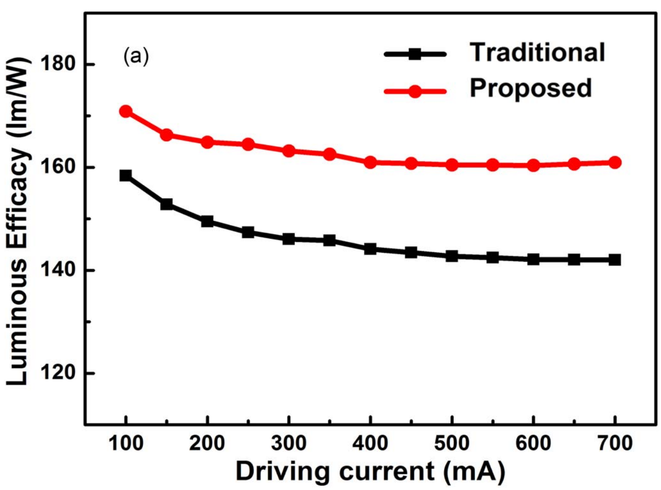
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Improvements on Remote Diffuser-Phosphor-Packaged Light-Emitting Diode Systems

Volume 6, Number 2, April 2014

Hua Xiao
Yi-Jun Lu
Tien-Mo Shih
Li-Hong Zhu
Si-Qi Lin
Patrick J. Pagni
Zhong Chen



DOI: 10.1109/JPHOT.2013.2293612

IEEE photonics SOCIETY
IEEE

Improvements on Remote Diffuser-Phosphor-Packaged Light-Emitting Diode Systems

Hua Xiao,[1] Yi-Jun Lu,[1] Tien-Mo Shih,[2,3,4] Li-Hong Zhu,[1] Si-Qi Lin,[1] Patrick J. Pagni,[5] and Zhong Chen[1]

[1]Department of Electronic Science, Fujian Engineering Research Center for Solid-State Lighting, State Key Laboratory for Physical Chemistry of Solid Surfaces, Xiamen University, Xiamen 361005, China
[2]Department of Physics, Xiamen University, Xiamen 361005, China
[3]OAEE, College of Engineering, University of Maryland, College Park, MD 20742 USA
[4]Institute for Complex Adaptive Matter, University of California, Davis, CA 95616 USA
[5]Department of Mechanical Engineering, University of California, Berkeley, CA 94720-1740 USA

DOI: 10.1109/JPHOT.2013.2293612

Manuscript received November 13, 2013; revised November 24, 2013; accepted November 26, 2013. Date of publication December 3, 2013; date of current version March 3, 2014. This work was supported in part by the Institute of Complex Adaptive Matters under Grant ICAM-UCD13-08291, by the 863 Project of China under Grant 2013AA03A107, by the Major Science and Technology Project between University–Industry Cooperation in Fujian Province under Grants 2011H6025 and 2013H6024, by the National Natural Science Foundation of China under Grant 11104230, and by the Key Project of Fujian Province under Grant 2012H0039. Corresponding author: Z. Chen and T.-M. Shih (e-mail: chenz@xmu.edu.cn; tmshih@xmu.edu.cn).

Abstract: By modifying traditional remote phosphor-diffuser-packaged light-emitting diode systems, we have managed to increase the luminous efficacy from 145.7 to 162.3 lm/W. One mechanism responsible for this achievement is associated with randomizing the directions of light beams transmitting through an interior diffuser, whose position is optimized based on an overall merit. The other mechanism is identified as the gradual attenuation of the undesirable blue-ring image along the distance from the diffuser toward the phosphor base. The identification of these two mechanisms is verified by luminous efficacy measurements, 3-D image plots, and combined Monte Carlo algorithm ray tracing simulation results. In addition, merits related to correlated color temperatures and issues pertaining to costs are briefly discussed.

Index Terms: Light-emitting diodes (LED), phosphor, luminous efficacy (LE), correlated color temperature (CCT).

1. Introduction

In recent years, phosphor-conversion LEDs (pc-LEDs) have played a leading role in the area of solid-state white lighting, which has attracted considerable attention as the next-generation lighting source to replace traditional ones, due to prominent advantages, such as high brightness, high efficiency, long lifetime, and environmental harmlessness [1]–[5]. In general, III-Nitride blue LED sources is utilized to stimulate down-conversion phosphor, which is directly coated on LED chips, to transform a mixture of blue and yellow light into white light [6]–[12]. In the late 1990s, the concept of remote phosphor-packaged LEDs started to emerge [13]. It was proposed primarily for the purpose

