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Application of dual-layer phosphor geometries for enhancing the optical properties of white-light LEDs

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ABSTRACT

This article compares the lumen output of two packages of two-remote phosphor (RP). The first package is flat dual-remote phosphor (FDRPS). The second package is concave dual-remote phosphor (CDRP). The dispersion qualities of the white-light-emitting diode are different as a result of their different cover designs, leading to a disparity between the FDRPS and CDRPS configurations. The results of the study show that the FDRPS package yields a lumen output superior to that of the CDRPS package. In the article, we can also see how the space among the phosphor films (d_1) and the space among the phosphor film and the light emitting diodes (LED) outer side (d_2) might affect the light characteristics in the CDRPS model. As the indicated distances shift, the characteristics of dispersion and absorptivity in the distant phosphor film will shift as well. Such an occurrence can have an impact on chromatic uniformity as well as optical performance in white light emitting diodes (WLEDs). If we modify the d_1 and d_2 values, it is necessary to change the phosphor $YAG:Ce^{3+}$ concentration in the WLEDs to keep the correlated color temperature at 8500 K.

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1. INTRODUCTION

Solid-state optical devices (for example, organic and inorganic optical diodes), which are designed to be environmentally friendly and power-efficient, have a huge potential for optical innovation [1]. Light emitting diodes (LEDs) were developed well and made available for commercial use not long ago, thanks to their exceptional performance, low power consumption, quick feedback, and significant endurance [2]. During the year 1994, Kim *et al.* [3] created the earliest technique of annealing for mass-producing high-performance blue-light LEDs. Their work has contributed to the creation of the blue LED, which is based-GaN and covered with down-conversion substances (for example, aluminate phosphor [4] and quantum dot phosphor) [5], [6], and is amongst the most comm used techniques for producing white LEDs [2]. LEDs are recently seen as the invention of the optical area for their usage in displays and general illumination [7]. However, we should note that LED growth is limited by a range of difficulties, one of which is achieving a higher lumen output. It has been known that distant-phosphor LEDs, which have a phosphor film that is not attached to the LED chips, can improve the transmutation performance and the duration of life of phosphor-transformed LEDs [8], [9].

Such LEDs are utilized frequently in common lighting (for example, downlightings). Nevertheless, synchronizing the phosphor setting with the LED chip's blue radiation zone is a difficult task. If this task is not completed, lumen efficiency will be lost. To resolve such drawback, we can enhance the geometries or the attributes of the distant phosphor motes in order to boost the lumen efficiency with patterned or shaped layers of phosphor [10], [11], poly-layer phosphor [12]-[14], nanoparticle-blended phosphor [15] and advanced phosphor substance [16]. Another way to overcome the disadvantage is to combine the LED's emissions with a reflecting lens for increased lumen efficiency [17], [18]. The idea of disconnecting the layer of phosphor from the chip in the remote phosphor model was proposed in earlier researches [19], [20]. We can employ an advanced light extraction internal reflection arrangement with a polymer lens in the form of a hemisphere internally coated with phosphor to boost extraction efficacy [21]. Furthermore, a plan with an empty space that can reflect downward light can improve lumen efficacy [22]. The phosphor concentration has a considerable impact on the lumen efficiency, in addition to the package layout. The rise in the concentration of phosphor can increase the loss of re-absorption in the layer of phosphor, and as a result, the lumen performance may suffer, especially as the correlated color temperature lowers [23]. According to several pieces of researches, excessive dispersion and reflecting events have a negative impact on lumen performance. In order to encourage the presence of blue and yellow lights, we must limit the illumination loss caused by backscattering and reflection.

To secure a greater lumen output, the dual-film remote phosphor (DRP) packages were proposed in various researches. Manufacturers, on the other hand, find it challenging to select a remote phosphor package with the optimum lumen. In this research, the two packages, namely flat dual-film remote phosphor structure (FDRPS) and concave dual-film remote phosphor structure (CDRPS), are introduced to perform the white light emitting diode (WLED) modeling, accompanied by the investigation of luminescent output (or luminous flux (LF)). When the range between the two films of phosphor, marked as d_1, and the range between the film of phosphor and the surface of the LED, marked as d_2, are varied, the FDRPS package showed a noticeable scattering difference. The YAG:Ce^{3+} changed as a result of this alteration. As a result, controlling d_1 and d_2 may regulate the lumen. Unlike the FDRPS package, the scattering in the CDRPS package displayed a minor change when the radius of the curved surface of the phosphor layer was adjusted. As a result, the task of managing the lumen might be challenging. Moreover, the CDRPS package complicates the creation process. This research proposes using the FDRPS with appropriate phosphor concentration to yield a higher lumen output.

