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Excellent luminous flux of WLEDs with flat dual-layer remote phosphor geometry

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Abstract

This paper focuses on the comparison of the luminous flux of two dual-remote phosphor structures named flat dual-remote phosphor (FDRP) and concave dual-remote phosphor (CDRP). These two configurations have different luminous flux values due to the disparity in scattering properties in white LEDs. However, the researched results showed that FDRP structure is more lucrative than the CDRP structure when it comes to the luminous flux effectiveness. To support the aforementioned idea, this article also presents the influence of the distance between two phosphor layers (d_1) and the distance between the phosphor layer with the LED surface (d_2) on the optical properties of the FDRP structure. Specifically, the scattering ability and absorption properties of the remote phosphor layer will vary sharply if d_1 and d_2 are adjusted into different values, which produces an immense impact on the chromatic homogeneity and illumination capability of WLEDs. Therefore, in order to stabilize the correlated color temperature (CCT) of WLEDs at 8500 K when there is a modification on d_1 and d_2, the concentration of YAG: Ce^{3+} phosphor also needs to be varied. Accordingly, the scattering process and absorption phenomenon in the remote phosphor layer will bottom out when $d_1=d_2=0$, leading to the worst color quality and luminous flux. The effect of the spectra generated as these distances are adjusted is obvious evidence for this point. In other words, the larger the d_1 and d_2, the larger the scattering surface, and thus the blending of blue and yellow light rays will become more homogeneous, yielding the smallest white light deflection and the lowest luminous flux at the same time. The paper's results indicated that the luminous flux will reach a peak at 1020 lm if $d_1=0.08$ mm or $d_2=0.63$ mm and the chromatic deflection will hit the lowest point as $d_1=0.64$ mm or $d_2=1.35$ mm. In the end, manufacturers can make their choice for the production of higher-standard WLEDs based on the general knowledge and helpful information that the article has provided and analyzed.

Keywords: color rendering index, lambert-beer law, luminous efficacy, WLEDs

1. Introduction

Solid-state lighting-lighting that utilizes polymer, organic, or semiconductor light-emitting diodes as sources of illumination rather than filament such as fluorescent lamps-is becoming the leading technology in the lighting industry [1-3]. These kinds of LEDs are frequently used in traffic lights as well as in remote controls, building exteriors etc. thanks to their high efficiency, energy savings, fast reflexes, and longevity [2-5]. Nowadays, LEDs' application areas are spreading from displays to general lighting, creating a revolution in the lighting market [6]. However, to obtain higher luminous flux of LEDs is truly challenging for both scientists and manufacturers. According to the previous studies, remote phosphor structure in which the phosphor layer is placed apart from the blue-LED chips has the ability to improve the conversion efficiency and lifetime of phosphor-converted LEDs [7]. However, to make the phosphor layout with the blue emission pattern of the LED chip fit together is extremely tough, which may lead to a reduction of luminous flux. One of the methods to solve this trouble is to use the optimal geometries or the outstanding features of the remote phosphor particles such as patterned or shaped phosphor layers [8], multi-layer phosphor [9], nanoparticle-mixed phosphor [10], and the new phosphor material [11-13]. Another way to increase luminous efficacy involves the mixing of the LED emissions using a lens reflector [14].

The procedure of separating the chip and the phosphor layer of remote phosphor structures has been mentioned and explained in the preceding works [15, 16]. The light extraction internal reflection structure was enhanced thanks to a polymer hemispherical shell lens with an interior phosphor coating in order to increase extraction efficiency. Besides, an air-gap embedded structure reflecting downward light can help enhance luminous efficiency [17]. However, not only the structure of the package but also the concentration of phosphor has a considerable effect on luminous efficiency. Specifically, the rise in phosphor concentration will make the re-absorption loss in the phosphor layer, leading to a decrease in luminous efficiency, especially at lower CCTs. Also, high scattering and reflecting were demonstrated to reduce luminous efficiency in some previous studies [18-20]. Therefore, enhancing the emission of blue and yellow rays as well as reducing the amount of light lost from backscattering and reflection are most essential in improving WLEDs quality.