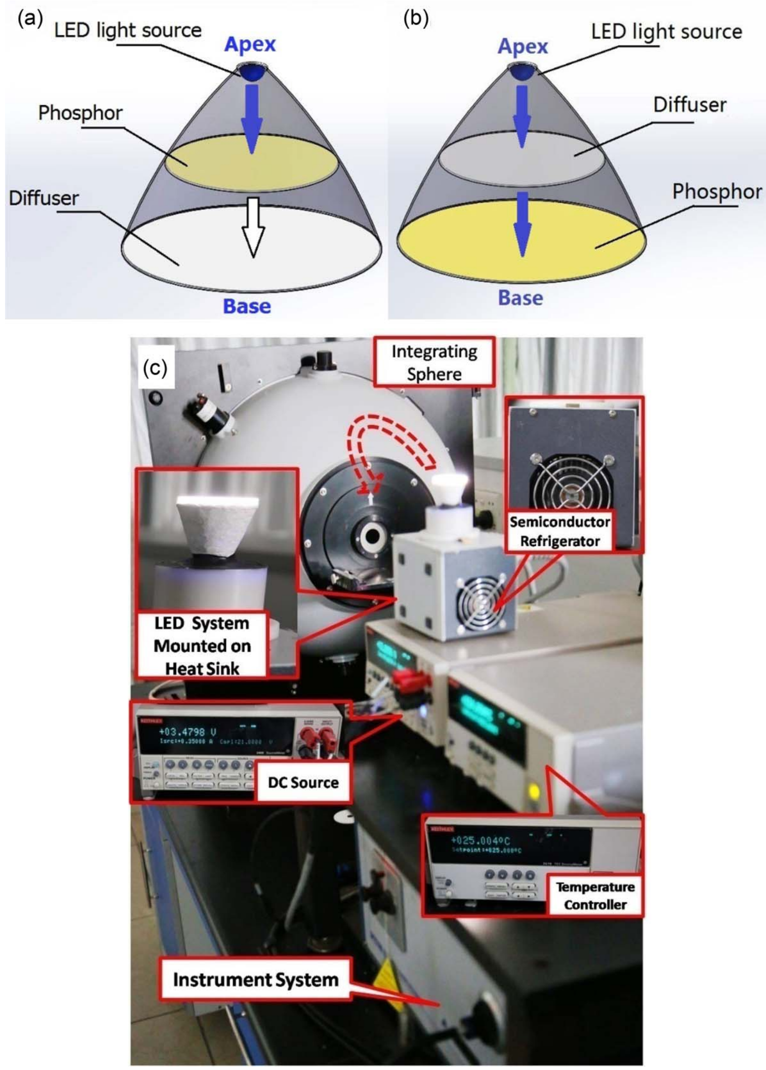


Fig. 1. Experimental configurations, apparatus, and samples. (a) The traditional system consists of the reflector, LED light source, phosphor, and diffuser. (b) The proposed system also consists of the same four components, but with the phosphor as the base and the diffuser as the interior piece. (c)The apparatus consists of heat sink, integrating sphere, instrument system, DC source meter, temperature-controlled device, and samples.

of reducing (a) the thermal energy generated from LED chips [14]–[16], and (b) the absorption of the light backscattered from the phosphor into chips [17]–[19]. After this proposal, immense research followed in related areas. Most of these studies have focused on phosphor characteristics without diffusers being installed, including LED's efficiencies [20]–[26], luminous fluxes [27], [28], chromaticity stability [29]–[33], and correlated color temperature (CCT) distributions [34]–[36], depending on varying phosphor shapes, thicknesses, concentrations, and positions. Later, the need of high-quality lighting conditions spontaneously prompted the insertion of additional diffusers [37]–[39]. These traditional systems, which are widely used today in the LED industry, share a common characteristic that the light first transmits through the phosphor, and then arrives at the diffuser base, as shown in Fig. 1(a). Within such a configuration, the emerging light from the phosphor is insufficiently diffusive, thus leading to non-uniformity in the white light at the diffuser base. In this letter, we have deviated from the tradition by allowing the light to transmit through the diffuser ahead of the phosphor base, as schematically depicted in Fig. 1(b). The blue-light beams have become

TABLE 1

Comparison of η for various positions of the interior phosphor or diffuser for two systems. Here, *D* denotes the diameter of the interior phosphor or diffuser, with its value proportional to the normal distance measured from the apex

	Overall merit (η)				
	D=13	D=18	D=22	D=28	D=32
Traditional	0.415	0.436	0.476	0.492	0.465
Proposed	0.431	0.483	0.524	0.519	0.513

diffusive even prior to the impingement on the phosphor base, effectively increasing the luminous efficacy (LE).

2. Experimental Details

The proposed LED system consists of four major components: (a) a cone-shaped reflector (manufactured by CREE Co.), with a white-painted outer surface for having low absorptivities, (b) a one watt blue LED light source mounted at the apex of the reflector, (c) a 2 mm-thick polycarbonate diffuser with a highly diffusive index, and (d) a YAG:Ce^{3+} phosphor-spread polycarbonate base, with the coated surface facing inward for protection purposes. The height of the reflector equals 27 mm; the diameter of the base 33 mm; the diameter of the apex 4 mm. In Fig. 1(c), this system is situated on a temperature-controlled heat sink maintained at 25 °C ± 0.5 °C. The light source is driven with a DC current ranging from 100 mA to 700 mA, supplied by a Keithley-2400 Source Meter. Finally, the optical output is collected by a 500 mm-diameter integrating sphere (ISP-500), which is connected to Instrument System (Spectro-320) that provides measurements of the optical power, CCT, and luminance.