2. SIMULATION WITH COMPUTER

2.1. Recreating the WLEDs models

We use the LightTools application and a 3-D ray tracking simulation to show how the two layers of phosphor affect the efficiency of pc-LEDs at 8500 K. The WLED model consists of 9 blue LED dies, 2 phosphor films, 1 reflection cup, and 1 silicon film. The true WLED template with a round-shaped lens and its simulated construction are shown in Figures 1(a) and Figure 1(b). FDRPS and CDRPS are two packages offered for optical efficiency comparison. The range between phosphor layers is d_1, and that between the first film and the chips is d_2 for the FDRPS package, as seen in Figure 1(c). Meanwhile, in Figure 1(d), r_1 and r_2 indicate the curving gaps of the phosphor films stacked upon each other of the CDRPS package.

A 2.07-mm-tall and 8-mm-wide reflector is connected to the chips shown. Furthermore, the dimensions (1.14 mm × 0.15 mm), radiative energy (1.16 W), and maximum wavelength of the aforementioned chips, as shown in Figure 1(b), are all properly tuned to produce the optimum outcomes (453 mm). The displayed layer of phosphor has a thickness of 0.08 mm and is placed above the chips. We created a light simulation with varying ranges between the layers of phosphor and the LED to show how the three layers of phosphor work. The average diameter of phosphor globular particles is 14.5 µm. In FDRPS, the values d_1 and d_2 vary from 0 mm – 0.64 mm and 0 mm – 1.43 mm, respectively. In CDRPS, r_1 is constant at 16 mm, while r_2 varies from 16.1mm – 16.9 mm. It is possible to achieve the highest lumen output and the lowest chromatic deviation by configuring d_1 and d_2 settings. Depending on the separation parameters between the layers of phosphor, the phosphor concentration ranges are adjusted to maintain the LED's hue temperature at 8500 K. Figure 2(a), Figure 2(b), and Figure 2(c) demonstrate the concentration range of the phosphor cluster linked to a specific distance. In particular, the concentration of phosphor varies in the range of 14 wt% – 26 wt%, 15 wt% – 21 wt%, and 16.6 wt% – 17 wt% for d_1, d_2, and r_2, respectively. From the figures, it is easy to see that the change in the concentration of phosphor in the CDRPS is not significant, compared to those in FDRPS, indicating a minor change in scattering. This may indicate that the lumen output did not display a significant change in the case of CDRPS. Besides, the CDRPS may complicate the creation process, compared to the FDRPS package. On the contrary, the FDRPS drastically changes the dispersion and absorption process in the WLEDs. As a result, there may be more opportunities to control the lumen output.

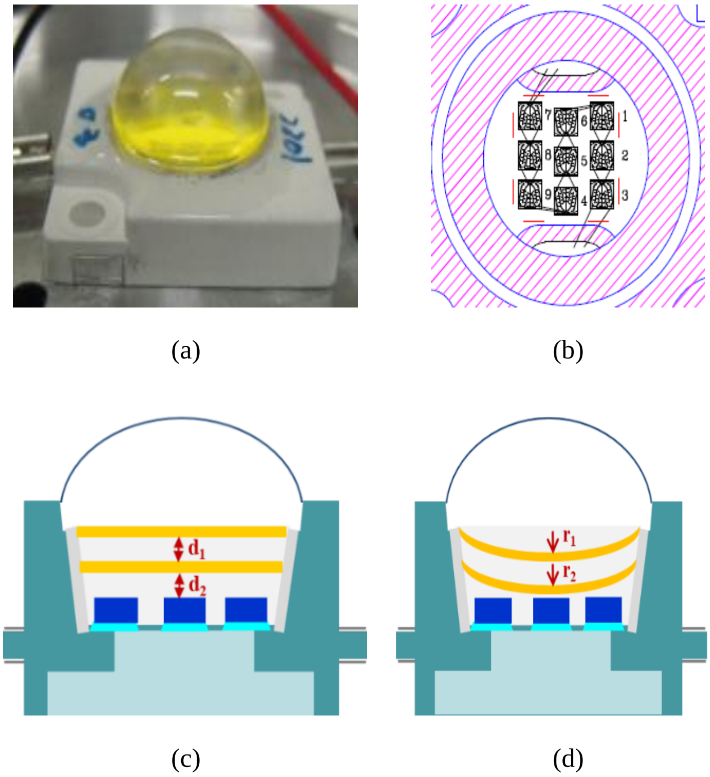


Figure 1. Images exhibiting a WLED model and its inner mechanism: (a) real WLED model, (b) wiring diagram of chips, (c) FDRPS organization, and (d) CDRPS organization