In previous papers, dual-layer remote phosphor configurations have been suggested as a method of enhancing luminous flux [21-26]. However, there are a variety of remote phosphor structures that makes manufacturers hard to select an optimal one between them. To provide information about the comparison between these configurations, this study introduced and demonstrated two different remote phosphor configurations that are flat dual-layer (FDRP) and concave dual-layer (CDRP). After the research, it can be seen that FDRP structure performed a significant change in scattering when the distance between the two phosphor layers (d1) and the distance between the phosphor layer with the LED surface (d_2) was modified. The change of these distances led to a variance in YAG:Ce^{3+} as well as the luminous flux. On the other hand, the scattering of the CDRP structure slightly varies when the curved radius of the phosphor layer is modified. In fact, to control this radius is more challenging than to control the gap between the two phosphor layers or between the phosphor layer with the LED surface, which means that controlling the optical properties of CDRP structure is much more difficult than the FDRP structure. Moreover, the fabrication of CDRP is also more complicated. That is why this study proposed the FDRP structure with an appropriate YAG:Ce^{3+} concentration to achieve higher luminous flux.

2. Computational Simulation
2.1. Constructing the WLEDs Configuration

In this section, a 3-D ray tracing simulation with LightTools software is used to demonstrate the two phosphor layers' impact on the performance of pc-LEDs at the correlated temperature of 8500 K. The components of a model WLED includes blue LED chips, two phosphor layers, a reflector cup, and a silicone layer. The photograph of actual WLEDs structure and a bonding diagram used for simulation were shown in Figure 1 (a) and Figure 1 (b). Figure 1 (c) revealed the illustration of the FDRP structure where d1 is the distance between the two phosphor layers and d_2 is the distance between the phosphor layer with the LED surface. Meanwhile, the illustration of the FDRP structure was shown in Figure 1 (d) where r_1 and r_2 are sequentially the curved radii of the upper and lower phosphor layers of the CDRP structure. In the WLEDs structure model shown in Figure 1, each blue chip has a reflector with a height of 2.07 mm and a bottom length of 8 mm mounted below it. These chips are coated with a 0.08 mm thick phosphor layer. Additionally, factors attached to the reflector has carefully been designed to achieve the greatest results such as the value of the dimension, the radiant power, and a peak wavelength are respectively 1.14 mm x 0.15 mm, 1.16 W, and 453 nm. Next, the optical simulation process is conducted based on the adjustment of the distance among phosphor layers with the LED surface to see how the phosphor layers affect the WLEDs. The phosphor particle is spherical and its average diameter is 14.5 µm. During the simulation process of the remote phosphor structure of WLEDs, d_1 is modified from 0 to 0.64 mm and d_2 varies from 0 to 1.43 mm for the FDRP structure while r_1 is constant at 16 mm and r_2 is changed between 16.1 mm and 16.9 mm for the CDRP structure.

When adjusting d_1 and d_2 of FDRP structure, the luminous flux and chromatic homogeneity can reach the highest value. To stabilize the color temperature of WLEDs at 8500 K, there is a need to vary the concentration of phosphor from 14%-26% wt. matching the distance of phosphor layers. On the other hand, in CDRP structure, r_1 of is steady at 16 mm and r_2 is varied between 16 mm and 17 mm. Therefore, the concentration of yellow phosphor YAG:Ce^{3+} changed from 16.6% to 17% to maintain average CCT as depicted in Figure 2 (c).

Compared with the concentration of yellow phosphor in case of FDRP structure in Figure 2 (a) and Figure 2 (b), the difference in YAG:Ce^{3+} concentration of the CDRP structure was much smaller and hence the scattering variation was insignificant. Compared with the concentration of yellow phosphor in case of FDRP structure in Figure 2 (a) and Figure 2 (b), the difference in YAG:Ce^{3+} concentration of the CDRP structure was much smaller and hence the scattering variation was insignificant, leading to the trivial change in luminous flux generated by CDRP structure. Conversely, the FDRP structure brings about many changes in scattering and absorption for WLEDs, which facilitates the control of emitted luminous flux.