To describe the section of results and discussion clearly, we are obligated to introduce an overall merit, defined as

$$\eta = \frac{\xi_1 LE^* + \xi_2 U^* + \xi_3 CCT^*}{\xi_1 + \xi_3 + \xi_3} \tag{1}$$

where $LE^* = (LE - LE_m)/(LE_M - LE_m)$, $U^* = (U - U_m)/(U_M - U_m)$, and $CCT^* = (CCT_M - CCT)/(CCT_M - CCT_m)$.

Subscripts "M" and "m" stand for "maximum" and "minimum". It is worth noting that $CCT^* = 1$ when CCT reaches the maximum. The term, LE known as luminous efficacy, denotes the ratio of the emitting optical power of the spectra perceived by human eyes ϕ_v to the total emitting optical power P_i, defined as

$$LE = \frac{\phi_v}{P_i} = \frac{K_m \int_{380}^{780} P(\lambda) V(\lambda)\, d\lambda}{\int_{380}^{780} P(\lambda)\, d\lambda} \tag{2}$$

where $P(\lambda)$ is the spectral power distribution of the white light; $V(\lambda)$ the CIE (Commission Internationale L'Eclairage) photonic eye sensitivity function, and $K_m = 683$ lm/W; U denotes

$$U = \frac{\text{Luminance}_m}{\text{Luminance}_M} \times 100\%. \tag{3}$$

In Eq. (1), ξ_1, ξ_2 and ξ_3, are weighting coefficients estimated by users at their discretion in terms of the degree of significance. Here, we select $\xi_1 = 1.2$, $\xi_2 = 1.0$ and $\xi_3 = 0.8$, along with $LE_M = 254$ lm/W [40], $LE_m = 0$ lm/W, $U_M = 1$, $U_m = 0$, $CCT_M = 25\,000$ K [41], and $CCT_m = 1000$ K [42].

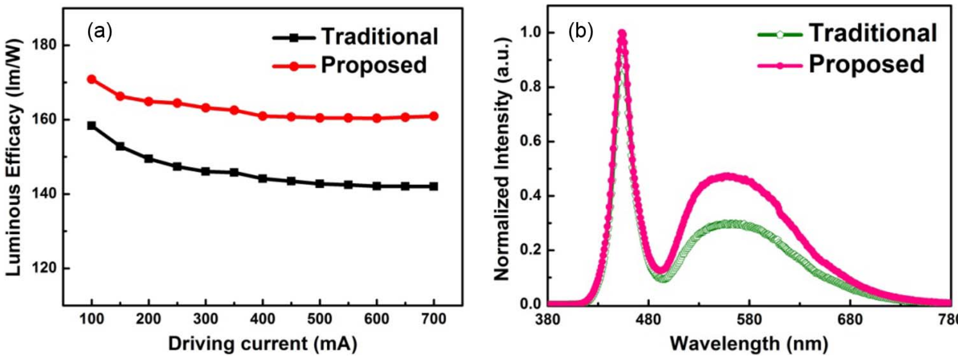


Fig. 2. (a) Luminous efficacy as a function of driving current for both traditional and proposed systems. (b) Normalized intensity as a function of wavelength for both systems.

According to the literature survey, *LE* has been found at least 20% more prominent than U, which is subsequently 25% more prominent than CCT. Maximums and minimums are based on reasonable values known in the LED industry. In our study, the optimal locations of the phosphor and the diffuser are determined by maximizing respective η values. Table 1 lists values of η for both systems at various locations of the interior phosphor or diffuser. All results presented in this Letter are based on $\eta = 0.492$ for the traditional system and $\eta = 0.524$ for the proposed counterpart.

3. Results and Discussion

Fig. 2(a) depicts the *LE* value versus the driving current for both traditional and proposed systems. It is observed that *LE* of the proposed system is higher for all currents within the range of [100 mA, 700 mA]. For reliability confirmation, we used several LED light sources that are manufactured by different companies, and obtained similar results, which were thus omitted for clarity. In particular, we further retrieve the data at the driving current of 350 mA and plot normalized intensities versus λ within [380 nm, 780 nm] for both systems in Fig. 2(b). As expected, a conspicuous hump exhibited in the red curve appears in the yellow region for the proposed system. The pronounced elevation from 0.29 to 0.47 at peaks convincingly explains the increase of *LE* shown in Fig. 2(a). Mechanisms for this increase are identified and described in detail below.