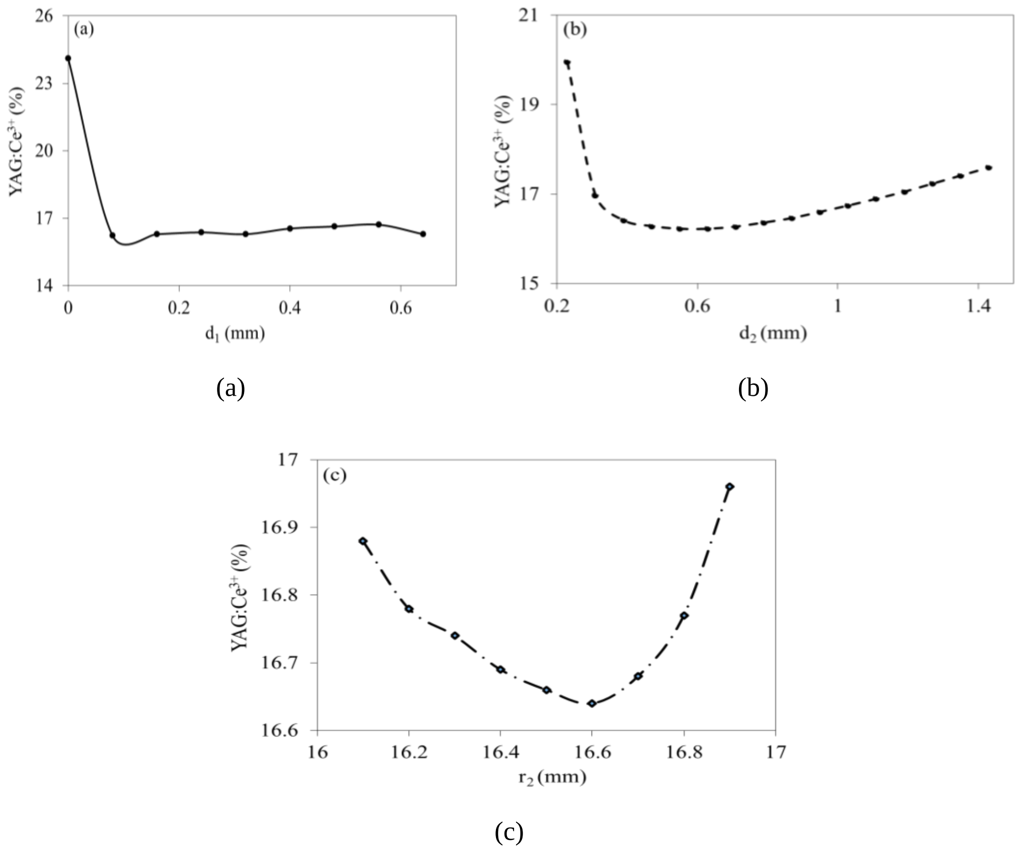


Figure 2. The concentration of yellow phosphor in the event of (a) d_1, (b) d_2, and (c) r_2

With this model, we are able to figure out the suitable values for positioning the phosphor layers; in other words, the best ranges among the films of phosphor that define the LEDs' light characteristics can be determined for implementation. For the simulation, we displace the layers of phosphor in between and attach the layer of phosphor in the highest position to the chip of LED. However, because of the optical absorption, dispersion, propagation, and transmutation, the arrangement of the layers in the two-layer package may result in a wide range of correlated color temperatures in LEDs. To maintain the same correlated color temperature (CCT) level, we must adjust the phosphor concentration in accordance with the separation parameters among the parts of two DRP packages, as mentioned above. From Figure 2, it is evident that the concentration of phosphor in the two-layer package goes down significantly with a small increase in the separation parameters in all structures, and then goes up as the gap becomes larger. As a result of these findings, we may deduce that lowering the phosphor concentration is required to keep the CCT constant during the simulation. It is also worth noting that the yellow phosphor concentration visibly changes as d_1 value is greater than 0.08 mm. The concentration of phosphor YAG:Ce^{3+} decreases significantly when the zero-value d_1 climbs to 0.08 mm, from 24.11% – 16.22%. In an identical trend, the stated phosphor concentration considerably decreases from 19.55% – 16.22% as d_2 value reaches 0.55 mm. When d_2 continuously expands, the gradual rise in YAG:$Ce^{\cdot 3+}$ concentration can be observed. The range between d_1 and d_2 clearly affects the dispersion and absorptivity in the distant phosphor film, which are light properties in WLEDs. Moreover, that the dispersion in the LED packages shows a visible fall would favor luminosity rather than chromatic homogeneity.

