Augmenting color homogeneity and luminous flux of WLEDs with dual-layer structure of the remote phosphor package

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This article indicates the impacts 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 remote phosphor structure. When the distances d_1 and d_2 are varied, the scattering and absorption properties of the remote phosphor layer change dramatically, which causes a huge influence on the color uniformity and illumination capability of WLEDs. To keep the correlated color temperature of WLEDs stable at 8500 K in case d_1 and d_2 are adjusted, the concentration of YAG:Ce^{3+} phosphor also needs to be modified. When $d_1 = d_2 = 0$, the scattering and absorption in the remote phosphor layer is minimum, leading to the infinitesimal color and luminous flux. This can be attested by the effects of the spectra generated in case these distances fluctuate. The larger the d_1 and d_2 get, the larger the scattering surface is, and the more homogeneous the blending of the blue and yellow rays becomes, which leads to the minimum white light deviation and simultaneously leads to the lowest luminous flux. According to the studied results, the luminous flux can be maximum at 1020 lm when d_1 = 0.08 mm or d_2 = 0.63 mm. Meanwhile, the smallest color deviation that is the paramount color consistency occurs when d_1 = 0.64 mm or d_2 = 1.35 mm. Consequently, choosing the two distances d_1 and d_2 becomes tremendously vital for the manufacturers who have to depend on the production objective to get well-chosen option. The research results will provide further information for this decision in order to better the quality of WLEDs.

(Received July 29, 2018; accepted June 16, 2020)

Keywords: WLEDs, Dual-layer structure, Remote phosphor package, Color homogeneity, Luminous flux

1. Introduction

As can be seen, phosphor converted white light emitting diodes (pc-WLEDs), the fourth potential generation light source used to replace the conventional one, has a variety of prospects in lighting solution [1]. The application of white light-emitting diodes has become more and more popular in many different fields of our daily life such as landscape, street lighting, backlighting, etc. while the light extraction efficiency and the angular homogeneity of correlated color temperature of white LED are still the challenging elements that restrict its development [2]. Due to the rising demand of the market and applications, further breakthroughs in luminous efficiency and color uniformity are essential [3]. Today's most common approach for white light generation is based on the combination of blue light from converse red phosphor with yellow light from LED chip. Although this concept seems to be rather familiar, it is undeniable that the structure of LEDs and the arrangement of phosphor layers play a significant role in determining the luminous efficiency, especially the angular homogeneity [4-8]. Several common phosphor coating methods have been proposed to produce LEDs such as dispensing coating and conformal coating [9, 10]. Nevertheless, these structures do not provide high luminous flux due to the degradation in light conversion of phosphor material caused by yellow emitting phosphor directly contacts with the LED chip, leading to the temperature increase at the junction of the LED and phosphor layer. Therefore, reducing the outcome of heat would improve the phosphor performance and avoid the irreversible damage to the phosphor. Many previous studies have established that the remote phosphor structure in which phosphor is placed far from the heat source (LED chip) can reduce the effect of heating. With a sufficient large distance of phosphor and the LED chip, LEDs could limit the backscattering and circulation of light inside. This approach is an optimal solution to manage the heat of LED and thus can enhance the luminous efficiency as well as the color quality of LEDs

[11-14]. Nonetheless, the remote phosphor structure is qualified enough for regular lighting but may not meet other requirements of many other illumination applications, which is probably the reason why the next generation of LED is needed to be created. For further development, some novel structures of remote phosphor are proposed to minimize the backward scattering of the phosphor towards the chip and enrich the luminous efficiency. Another study showed that an inverted cone lens encapsulant and a surrounding ring remote phosphor layer can redirect the light from the LED chip to the surface of the LED and then reduce the loss caused by internal reflection inside LED [15]. A patterned remote phosphor structure with a clear region in the perimeter area without coating phosphor on the surface surrounding could achieve high uniformity of angular-dependent correlated color temperature and chromatic stability [16]. Moreover, the patterned sapphire substrate applied in the remote phosphor could deliver much better uniformity of the correlated color temperature in a far field pattern than a conventional pattern [17-20]. Remote phosphor with dual layer package is proposed to improve the light output of LEDs. However, these structures still do not bring about an optimized color uniformity with superior light efficiency.