Fig. 3 presents photos, 3-D images, and simulation results related to the undesirable presence of the ring. In Fig. 3(a) and (b), ring images on the interior phosphor and the interior diffuser are shown, respectively, for traditional and proposed systems. The color of the image in Fig. 3(a) is white because the blue light has been down converted. Although the presence of ring-like images can readily be observed, and can imply undesirable non-uniformity in the luminance, this phenomenon seems to have rarely been studied for unknown reasons. In the present study, however, we believe that it closely and inevitably affects the *LE* values. To quantify Fig. 3(a) and (b), we depict a 3-D plot with RGB conversion in Fig. 3(c) and (d).

Fig. 3(e) shows the spatial distribution of the light beams emerging from the reflector in the absence of an interior piece, using the combination of the Monte Carlo algorithm and the ray tracing Method [43], [44]. This combination approximates the solution to the integral equation, given as

$$B_O(\overline{x}, \omega_o) = B_e(\overline{x}, \omega_o) + \int_{\Omega} f_r(\overline{x}, \omega_i, \omega_o) B_i(\overline{x}, \omega_i)(\omega_i \cdot \overline{n})\, d\omega_i \tag{4}$$

where subscripts "*e*" and "*i*" denote "emitting" and "incoming". The subscript "*o*" denotes "outgoing", which is the sum of incoming beams and reflected incoming beams. The symbol, $\bar{x}$, is the location in the space where the outgoing light beam is perceived; ω the directional solid angle; Ω the hemispherical solid angle; f_r the bidirectional reflectance distribution function; *B* the

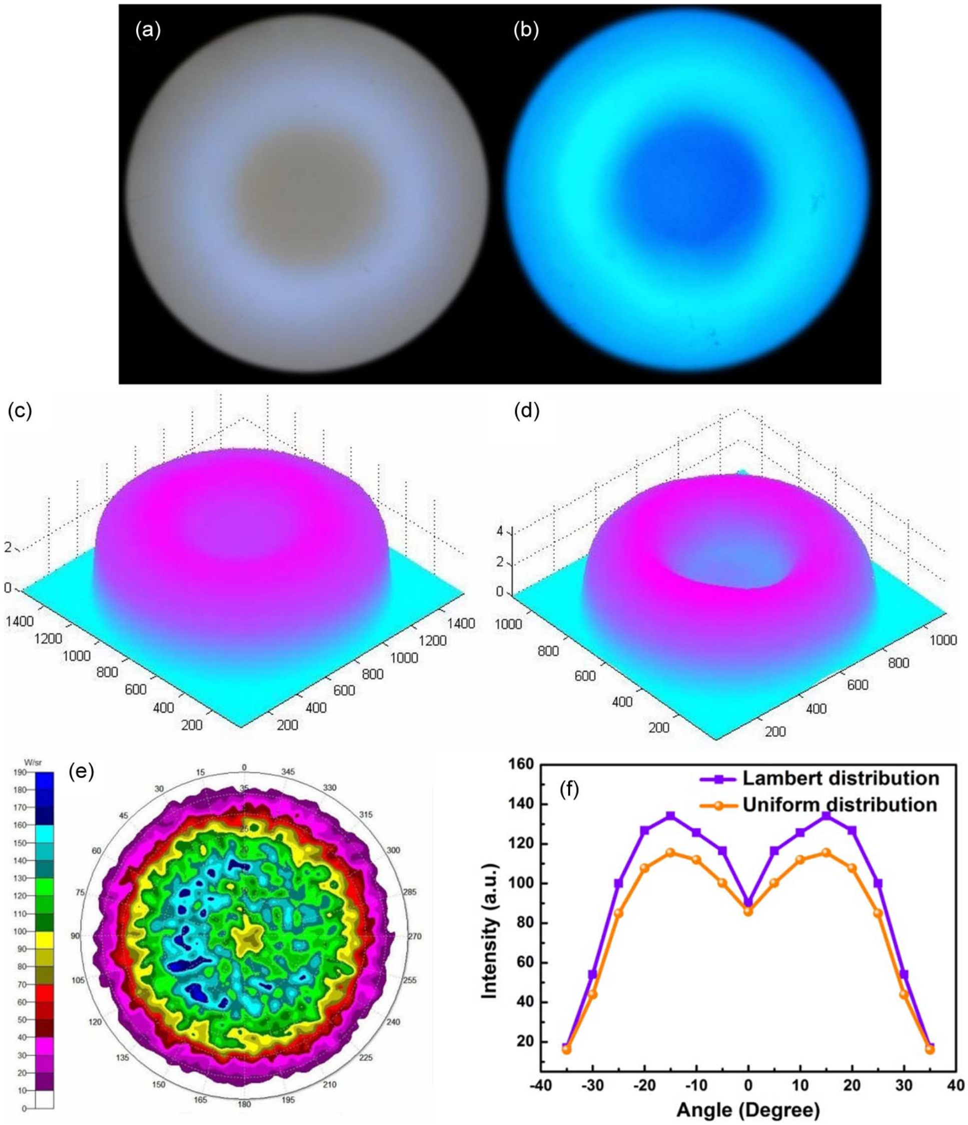


Fig. 3. (a) Photo image of the interior phosphor for the traditional system, taken under 50 mA Currents stronger than 100 mA render the clarity of images to drastically decrease, and hence are not used. (b) The counterpart of (a) for the proposed system. (c) A 3-D image of luminance corresponding to (a). (d) A 3-D image of luminance corresponding to (b). (e) The graphical result of the combination of Monte Carlo algorithm and Ray Tracing Method. (f) Angular-dependent optical power for both uniform and Lambert distributions of light beams emitted by the light source.