(a)   (b)
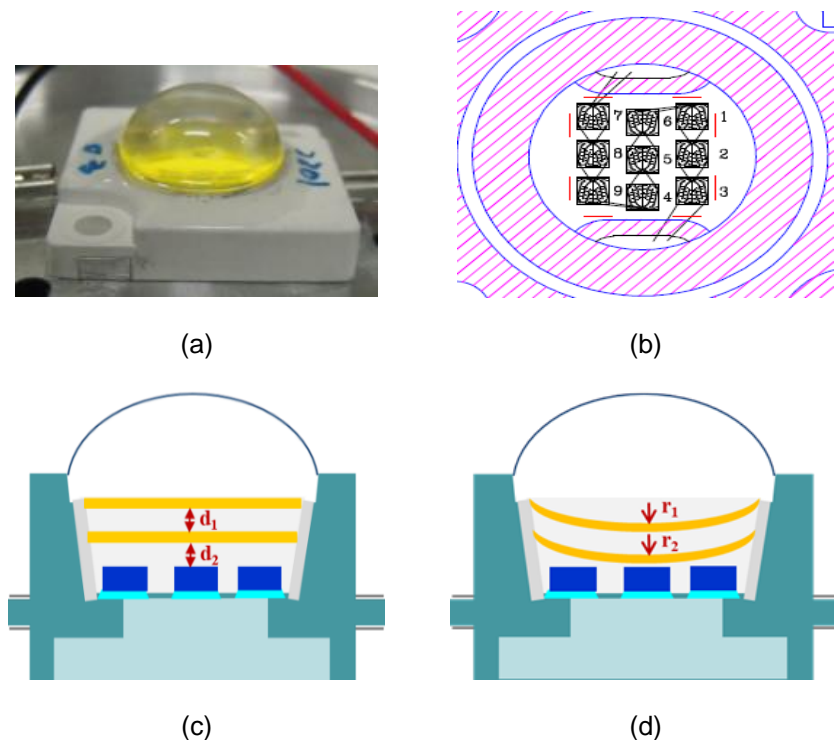

(c)   (d)

Figure 1. Photograph of WLEDs structure: (a) actual WLEDs; (b) bonding diagram;
(c) illustration of FDRP; (d) illustration of CDRP

To improve the optical properties of WLEDs, especially the luminous flux, the phosphor layers' position need to be adjusted until getting a suitable distance that can yield the highest results. The arrangement of phosphor layers in the FDRP structure can yield a great variation in correlated color temperature of LEDs due to the absorption, scattering, transmission, and light conversion properties. Hence, in order to keep the CCT of this package stable, the phosphor concentration was varied dependently on the distance between the two phosphor layers in pc-LEDs as shown in Figure 2 (a) and Figure 2 (b). Obviously, the concentration of yellow phosphor YAG:Ce3+ had a tendency to drop from 26% to 14% when the distances changed in the range of 0-1.43 mm. Noticeably, there is a moderate difference in the concentration of yellow