This is the first time a study about the influence of two phosphor layers on the performance of pc-WLEDs, including lumen efficiency and color angular uniformity has been investigated and presented. The simulation is conducted by moving two phosphor layers between the first layer and the LED chip, then choosing the most suitable distance to obtain higher lumen output and higher color quality. The simulation results show that when the lumen output is highest, the angular uniformity will occur if the distances between two phosphor layers and between the phosphor layers with blue LED surface are selected appropriately. Consequently, the backscattered photons can be extracted as well as the overall light output and luminous efficacy can be significantly increased. This study aims to find out how two phosphor layers affect the final performance of a remote-phosphor white LED in terms of light output and color properties.

2. Computational simulation

2.1. Constructing the WLEDs configuration

Fig. 1 (a) illustrated the WLED model used in this study which is the actual W-LEDs having the best optical-thermal stability performance. The simulation is designed and fabricated precisely to make sure that it and the actual one are identical. The simulated model has normalized cross correlations of approximately 99.5%, which means that it is similar to the actual package. Moreover, the influences of LED wavelength, temperature, and light intensity on the lumen output and correlated color temperature can be significantly decreased. The simulation of the phosphor compounding of the LED is carried out by applying the LightTools program. Moreover, the weight of $YAG:Ce^{3+}$ phosphor is controlled in this simulation process. To carry out the demonstration of the two phosphor layers' impacts on the performance of pc-LEDs at the correlated temperature of 8500 K, 3-D ray tracing simulation with LightTools software is employed. It can be seen from the model structure that the components of a WLED includes blue LED chips, two phosphor layers, a reflector cup, and a silicone layer. The structure of WLED model with a dome-lens are used for simulation from the real one as shown in Fig. 1 (c).

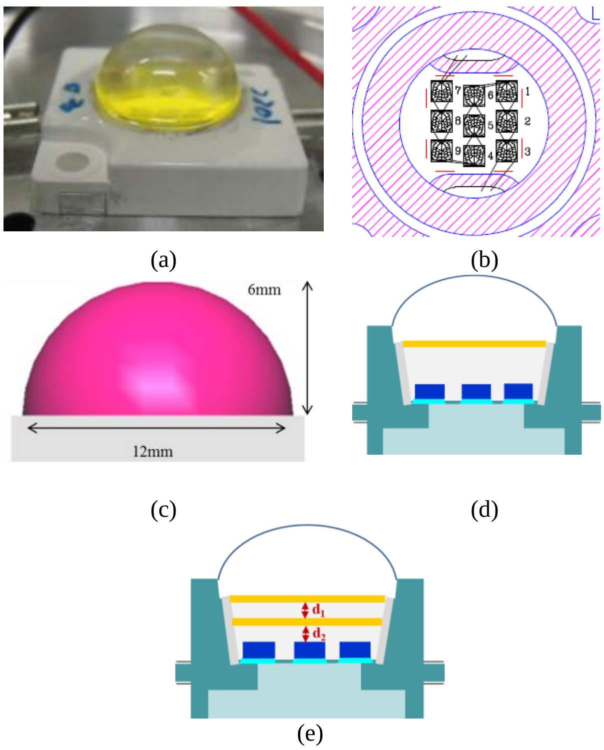

Fig. 1. Photograph of WLEDs structure: (a) Actual WLEDs, (b) Bonding diagram, (c) Simulation of WLEDs using LightTools commercial software, (d) Single remote phosphor package, (e) Dual flat remote phosphor package (color online)

A reflector which has a height of 2.07 mm and a bottom length of 8 mm is boned with these chips. In addition, every factor of each blue chip which is attached to the reflector has been carefully designed to get the superlative outcomes. Specifically, as shown in Fig. 1 (b), the value of dimension, the radiant power, and a peak wavelength are 1.14 mm × 0.15 mm, 1.16 W, and 453 nm, respectively. The traditional single-layer remote phosphor structure (SRP) is illustrated in Fig. 1 (d). In this study, we present five actual LED packages with average CCT from 5600 K to 8500 K to help readers make comparisons easily. Fig. 1 (e) demonstrated the dual-layer remote phosphor structure (DRP) with 8500 K average CCT. The chips are covered with a 0.08 mm thick phosphor layer as depicted in SRP and DRP. In order to clarify the effect of using three phosphor layers, the optical simulation process is conducted with the variation of distance among phosphor layers with the LED. The shape of phosphor particle is spherical and its average diameter is 14.5 µm. In the simulation process of the remote phosphor structure of WLEDs, two phosphor layers are separated by a distance called d_1 while the distance between the LED surface and the lower phosphor layer is called d_2 as illustrated by Fig. 1 (e), where d_1 is varied from 0 to 0.64 mm and d_2 is differed from 0 to 1.43 mm.