radiance; $\bar{n}$, the normal direction to the hemispherical surface. The simulation results can be validated by

$$\beta_{\text{outgoing}} = 2\beta_{\text{tangent}} - \beta_{\text{incoming}} \tag{5}$$

where β denotes the slope of a straight line. Equation (5) dictated by the fact that the sum of the slope of the incoming ray, which impinges on the inner circumferential mirror-like surface of the reflector, and the slope of the outgoing ray must equal twice that of the tangent to the surface at the ray incident position. The simulation input data, including a Lambert-distribution light source, are taken to be the same as those used in the experiment.

Via simulations, we discovered that the formation of the ring was caused by both mechanisms of (a) Lambert distribution and (b) light reflections from the reflector surface. In Fig. 3(f), two curves of

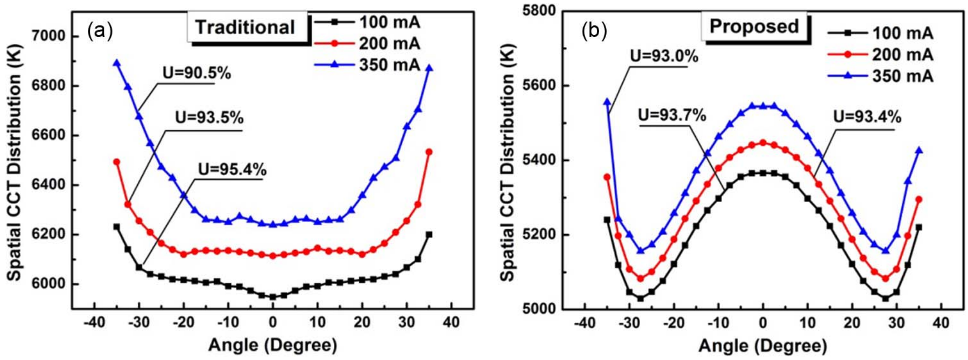


Fig. 4. Spatial CCT distributions and uniformities of (a) traditional and (b) proposed systems ranging from -35° to 35°.

light luminance versus the spanned angle are shown. The lower curve represents the hypothetical uniform angular distribution of the optical power, whereas the upper one indicates the realistic output with Lambert distribution. The deviation between the two curves clearly suggests that the undesirable ring can be formed merely by light reflections of the reflector, and that mechanism (b) constitutes the primary cause. Here, let us mention in passing that it is difficult for such a deviation to be detected by experiments.

In the traditional model, the conversion efficiency varies along the radial direction on the interior phosphor due to the presence of the ring. Namely, in the zone where the blue light intensifies (inside the concentric area of the ring), only a portion of the light is down converted to yellow, whereas in the zone where the light under-shines, part of the phosphor particles miss the bombardment by the incoming photons, and lose chances to interact with them. The existence of both excessive photons and insufficient photons results in non-uniform magnitudes of emerging white light. Such non-uniformity persists as light beams leave the phosphor and arrive at the diffuser base, even though the magnitude of the optical flux decreases. Eventually, the overall conversion efficiency of the phosphor is lowered.

In the proposed model, the ring also appears on the diffuser. Fortunately, its presence does not reduce *LE* values as much. Due to the mechanism that the blue light beams diffuse downward and transmit through the diffuser, the emerging rays tend to diffuse. Afterwards, they continue to travel toward the phosphor base in random directions, with their magnitudes being inversely proportional to the square of the traveling distance D, because the total emitting optical power (in *watts*), $E \approx AJ$, is conserved, where $A \approx 4\pi D^2$ and J is the optical flux (in $\mathrm{W/m^2}$. Therefore, attenuation combined with diffusion-induced interferences results in the disappearance of the ring and the uniformity of the optical fluxes. Finally, ring-less blue light beams impinge upon the phosphor base, naturally elevating the conversion efficiency and thus *LE* values. In essence, it is to delay the blue-to-yellow conversion for photons until they arrive at the base, where the ring-less uniformity prevails.

In the LED industry, products of lower *CCT* values are generally deemed desirable in indoor lighting conditions. Fig. 4(a) and (b) show spatial *CCT* distributions for both systems. For the proposed system, we observe that *CCT* is lower by 694 K at zero-degree angle under 350 mA. In addition to *CCT* distributions, the uniformity, $U = (CCT_m/CCT_M) \times 100\%$, is another criterion for evaluating LED performances. In comparison of this criterion, the proposed system also enjoys higher values under various currents.

