Optical Analysis of Color Distribution in White LEDs With Various Packaging Methods

Zongyuan Liu, Sheng Liu, *Member, IEEE*, Kai Wang, and Xiaobing Luo, *Member, IEEE*

***Abstract*—Uniform color distribution is essential for the packaging of light emitting diodes (LEDs). The Monte Carlo ray tracing method is applied to analyze the color distribution of white LEDs. Five packaging methods are investigated and the location of phosphor layer is varied. Results reveal that the packaging method is the primary factor affecting the color distribution and a nonreflector packaging method presents better color uniformity. The location of phosphor has a small impact on the color uniformity but remote location, if too far, can reduce the uniformity significantly. The reduction of color uniformity may exceed 88%.**

***Index Terms*—Color distribution, light-emitting diodes (LEDs), packaging, phosphor.**

I. Introduction

AS AN attractive illumination source, white light-emitting diodes (LEDs) have developed rapidly in recent years [1], [2]. To compete with traditional lamps, white LEDs should provide high luminous efficiency to more than 150 lm/W in 2012 by innovations in epitaxy growth, chip design, and packaging [3]. However, color uniformity is also important in the efforts to achieve high quality white LEDs. Nowadays, most white LEDs are phosphor converted LEDs. It is perceived that phosphor and packaging structure may influence the color distribution significantly. Sommer *et al.* has revealed that the thickness, size, and concentration of phosphor can affect the color uniformity [4]. A nonoptimized packaging method will induce unexpected phenomenon such as yellow ring. This can be found in some commercial products as shown in Fig. 1. Color inhomogeneity will influence the actual illumination effects and results in discomfort for eyes.

Sommer *et al.* mainly discussed the case that phosphor was directly coated on chip. There was no lens and reflector in the simulation. Researchers and corporations proposed another packaging method that fabricated the phosphor layer in remote location [5]. Patents were also filed to fabricate the phosphor layer with convex shape [6]. However, the previous studies were all focused on the improvement of light extraction, whereas the color distribution was not considered. Therefore, the color distribution in various packaging methods with different phosphor locations will be discussed in this letter.

Fig. 1. Illustration of yellow ring in LED modules.

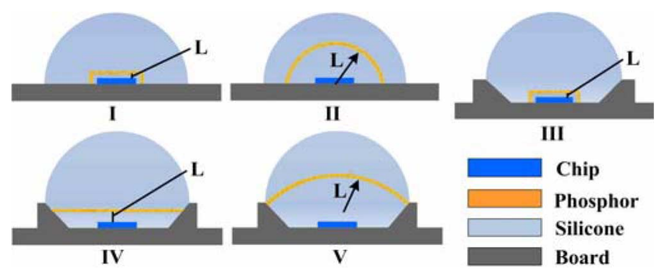

Fig. 2. Five packaging methods for the analysis. L represents the location. In Methods I, III, and IV, L is the gap between phosphor layer and chip. In Methods II and V, L is the radius of phosphor layer.

TABLE I
Variation of Location in Five Packaging Methods

Methods	I, III	II	IV	V
Location (mm)	0-0.1	0.8-3.9	0.1-1.9	4.25-10

II. Models, Analysis, and Discussion

Five packaging methods are discussed as depicted in Fig. 2. The first and third methods conformally coat the phosphor to replicate the shape of the chip. The second and fifth methods fabricate the phosphor layer with convex shape, whereas the phosphor layer is plane shaped with remote location in the fourth method. The location is varied as shown in Table I.

The baseline diameter of the reflector is 3 mm, and the height is 2 mm. To minimize the effects of lens' size on light propagation, the radius of a lens in all types is large enough to be 4 mm. Optical parameters of the surface on board and reflector are 85% perfect reflection, 5% scattering, and 10% absorption.

The chip is lifted-off from sapphire and bonded on Si. The top surface of Si is coated with Ag to reflect light rays. The size of the chip is 1×1 mm. The thickness of each layer is N–GaN 4 μm, MQW 100 nm, P–GaN 300 nm, and Si 100 μm. Blue light (465 nm) is isotropically emitted from the top and bottom

Manuscript received August 11, 2008; revised September 06, 2008. First published October 31, 2008; current version published December 12, 2008. This work was supported in part by the Nature Science Foundation of China (NSFC) Key Project under Grant 50835005.

