

Conclusions

Phosphor-converted WLEDs were fabricated using the open remote method. The separation distance between the LED chip and phosphor layer was varied from 0.47 to 0.74 mm to determine the effects of the separation distance on the properties of the WLEDs. The luminous efficiency of the 0.55-mm sample showed the highest luminous efficiency. The ratio of the luminous efficiency of this sample to that of the slurry sample at 350 mA was 0.96, even though the quantity of phosphor used was less than 25% of the amount used in the slurry sample. The correlated color temperature for the open remote WLEDs was observed in the range of 7,500-11,000K, which is bluish white. This indicated that some of the light emitted from LED chip passed through the annular gaps between the phosphor layer and reflector cup without being converted.

Acknowledgments

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