Finally, the issue pertaining to the cost of the phosphor deserves mentioning. The volume of the phosphor is the product of the area and the thickness. For the traditional systems, the thickness tends to become large if maintaining low *CCT* values is desired. For proposed systems, the area of the base is clearly larger than that of an interior counterpart. As a result, nonetheless, quantities of phosphor for both cases turn out to be similar.

4. Conclusion

Our findings indicate that placing the diffuser instead of the phosphor inside the reflector plays a promising role in elevating *LE* values from 145 lm/W to 162.3 lm/W under 350 mA driving current, and in decreasing CCT values by 694 K at zero-degree angle. The rough surfaces of the diffuser randomize directions of Lambert-distributed LED rays, allowing these rays to emerge from the diffuser in a diffusive manner. Furthermore, the position of the diffuser is optimized based on the maximum value of the overall merit introduced in the proposed study. Thereafter, these randomly-directional rays are attenuated along traveling distances and reflected by the reflector surface, such that interferences and overlapping of light waves occur on the phosphor base, rendering the ring image nearly disappearing. Contrarily, placing the phosphor inside the reflector, as done in traditional systems, may not allow the diffuser to fully realize its utility.

References

[1] C. W. Chow, C. H. Yeh, Y. F. Liu, and P. Y. Huang, "Mitigation of optical background noise in Light-Emitting Diode (LED) optical wireless communication systems," *IEEE Photon. J.*, vol. 5, no. 1, p. 7900307, Feb. 2013.
[2] H. Rao, W. Wang, X. L. Wan, L. S. Zhou, J. Y. Liao, D. Zhou, Q. L. Lei, and X. M. Wang, "An improved slurry method of self-adaptive phosphor coating for white pc-LED packaging," *J. Display Technol.*, vol. 9, no. 6, pp. 453–458, Jun. 2013.
[3] F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, H. T. Huang, and S. Chi, "Performance comparison of OFDM signal and CAP signal over high capacity RGB-LED-based WDM visible light communication," *IEEE Photon. J.*, vol. 5, no. 4, p. 7901507, Aug. 2013.
[4] Z. Q. Guo, T. M. Shih, Y. L. Gao, Y. J. Lu, L. H. Zhu, G. L. Chen, Y. Lin, J. H. Zhang, and Z. Chen, "Optimization studies of two-phosphor-coated white light-emitting diodes," *IEEE Photon. J.*, vol. 5, no. 2, p. 8200112, Apr. 2013.
[5] H. Jin, S. Jin, K. Yuan, and S. Cen, "Two-part gauss simulation of phosphor-coated LED," *IEEE Photon. J.*, vol. 5, no. 4, p. 1600110, Aug. 2013.
[6] H. Zhao, G. Liu, J. Zhang, J. D. Poplawsky, V. Dierolf, and N. Tansu, "Approaches for high internal quantum efficiency green InGaN light-emitting diodes with large overlap quantum wells," *Opt. Exp.*, vol. 19, no. S4, pp. A991–A1007, Jul. 2011.
[7] B. C. Krummacher, M. Mathai, F. So, and S. Choulis, "Light extraction from solution-based processable electrophosphorescent organic light-emitting diodes," *J. Display Technol.*, vol. 3, no. 2, pp. 200–210, Jun. 2007.
[8] Y.-K. Ee, X.-H. Li, J. Biser, W. Cao, H. M. Chan, R. P. Vinci, and N. Tansu, "Metal organic vapor phase epitaxy of III-nitride light-emitting diodes on nano-patterned AGOG sapphire substrate by abbreviate growth mode," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 4, pp. 1066–1072, Jul./Aug. 2009.
[9] Y.-K. Ee, X.-H. Li, J. Biser, W. Cao, H. M. Chan, R. P. Vinci, and N. Tansu, "Abbreviated MOVPE nucleation of III-nitride light-emitting diodes on nano-patterned sapphire," *J. Cryst. Growth*, vol. 312, no. 8, pp. 1311–1315, Apr. 2010.
[10] X. H. Li, P. F. Zhu, G. Y. Liu, J. Zhang, R. B. Song, Y. K. Ee, P. Kumnorkaew, J. F. Gilchrist, and N. Tansu, "Light extraction efficiency enhancement of III-Nitride light-emitting diodes by using 2-D close-packed TiO_2 microsphere arrays," *J. Display Technol.*, vol. 9, no. 5, pp. 324–332, May 2013.
[11] H. P. Zhao, G. Y. Liu, X. H. Li, R. A. Arif, G. S. Huang, J. D. Poplawsky, S. T. Penn, V. Dierolf, and N. Tansu, "Design and characteristics of staggered InGaN quantum-well light-emitting diodes in the green spectral regime," *IET Optoelectron.*, vol. 3, no. 6, pp. 283–295, Dec. 2009.
[12] H. P. Zhao, G. Y. Liu, J. Zhang, R. A. Arif, and N. Tansu, "Analysis of internal quantum efficiency and current injection efficiency in III-Nitride light-emitting diodes," *J. Display Technol.*, vol. 9, no. 4, pp. 212–225, Apr. 2013.
[13] H. Chen, "LED structure with ultraviolet-light emission chip and multilayered resins to generate various colored lights," U.S. Patent 5 962 971, Oct. 5, 1999.
[14] X. B. Luo, X. Fu, F. Chen, and H. Zheng, "Phosphor self-heating in phosphor converted light emitting diode packaging," *Int. J. Heat. Mass Transf.*, vol. 58, no. 1/2, pp. 276–281, Mar. 2013.
[15] H. C. Chen, K. J. Chen, C. C. Lin, C. H. Wang, C. C. Yeh, H. H. Tsai, M. H. Shih, and H. C. Kuo, "Improvement of lumen efficiency in white light-emitting diodes with air-gap embedded package," *Microelectron. Reliab.*, vol. 52, no. 5, pp. 933–936, May 2012.
[16] B. F. Fan, H. Wu, Y. Zhao, Y. L. Xiao, and G. Wang, "Study of phosphor thermal-isolated packaging technologies for high-power white light-emitting diodes," *IEEE Photon. Technol. Lett.*, vol. 19, no. 15, pp. 1121–1123, Aug. 2007.
[17] J. K. Kim, H. Luo, E. F. Schubert, J. Cho, C. Sone, and Y. Park, "Strongly enhanced phosphor efficiency in GaInN white light-emitting diodes using remote phosphor configuration and diffuse reflector cup," *Jpn. J. Appl. Phys.*, vol. 44, no. 21, pp. L649–L651, May 2005.
[18] D. K. Kang, E. Wu, and D. M. Wang, "Modeling white light-emitting diodes with phosphor layers," *Appl. Phys. Lett.*, vol. 89, no. 23, pp. 231102-1–231102-3, Dec. 2006.
[19] M. T. Lin, S. P. Ying, M. Y. Lin, K. Y. Tai, S. C. Tai, C. H. Liu, J. C. Chen, and C. C. Sun, "Ring remote phosphor structure for phosphor-converted white LEDs," *IEEE Photon. Technol. Lett.*, vol. 22, no. 8, pp. 574–576, Apr. 2010.
[20] N. Narendran, Y. Gu, J. P. Freyssinier-Nova, and Y. Zhu, "Extracting phosphor - scattered photons to improve white LED efficiency," *Phys. Stat. Sol. (A)*, vol. 202, no. 6, pp. R60–R62, May 2005.
[21] Z. Y. Liu, S. Liu, K. Wang, and X. B. Luo, "Optical analysis of phosphor's location for high-power light-emitting diodes," *IEEE Trans. Device Mater. Rel.*, vol. 9, no. 1, pp. 65–73, Mar. 2009.