Z. Liu and K. Wang are with the Huazhong University of Science and Technology, Wuhan 430074, China.

S. Liu is with the School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: victor_liu63@126.com).

X. Luo is with the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2005998

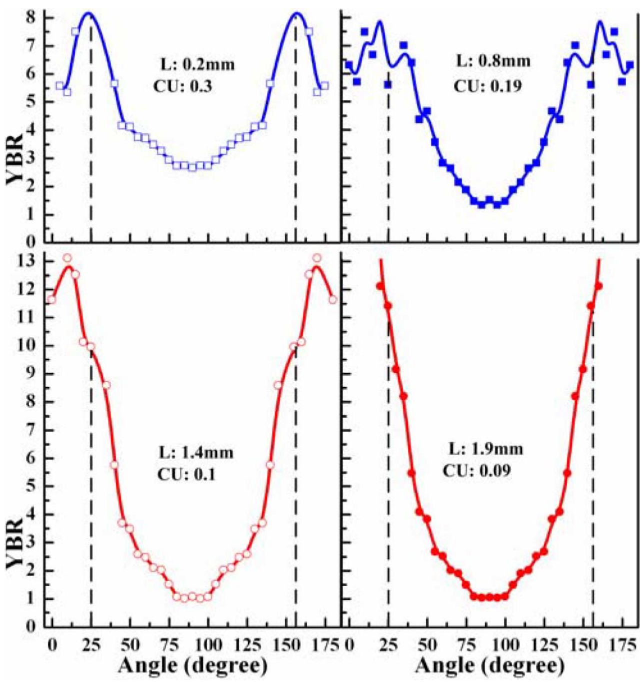

Fig. 3. YBR curve and color uniformity in Method IV.

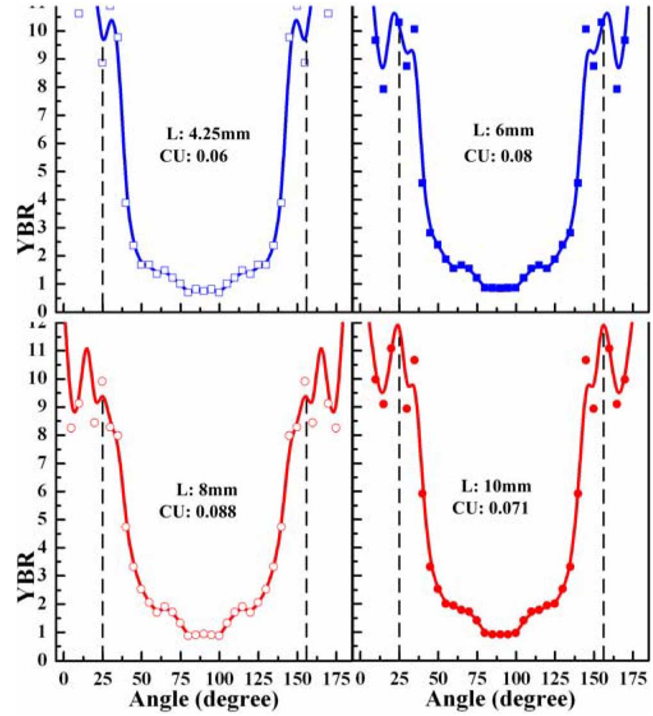

Fig. 4. YBR curve and color uniformity in Method V.

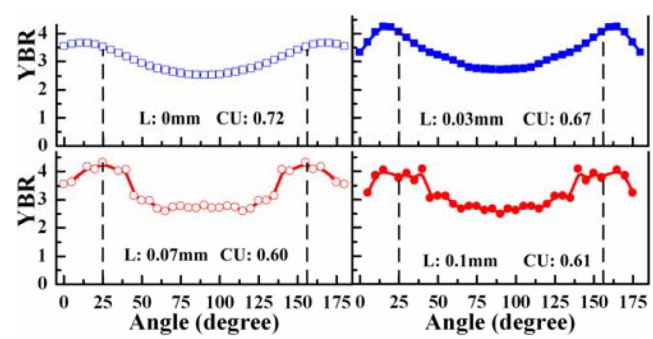

Fig. 5. YBR curve and color uniformity in Method I. The first specific case directly coats the phosphor on the chip.

surfaces of MQW with uniform distribution. The absorption coefficient for N–GaN, MQW, and P–GaN is 8 mm^{-1}.