When d_1 and d_2 are adjusted, the luminous flux can reach the highest value and the color deviation will receive the smallest index. To maintain the color temperature of LED at 8500 K, the concentration of phosphor needs to be varied from 14%-26% wt. corresponding to the distance of phosphor layers.

This model allows us to adjust the phosphor location to find out the optimal distance between phosphor layers that can determine the optical characteristics of LEDs. In the simulation process, the position of the middle phosphor layers is modified and the position of the top phosphor layer is fixed to the LED chip. Notwithstanding, the placement and arrangement of phosphor layers in dual-layer package can generate the substantial variation of the correlated color temperature of LEDs due to the absorption, scattering, transmission, and conversion of light. To maintain the same CCT of this package, depending on the distance between two phosphor layers in pc-LEDs, the phosphor concentration needs to be varied appropriately as shown in Fig. 2. Obviously, the phosphor concentration of dual-layer package has a tendency to drop from 26% to 14% in the range of 0 - 1.43 mm. According to these results, it can be deduced that the phosphor concentration needs to be reduced to ensure that this package's CCT is constant during the simulation process. Another noticeable point is that the concentration of yellow phosphor changes moderately when d_1 exceeds 0.08 mm.

Specifically, when d_1 climbs from 0 to 0.08 mm, $YAG:Ce^{3+}$ concentration declines sharply from 24.11% to 16.22%. Simultaneously, the scattering in the LED packages slumps markedly, which is only conducive to the color uniformity but not to the luminous flux. However, as d_1 continues to go up to 0.64, the $YAG:Ce^{3+}$ concentration changes slightly. Similarly, the concentration of $YAG:Ce^{3+}$ falls steeply from 19.55% to 16.22% when d_2 climbs to 0.55 mm. Then, d_2 keeps increasing with different $YAG:Ce^{3+}$ concentration. From Fig. 2, it is clear that the distance d_1 and d_2 have enormous influences on the scattering and absorption of the remote phosphor layer, i.e., which affects the optical properties of the WLEDs.

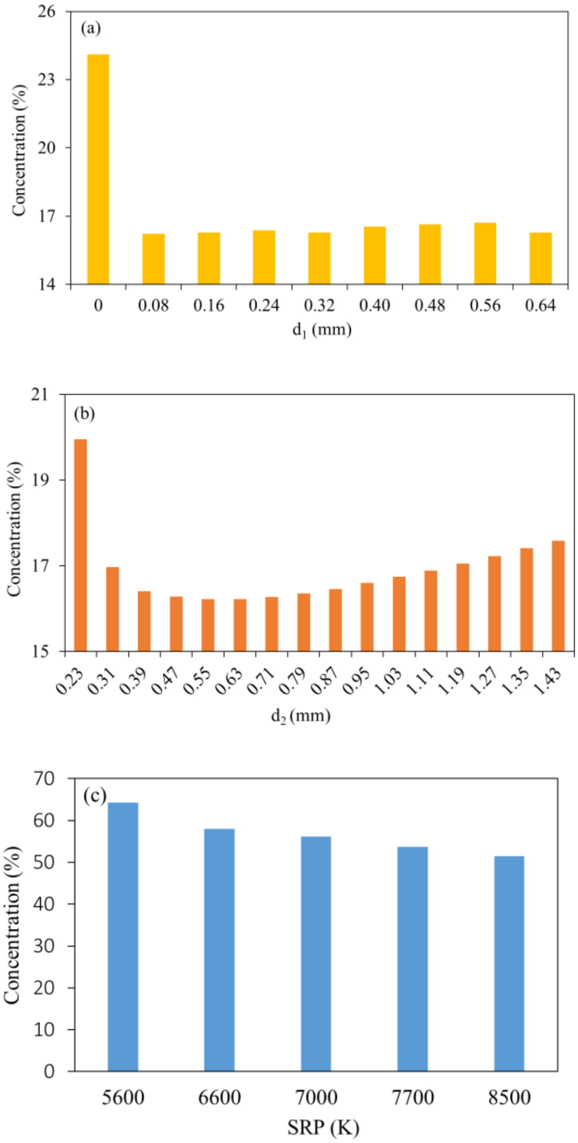

Fig. 2. The concentration of yellow phosphor with different distance between two phosphor layers (a) between phosphor layer with LED surface (b), (c) case of SRP (color online)