2.2. Calculating the optical propagation

The following section will display the equations of the lightings of blue and yellow (transmitted and converted respectively) in the package of two-layer phosphor, which could lead to a considerable increase in the efficacy of LED. The blue and yellow light (transmitted and converted, respectively) of a one-layer remote phosphor (RP) package with a *2h*-thick phosphor layer is shown in the (1) and (2) [24]-[26].

$$PB_1 = PB_0 \times e^{-2\alpha_{\beta 1}h} \tag{1}$$

$$PY_1 = \frac{1}{2}\frac{\beta_1 \times PB_0}{\alpha_{B1} - \alpha_{Y1}}\left(e^{-2\alpha_{Y1}h} - e^{-2\alpha_{\beta 1}h}\right) \tag{2}$$

The blue and yellow lights (transmitted and converted, respectively) of a two-layer RP packet that has the h-thick phosphor film are represented by the (3) and (4).

$$PB_2 = PB_0 \times e^{-2\alpha_{B2}h} \tag{3}$$

$$PY_2 = \frac{1}{2}\frac{\beta_2 \times PB_0}{\alpha_{B2} - \alpha_{Y2}}\left(e^{-2\alpha_{Y2}h} - e^{-2\alpha_{\beta 2}h}\right) \tag{4}$$

The width of the phosphor film is counted as h in the formulas presented. The small numerals "1" and "2" are put below the letters denote one-layer and two-layer remote phosphor packages, respectively. The transformation factor of blue light to yellow light is represented by the symbol β. The backscattering factor of the yellow light is represented by γ. Power-blue (PB) and power-yellow (PY) (the blue light and yellow light intensities respectively) indicate the intensity of light in blue LED, which is displayed by the symbol PB_0. The α_B and α_Y illustrate small portions of the energy amount wasted in the transmission processes of the blue illumination and yellow illumination, respectively. The following calculation shows how the two-layer package of pc-LEDs outperforms the one-layer package in terms of optical efficacy.

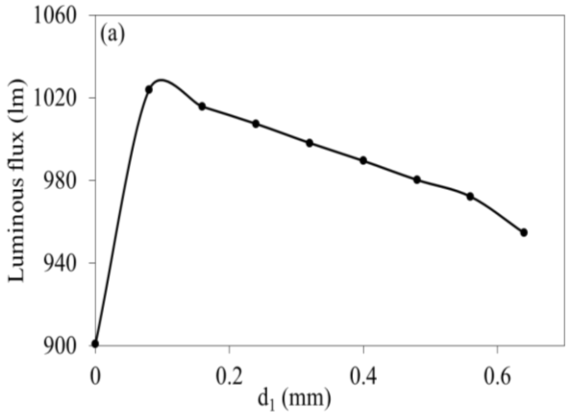
$$\frac{(PB_2 + PY_2) - (PB_1 + PY_1)}{PB_1 + PY_1} > 0 \tag{5}$$

At two wavelength ranges, 380 mm – 480 mm and 480 mm – 580 mm, the intensity of the spectrum at zero-value d_1 is lower than the intensity at d_1 value greater than zero. In terms of d_2, as the range between the surface of the blue LED and the layer of phosphor closer to the chip is 0.23 mm or greater, the lumen has the worst value, which is inferior to the value when d_2 exceeds 0.23 mm. As a result, the two-layer package generates more photons than the one-layer package.

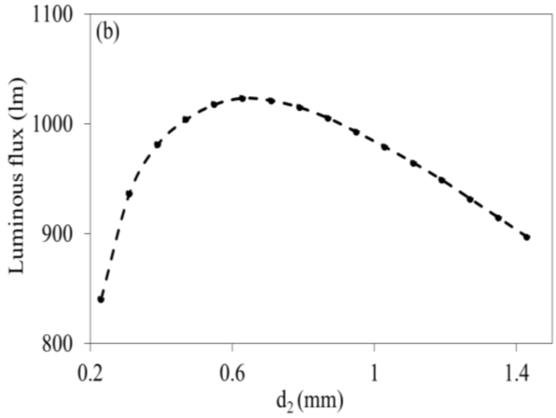
3. RESULTS AND DISCUSSION

Apparently, the different separation values between the phosphor layers and the LED dies impact lumen performances of the DRPs, as shown in Figures 3(a), Figures 3(b), and Figures 3(c). The results show that changing the range has a considerable impact on optical extraction. The massive shift at the start shows that the lumen performance is prone to substantially increase and achieve the greatest value when d_1 stays in the 0 mm – 0.08 mm range and d_2 stays in the 0.23 mm – 0.63 mm range. The greatest lumen value of the