The phosphor layer is a bulk scattering material, which is fabricated by mixing the transparent silicone with phosphor particles. The thickness of the phosphor layer is 0.1 mm. Analysis considers the phosphor particle as a sphere with average radius of 7.5 μm. Based on Mie scattering model, the absorption and scattering coefficient is 8 and 11.85 mm^{-1} for blue light and 0 and 16.25 mm^{-1} for yellow light. The parameters have been verified by comparing the simulation data with experimental results [7].

Blue light (465 nm) and yellow light (555 nm) are separately calculated with a Monte Carlo ray tracing method. The phosphor layer first collects the totally absorbed blue light and then re-emits the yellow light from top and bottom surfaces. Experiments show that the radiation pattern of yellow light is similar to Lambertian when blue light passes the phosphor layer. Optical power from 0° to 180° in the space is collected to analyze the color distribution. Test results reveal that yellow–blue ratio (YBR) can illustrate the variation of correlated color temperature (CCT). In those LEDs tested, YBR is the ratio of optical power in 490–780 nm to optical power in 380–490 nm. However, in the analysis, YBR is the ratio of yellow light to blue light. The color uniformity (CU) is the ratio of minimum YBR to maximum YBR in the range of 25° to 155°.

Each packaging method considers four specific cases with different locations. Simulation data are displayed in the following figures. Longitudinal axes for all cases are set with the same unit length to easily compare the fluctuations of curves.

It can be found that YBR at side angles are normally larger than that at central angles, especially in Methods IV and V, as shown in Figs. 3 and 4. This indicates that there is a yellow ring around the central white zone. The difference cannot be distinguished if the change of YBR from center to side is small and smooth such as in Fig. 5 of Method I.

Color uniformity is decreased with the increase of location in most methods. However, the influences of packaging methods are more significant than that of location. The variations of color uniformity in each method are 16.67%, 9.8%, 12.5%, 70%, and 31.82% by location, respectively. The average color uniformity is 0.65, 0.67, 0.45, 0.17, and 0.075 in each method. In Figs. 6 and 4, the variation of color uniformity between Methods II and V exceeds 88%. Therefore, the packaging method is most critical to determine the color uniformity, while location plays the secondary role. The tendencies of YBR curves also prove this viewpoint. The tendencies are similar with the variation of location, whereas there are obvious differences for YBR curves in various packaging methods.

Methods I and II present higher color uniformity than other methods with a reflector. This is because that reflector can converge the side rays to central angle especially for blue light. More blue light is converged to central angles, then less blue

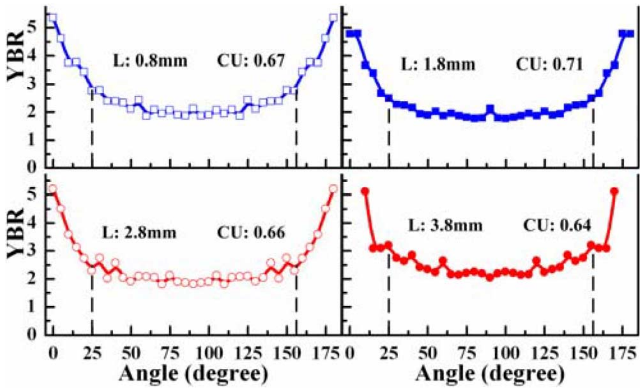

Fig. 6. YBR curve and color uniformity in Method II.

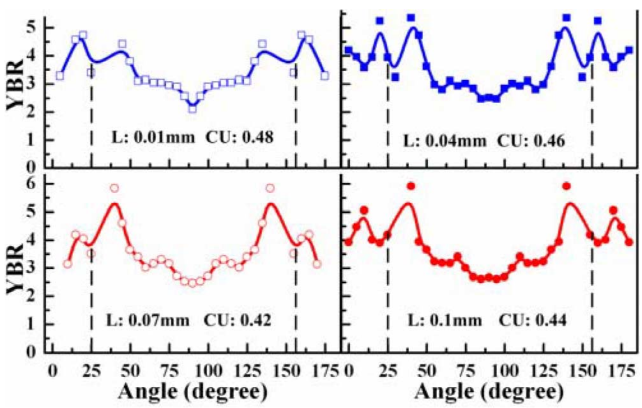

Fig. 7. YBR curve and color uniformity in Method III.

light can emit out at side angles. The increase of location can enhance this phenomenon. For example, YBR is reduced from 2.5 to near 1 at a central angle in Fig. 3.