[22] K. J. Chen, H. C. Chen, M. H. Shih, C. H. Wang, H. H. Tsai, S. H. Chien, C. C. Lin, and H. C. Kuo, "Enhanced luminous efficiency of WLEDs using a dual-layer structure of the remote phosphor package," *J. Lightwave Technol.*, vol. 31, no. 12, pp. 1941–1945, Jun. 2013.

[23] R. Hu, B. Cao, Y. Zou, Y. M. Zhu, S. Liu, and X. B. Luo, "Modeling the light extraction efficiency of bi-layer phosphors in white LEDs," *IEEE Photon. Technol. Lett.*, vol. 25, no. 12, pp. 1141–1144, Jun. 2013.

[24] S. C. Allen and A. J. Steckl, "ELiXIR—Solid-state luminaire with enhanced light extraction by internal reflection," *J. Display Technol.*, vol. 3, no. 2, pp. 155–159, Jun. 2007.

[25] H. Luo, J. K. Kim, E. F. Schubert, J. Cho, and C. Sone, "Analysis of high-power packages for phosphor-based white-light-emitting diodes," *Appl. Phys. Lett.*, vol. 86, no. 24, pp. 243505-1–243505-3, Jun. 2005.

[26] M. T. Lin, S. P. Ying, M. Y. Lin, K. Y. Tai, S. C. Tai, C. H. Liu, J. C. Chen, and C. C. Sun, "Design of the ring remote phosphor structure for phosphor-converted white-light-emitting diodes," *Jpn. J. Appl. Phys.*, vol. 49, no. 7, pp. 072101-1–072101-6, Jul. 2010.

[27] R. Y Yu, S. Z. Jin, S. Y. Cen, and P. Liang, "Effect of the phosphor geometry on the luminous flux of phosphor-converted light-emitting diodes," *IEEE Photon. Technol. Lett.*, vol. 22, no. 23, pp. 1765–1767, Dec. 2010.

[28] S. C. Allen and A. J. Steckl, "A nearly ideal phosphor-converted white light-emitting diode," *Appl. Phys. Lett.*, vol. 92, no. 14, pp. 143 309-1–143 309-3, Apr. 2008.