Specifically, when d_1 or d_2 changes, the internal scattering characteristic of LED can be changed flexibly. For the traditional SRP structure, after considering various studies, optical parameters such as the distance between the phosphor layer and the LED surface, the phosphor layer thickness or the particle size and concentration of phosphor are optimized quite completely. Meanwhile, in terms of the proposed DRP structure in this article, two parameters d_1 and d_2 are unknowns, which have not been discussed in any research before.

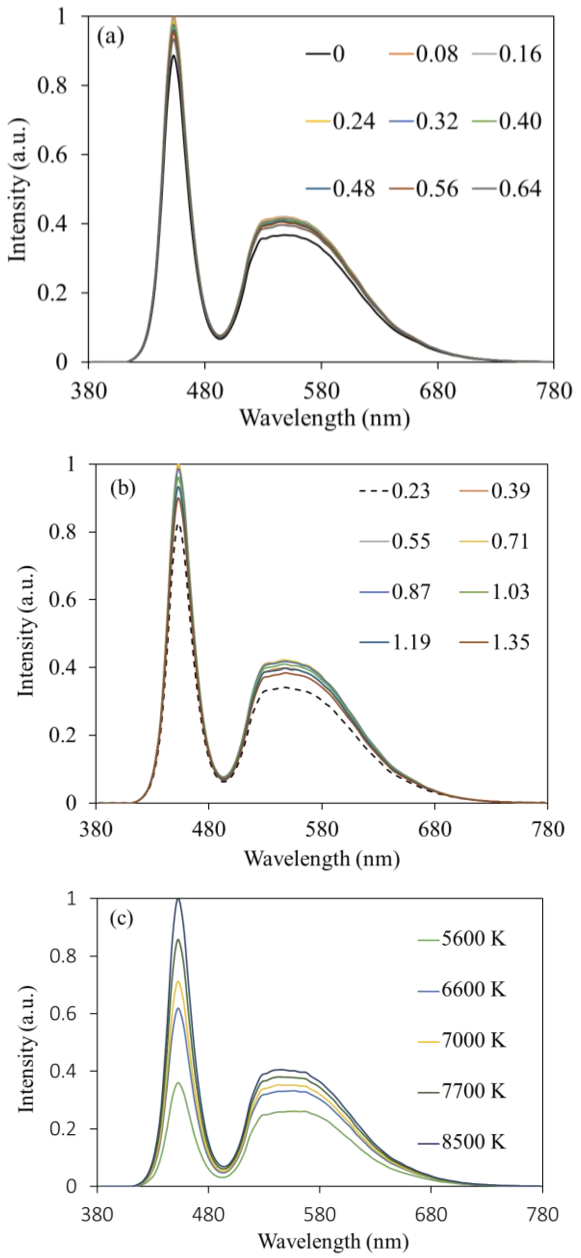

Fig. 3. Emission spectra of dual-layer phosphors: (a) case of d_1; (b) case of d_2, case of SRP (color online)

2.2. Computing the transmission of light

This part will present and demonstrate the mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure, from which a huge improvement of LED efficiency can be obtained.

The transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of 2*h* are expressed as follows [21, 22]:

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

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

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 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:

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

To verify the increase of the flux, Fig. 3 depicts the emission spectrum of the dual-layer phosphor. For d_1, the emitted spectral intensity when $d_1 = 0$ is smaller than that in the cases $d_1 > 0$, at the two wavelength ranges of 380 - 480 nm and 480 - 580 nm. For d_2, when the blue LED surface is separated at least 0.23 mm from the lower phosphor layer, the luminous flux is the lowest, compared to the case of $d_2 > 0.23$ mm. Thus, the photon emitted in dual-layer phosphor structure is larger than that of the single layer phosphor structure.