phosphor when d1 exceeds 0.08 mm. Accordingly, the yellow phosphor concentration needs to be reduced to keep this package's CCT constant during the simulation process.

Definitely, when d_1 rises from 0 to 0.08 mm, the YAG:Ce^{3+} concentration decreases distinctly from 24.11% to 16.22%, causing the marked slump in the scattering of LED packages, which only benefits the luminous flux but not help increase the chromatic homogeneity. However, as d_1 goes up to 0.64, there is a slight change in YAG:Ce^{3+} concentration. Similarly, the concentration of YAG:Ce^{3+} falls steeply from 19.55% to 16.22% if d_2 climbs to 0.55 mm. After that, d_2 keeps increasing when the YAG:Ce^{3+} concentration is modified into different values. In sum, d_1 and d_2, or the distances between the phosphor layers and the LED surface were proved to affect enormously the scattering and absorption abilities of the WLEDs.
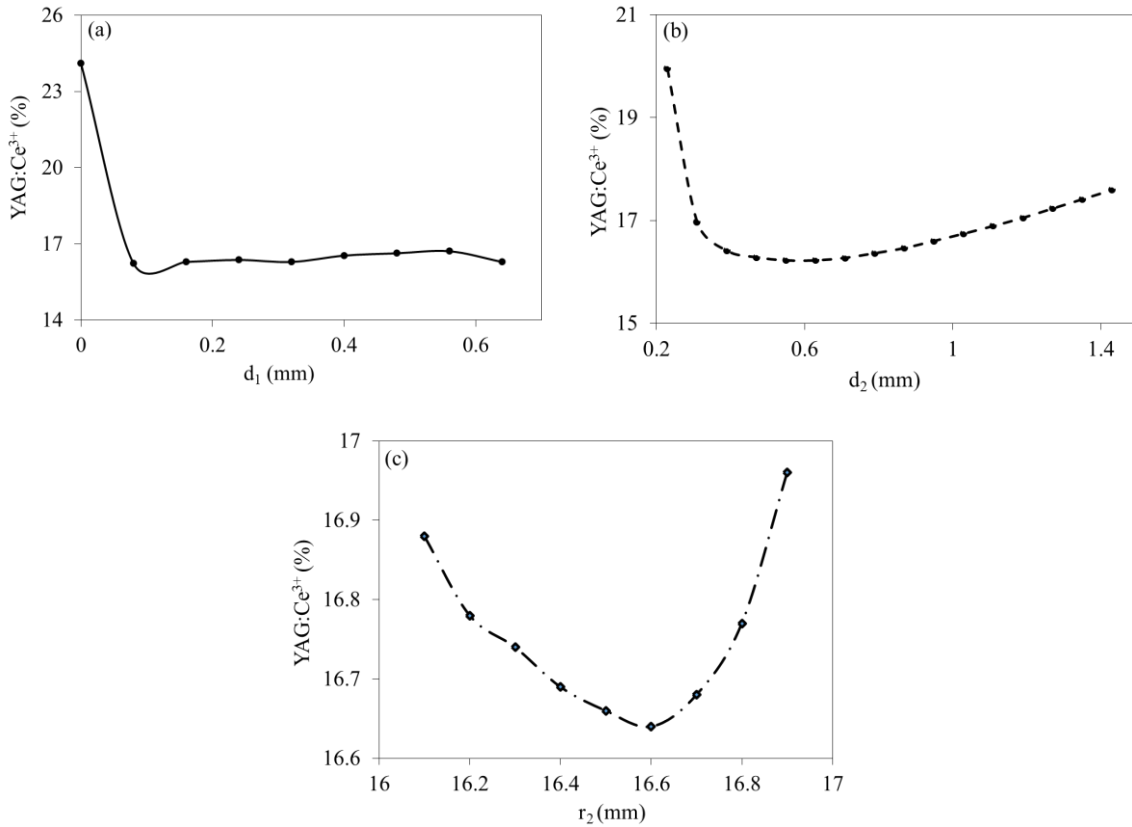
Figure 2. The concentration of yellow phosphor in case of (a) d_1; (b) d_2 and (c) r_2