[29] Y. Zhu and N. Narendran, "Optimizing the performance of remote phosphor LEDs," *J. Light Vis. Environ.*, vol. 32, no. 2, pp. 115–119, May 2008.

[30] J. Burgin, V. Jubera, H. Debéda, B. Glorieux, A. Garicia, and C. Lucat, "Screen-printed phosphor coatings for white LED emission," *J. Mater. Sci.*, vol. 46, no. 7, pp. 2235–2241, Apr. 2011.

[31] S. E. Brinkley, N. Pfaff, K. A. Denault, Z. J. Zhang, H. T. (Bert) Hintzen, R. Seshadri, S. Nakamura, and S. P. DenBaars, "Robust thermal performance of Sr2Si5N8:Eu^{2+}: An efficient red emitting phosphor for light emitting diode based white lighting," *Appl. Phys. Lett.*, vol. 99, no. 24, pp. 241106-1–241106-3, Dec. 2011.

[32] L. Y. Chen, J. K. Chang, Y. R. Wu, W. C. Cheng, J. H. Chen, C. C. Tsai, and W. H. Cheng, "Optical model for novel glass-based phosphor-converted white light-emitting diodes," *J. Display Technol.*, vol. 9, no. 6, pp. 441–446, Jun. 2013.

[33] Y. T. Zhu and N. Narendran, "Investigation of remote-phosphor white light-emitting diodes with multi-phosphor layers," *Jpn. J. Appl. Phys.*, vol. 49, no. 10, pp. 100203-1–100203-3, Oct. 2010.

[34] H. C. Chen, K. J. Chen, C. C. Lin, C. H. Wang, H. V. Han, H. H. Tsai, H. T. Kuo, S. H. Chien, M. H. Shih, and H. C. Kuo, "Improvement in uniformity of emission by ZrO_2 nano-particles for white LEDs," *Nanotechnology*, vol. 23, no. 26, pp. 1–5, Jun. 2012.

[35] A. Keppens, S. Denijs, S. Wouters, W. R. Ryckaert, G. Deconinck, and P. Hanselaer, "Modelling the spatial colour distribution of phosphor-white high power light-emitting diodes," in *Proc. Int. Soc. Opt. Photon.*, 2010, vol. 7717, pp. 77170J-1–77170J-10.

[36] H. C. Kuo, C. W. Hung, H. C. Chen, K. J. Chen, C. H. Wang, C. W. Sher, C. C. Yeh, C. C. Lin, C. H. Chen, and Y. J. Cheng, "Patterned structure of remote phosphor for phosphor-converted white LEDs," *Opt. Exp.*, vol. 19, no. 104, pp. A930–A936, Jul. 2011.

[37] C. Hoelen, H. Borel, J. Graaf, M. Keuper, M. Lankhorst, C. Mutte, L. Waumans, and R. Wegh, "Remote phosphor LED modules for general illumination: toward 200 lm/W general lighting LED light sources," in *Proc. Int. Soc. Opt. Photon.*, 2008, vol. 7058, pp. 70580M-1–70580M-10.

[38] H. T. Huang, Y. P. Huang, and C. C. Tsai, "Planar lighting system using array of blue LEDs to excite yellow remote phosphor film," *J. Display Technol.*, vol. 7, no. 1, pp. 44–51, Jan. 2011.

[39] G. Singh and D. S. Mehta, "Photoluminescence studies of organic phosphor coated diffusing surface using blue inorganic light-emitting diode as excitation source," *J. Opt.*, vol. 15, no. 2, pp. 025710-1–025710-8, Dec. 2013.

[40] *Cree Sets New R and D Performance Record With 254 Lumen-Per-Watt Power LED*, Cree Inc., Durham, NC, USA, 2012. [Online]. Available: http://www.cree.com/news-and-events/cree-news/press-releases/2012/april/120412-254-lumen-per-watt

[41] E. Perales, J. M. Maciel Linhares, O. Masuda, F. M. Martínez-Verdú, and S. M. Cardoso Nascimento, "Effects of high-color-discrimination capability spectra on color-deficient vision," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 30, no. 9, pp. 1780–1786, Sep. 2013.

[42] S. Tominaga, S. Ebisui, and B. A. Wandell, "Color temperature estimation of scene illumination," in *Proc. Color Imaging Conf. Soc. Imaging Sci. Technol.*, Jan. 1999, vol. 1, pp. 42–47.

[43] R. S. Thing, U. Bernchou, E. Mainegra-Hing, and C. Brink, "Patient-specific scatter correction in clinical cone beam computed tomography imaging made possible by the combination of Monte Carlo simulations and a ray tracing algorithm," *Acta Oncol.*, vol. 52, no. 7, pp. 1477–1483, Oct. 2013.

[44] S. Dap, D. Lacroix, R. Hugon, and J. Bougdira, "Retrieving particle size and density from extinction measurement in dusty plasma, Monte Carlo inversion and ray-tracing comparison," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 128, pp. 18–26, Oct. 2013.