However, the variation of color uniformity in Methods III and V is not as significant as that in Method IV. In Method III, as shown in Fig. 7, the variation in location is small compared to the size of the reflector, which cannot efficiently affect the light propagation. In Method V, the location is too remote. It can be found that the variation in color uniformity is small when the location is larger than 1.4 mm in Method IV. Therefore, when the location is remote enough, the change of location plays a minor role in color distribution.

The initial color uniformity of Method II is lower than that of Method I; however, the average color uniformity is higher. This is due to the fact that phosphor layer is hemispherical. The radiation pattern of blue light emitted out of the chip is similar to Lambertian. Blue light can almost vertically enter the phosphor layer and improve the extraction of side rays. The increase of location cannot affect light propagation fundamentally. Therefore, Method II presents more stable color distribution.

The reason why the initial color distribution of Method I is more uniform than other methods is that the chip and phosphor are located in the center of the lens. The radiation patterns of blue light out of the chip and yellow light from the phosphor layer are both similar to Lambertian. Since the lens' size is significantly larger than chip and phosphor layer, they can be treated as small sources. Therefore, most of the rays could directly emit out without being internally reflected. This induces that the initial color uniformity is high. However, with the increase of location, enlarged dimension and height of the phosphor layer will gradually disorder the directions of blue light and the phosphor layer cannot be seen as a small source.

Actually, to obtain high color uniformity, packaging elements should make the blue light and yellow light have a similar radiation pattern. That means the packaging elements such as lens and reflector should affect the propagation of blue light and yellow light simultaneously. This is the fundamental reason why Methods IV and V have so low color uniformity. The reflector affects the propagation of most blue light rays and converges them to center, whereas only part of the back scattered yellow light is affected by the reflector. This induces that the radiation pattern of blue light and yellow light is obviously different after passing through the phosphor layer. Therefore, the color distribution is significantly nonuniform.

III. Conclusion

Analysis confirms the generation of a yellow ring and reveals that the packaging method is the primary factor affecting the color distribution. Remote phosphor location, if too far, does not benefit the color uniformity. Packaging the chip without a reflector and coating the phosphor layer close to the chip can improve the color uniformity. A phosphor layer with spherical shape presents more stable color distribution when the location is varied.

References

[1] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and future of high-power light-emitting diodes for solid-state lighting," *J. Display Technol.*, vol. 3, pp. 160–175, 2007.

[2] R. D. Dupuis and M. R. Krames, "History, development, and applications of high-brightness visible light-emitting diodes," *J. Lightw. Technol.*, vol. 26, no. 7, pp. 1154–1171, May 1, 2008.

[3] Light Emitting Diodes (LEDs) for General Iillumination, an OIDA Technology Roadmap Update 2002 OIDA, 2002 [Online]. Available: http://lighting.sandia.gov/lighting-docs/OIDA_SSL_LED_Roadmap_Full.pdf

[4] C. Sommer, F. P. Wenzl, P. Hartmann, P. Pachler, M. Schweighart, and G. Leising, "Tailoring of the color conversion elements in phosphor-converted high-power LEDs by optical simulations," *IEEE Photon. Technol. Lett.*, vol. 20, no. 5, pp. 739–741, Mar. 1, 2008.

[5] H. Luo, J. K. Kim, E. F. Schubert, J. Cho, C. Sone, and Y. Park, "Analysis of high-power packages for phosphor-based white-light- emitting diodes," *Appl. Phys. Lett.*, vol. 86, pp. 243505–3, 2005.

[6] G. Muller, R. Muller, G. Basin, R. S. West, P. S. Martin, T. S. Lim, and S. Eberle, LED with Phosphor Tile and Overmolded Phosphor in Lens (Patent Style) 2008, U.S. Patent 20 080 048 200.

[7] Y. Zhu, N. Narendran, and Y. Gu, "Investigation of the optical properties of YAG:Ce phosphor," in *Proc. Sixth Int. Conf. Solid State Lighting*, San Diego, CA, 2006, pp. 63370S–8.