2.2. Computing the Transmission of Light

In this part, the mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure will be presented and demonstrated, which yields a great improvement of LED efficiency. The transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of $2h$ are expressed as follows:

$$PB_1 = PB_0 \times e^{-2\alpha_{B1}h} \tag{1}$$

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

the transmitted blue light and converted yellow light for double layer remote phosphor package with the phosphor layer thickness of h are defined as:

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

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

where h is the thickness of each phosphor layer. The subscript "1" and "2" are used to describe single layer and double-layer remote phosphor package. β presents the conversion coefficient for the blue light converting to yellow light. γ is the reflection coefficient of the yellow light. The intensities of blue light (PB) and yellow light (PY) are the light intensity from blue LED,

indicated by PB_0. α_B; α_Y are parameters describing the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer respectively.

The lighting efficiency of pc-LEDs with the double-layer phosphor structure enhances considerably compared to a single layer structure:

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

(5)

Figure 3 depicted the emission spectrum of the dual-layer phosphor at different wavelengths, where the emitted spectral intensity when $d_1=0$ is smaller than that when $d_1>0$ at the two wavelength ranges: 380-480 nm and 480 - 580 nm. Meanwhile, the blue LED surface is far at least 0.23 mm from the lower phosphor layer ($d_2<0.23$ mm), yielding the lowest luminous flux compared to the case $d_2>0.23$ mm. Thus, the luminous flux in dual-layer phosphor structure is larger than that of the single layer phosphor structure.
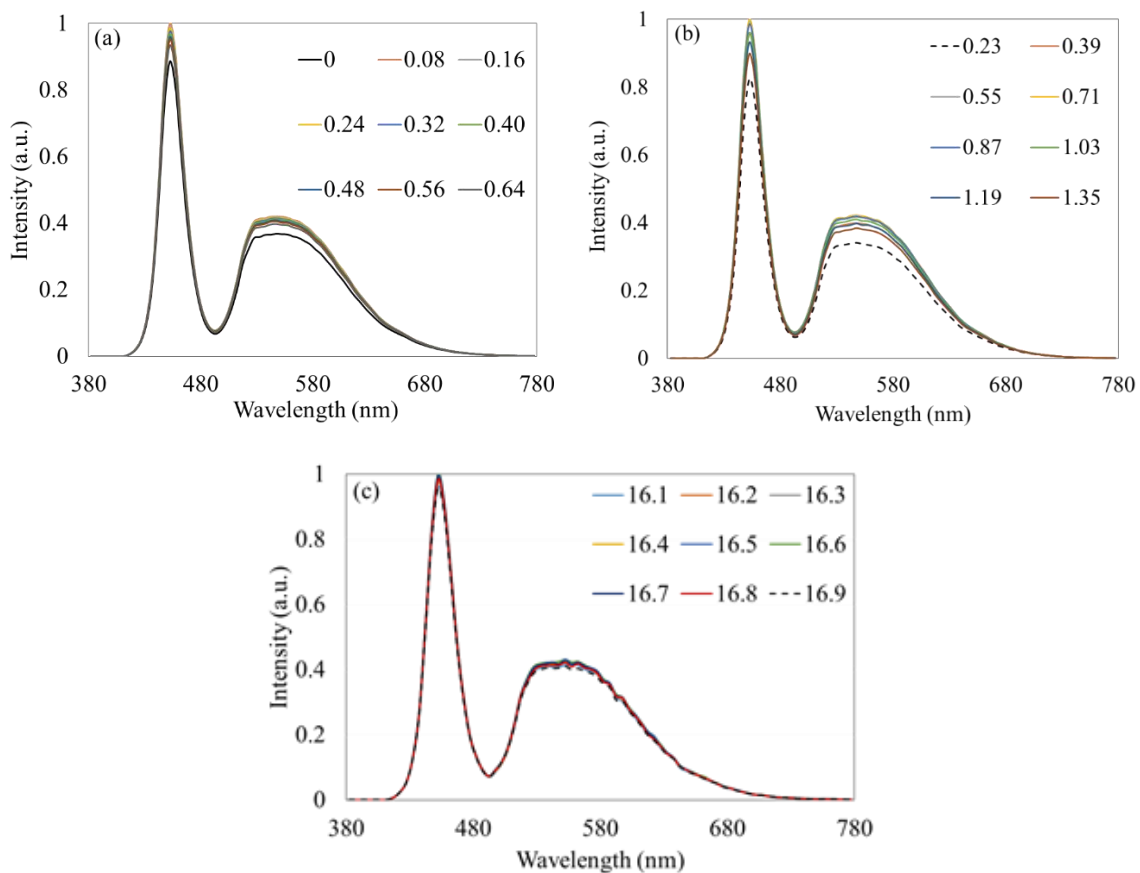

Figure 3. Emission spectra of dual-layer phosphors:
(a) case of d_1; (b) case of d_2 and (c) case of r_2

3. Results and Analysis

As can be seen from Figure 4, the influence of the distances among phosphor layers and the LED chip of remote phosphor package on the lumen output was explicitly illustrated. The results showed that varying the distance results in a dramatic impact on light extraction. Simultaneously, the luminous flux tends to increase considerably and reach the peak when d_1 is in the range of 0 to 0.08 mm and d_2 is in the range of 0.23 mm to 0.63 mm. For FDRP configuration, the luminous flux is maximum at 1020 lm when $d_1=0.08$ mm or $d_2=0.63$ mm while in CDRP configuration, the luminous flux is maximum at 894 lm when $r_2=16$ mm and

r_2=16.6 mm. Conversely, the luminous flux has a weak descending tendency when the distance between the phosphor layers continuously rises. The blue light from the LED chip will confront the lower phosphor layer and be converted to the yellow light. After that, parts of light will be trapped inside the LEDs due to the backscattering, absorption, and reflection phenomenon while other parts will be converted to yellow light and then transmitted throughout the upper phosphor layer. Due to the increase of the distances, the phosphor layers move closer to the LED chips, which makes the light is trapped more and reflected inside the distance between the lower phosphor layer with the LED chips. That is why the temperature at the junction of phosphor layers and the LED chips increases can yield the low conversion efficiency.