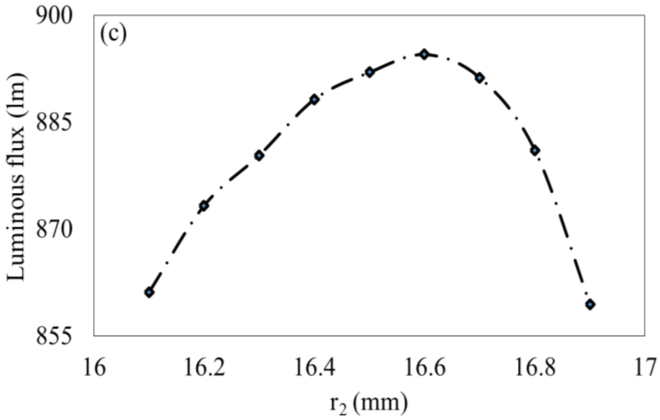
FDRPS package is 1020 elm, with a d_1 value of 0.08 mm and a d_2 value of 0.63 mm. In the case of CDRPS package, its highest lumen value is 894 am as r_2 value is 16 mm and 16.6 mm. On the contrary, the lumen performance suffers from a minor fall if the range between the layers of phosphor gets bigger. The LED chip’s blue light will turn into yellow light once it reaches the first layer of phosphor. However, while the light is changed into yellow light and bypasses the second layer of phosphor, a partial loss of light will occur in the LEDs, which is caused by backscattering, absorption, and reflection. The larger the range, the closer the phosphor film gets to the LED chip. As a result, more illumination is stuck and backscattered in the area among the first phosphor film and the LED chips. Therefore, a greater joint temperature of the phosphor films and LED chips would result in lower conversion efficiency. For the CDRPS package, the curving-in surface of the phosphor films allows more lights to backscatter towards the LED chip’s surface. Therefore, the optical energy generated suffers a greater loss. This explains why r_2 becomes increasingly greater but lumen output becomes increasingly lower. The phosphor surface becomes closest to the LED chip’s surface as the r_2 value approaches 16.9 mm, and the backscattering event becomes more prominent. Besides the backscattering of the lower phosphor film to the LED’s surface, the same process also occurs in the higher phosphor sheet for the CDRPS package. As r_2 continues increasing to 16.6 mm, the backscattering energy gradually decreases due to the increase in the range between the two layers of phosphors. This improves linear optical transmission, resulting in increasing LF. As r_2 rises, the gap between the upper and lower layers of phosphor decreases, which eventually causes the mentioned backscattering event to increase and lower the luminosity efficiency. The lumen output of the two FDRPS and CDRPS packages is determined by the distinct phosphor coating patterns. In comparison to the CDRPS package, lights in FDRPS can transmit through both layers in a straightforward direction, thus the luminous intensity is likely to be higher as a function of limited backscattering events.



(a)



(b)



(c)

Figure 3. LF performances of DRPs corresponding with: (a) d_1, (b) d_2, and (c) r_2

4. CONCLUSION

In conclusion, our study intricately assesses and displays how the range between the two films of phosphor and the range between the film of phosphor and the surface of LED can affect the attributes of light in the distant phosphor configuration. The lumen output is dependent on the different covering forms of phosphor of the FDRPS and CDRPS. In comparison to the CDRPS, the FDRPS can allow a greater proportion of lights to pass straight through the phosphor films. The findings of our research suggest that altering the location of the phosphor film in the distant phosphor configuration can result in a significant increase in the luminosity of WLEDs. When the d_1 or d_2 is 0.08 or 0.63 mm, respectively, LF strength increases significantly and becomes the maximum, although the chromatic homogeneity suffers a loss. On the other hand, when the d_1 or d_2 expands over 0.08 or 0.63 mm respectively, LF strength and the chromatic deviation appear to decrease, which is the result of the increased optical trapping, absorption, and re-scattering of the LED, as well as the inefficient chemical conversion by high heating features occurring between the phosphor layers and the chips. As a result, determining an adequate range between the layers of phosphor in the remote phosphor structure is critical for us to produce high-productivity pc-LEDs.

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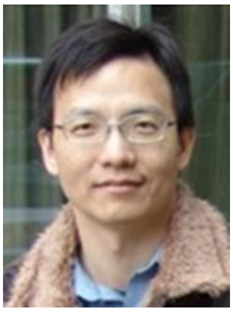

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