For the CDRP structure, the concave surface facilitates light to be back-scattered to the surface of the LED chip and thus there is much more light emitting energy loss. Therefore, when r_2 is increased, the luminous flux will drop off. Specifically, as r_2 rises to 16.9 mm, the phosphor surface is extremely near the LED chip surface and hence the light back-scattered is largest. In addition to the scattering phenomenon on the LED surface of the underlying phosphor layer, this is also reflected in the upper phosphor layer in the CDRP structure. Where, as r_2 increases from 16.1 mm to 16.6 mm, the back-scattering energy will decrease. This facilitates the direct transmission of light rays, leading to increased luminosity. However, as r_2 goes up, the distance between the phosphor layer and the LED surface is narrowed down. As a result, the back-scattering of this lower phosphor layer increases, resulting in reduced luminous flux. To sum up, the luminous flux tightly depends on the different phosphor coatings of FDRP and CDRP structures. However, light can be more easily transmitted straightly through the two phosphor layers in the FDRP structure than the CDRP structure.
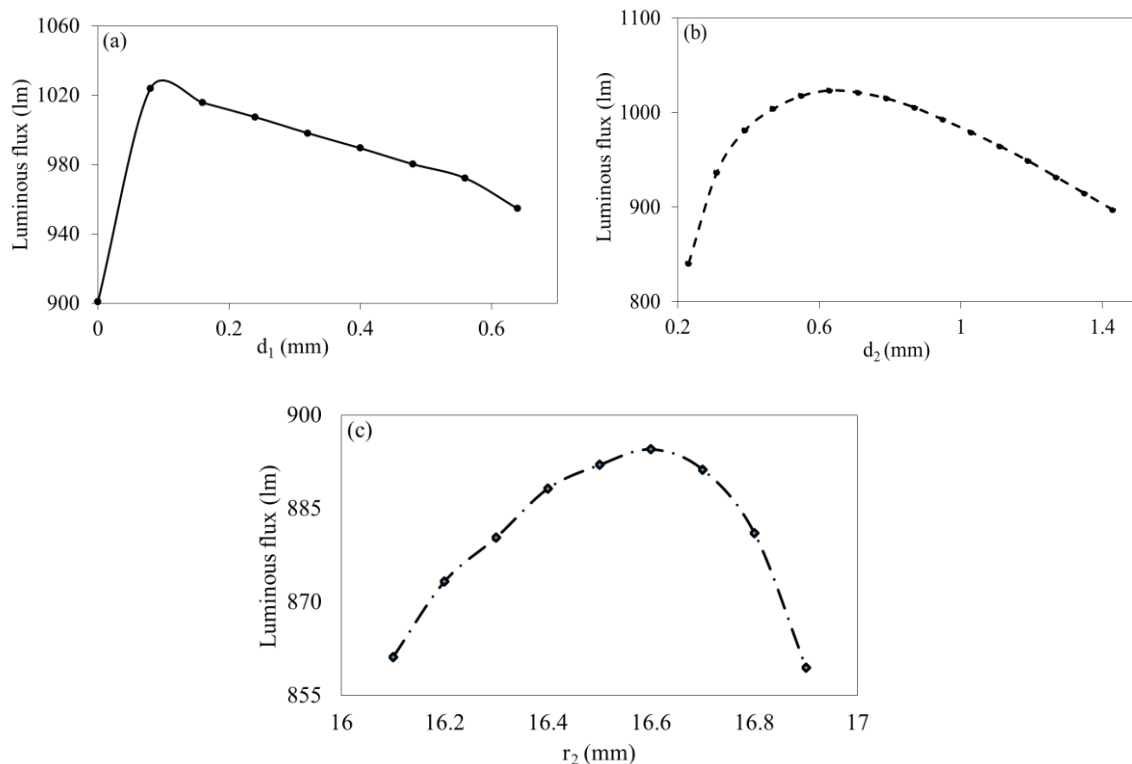
Figure 4. The luminous output of WLEDs at
the same CCT in cases of (a) d_1; (b) d_2 and (c) r_2

4. Conclusion

To summarize, in this paper, the influence of the distance between dual-phosphor layers and the phosphor layer with the LED surface on the optical properties of the remote phosphor package has been examined and demonstrated specifically. Each of the different

phosphor coating shapes of the FDRP and CDRP structures will yield different luminous flux values. Compared to the CDRP structure, the straight transmission of light through the two phosphor layers of the FDRP structure is more advantageous. According to the researched results, WLEDs luminous flux will be enhanced sharply if the position of the phosphor layer in remote phosphor package is well fit. Moreover, the luminous flux will notably rise and reach the greatest value if d_1=0.08 mm or d_2=0.63 mm while the chromatic homogeneity will be lessened in both cases. On the other hand, if d_1>0.08 mm or d_2>0.63 mm, the luminous flux has a tendency to drop but the color uniformity goes up. This is the result of the impact of the trapped increase, the absorption, and the re-scattering of light in the LED package as well as the chemical transformation of the heated phosphor layer. In conclusion, in order to produce a new high-efficiency pc-LEDs generation, great emphasis must be put on studying a proper distance between phosphor layers in remote phosphor package.

Acknowledgements

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