3. Results and discussion

Fig. 4 illustrates the influence of the distance among phosphor layers and the LED chip of remote phosphor package on the lumen output. The obtained results show that the variation of the distance has a dramatical impact on the light extraction. An enormous change from the beginning is that the lumen output tends to increase sharply and reach its peak in the range of 0 - 0.08 mm for d_1 and 0.23 mm - 0.63 mm for d_2. The luminous flux is maximum at 1020 lm when $d_1 = 0.08$ mm or $d_2 = 0.63$ mm. Conversely, the lumen output has a slight downward trend when the distance between the phosphor layers continuously increases further. The blue light from LED chip will encounter the first phosphor layer and be converted to the yellow light. Still, some portions of light are lost inside the LEDs due to the backscattering, absorption, and reflection while other portions are converted to yellow light and transmitted throughout the second phosphor layer.

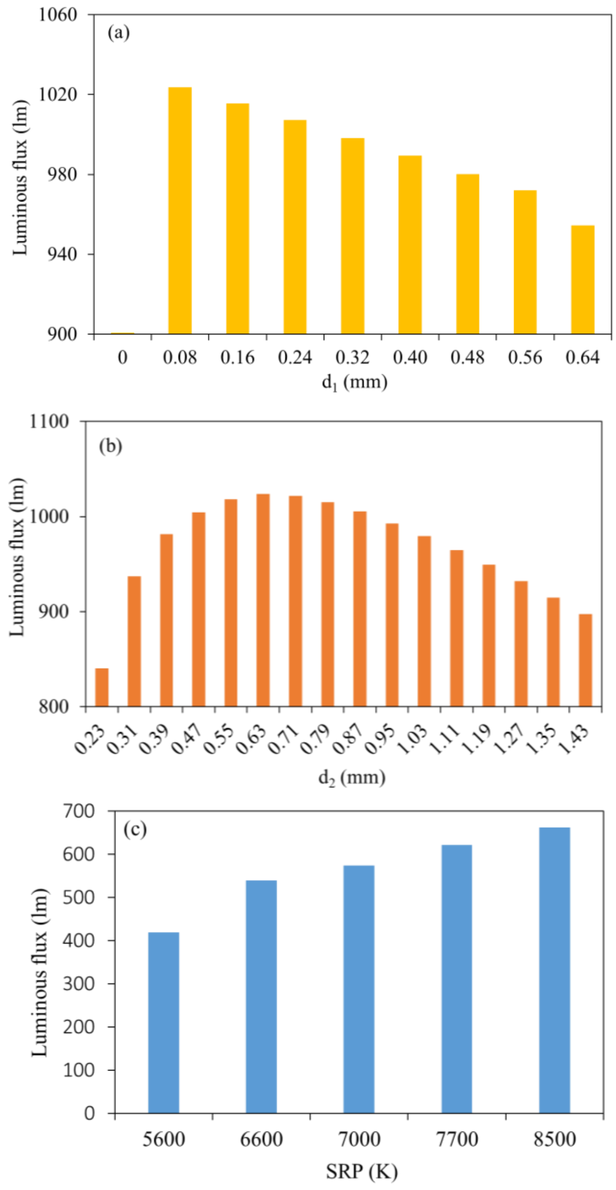

Fig. 4. The luminous output of WLEDs at the same CCT with different distance between phosphor layers: (a) case of d_1; (b) case of d_2; (c) case of SRP (color online)

The increase of the distance leads to the closer gap between the phosphor layer and the LED chips, and thus, the light is trapped more and reflected inside the gap between the first phosphor layer with the LED chips. This is the reason why the increase of the junction temperature of phosphor layers and the LED chips may produce the low conversion efficiency.

Equation 5 proved that DRP structure results in higher lumen output than the SRP. Also, in Fig. 4, this result is demonstrated clearly, which confirmed the benefit of DRP structure for the luminous flux of LED. Particularly, Fig. 4 (a) shows that the luminous flux of DRP structure decreases to 954 lm when d_1 = 0.64 mm. Meanwhile, when d_2 = 0.23 mm, the attained lumen output is 840 lm, as presented in Fig. 4 (b). These values indicated that the minimum values of lumen output of DRP structure, as in two aforementioned cases, are higher than that of the SRP. Moreover, from these results, there is an essential need in controlling d_1 and d_2 for DRP to reach the optimal luminous flux.

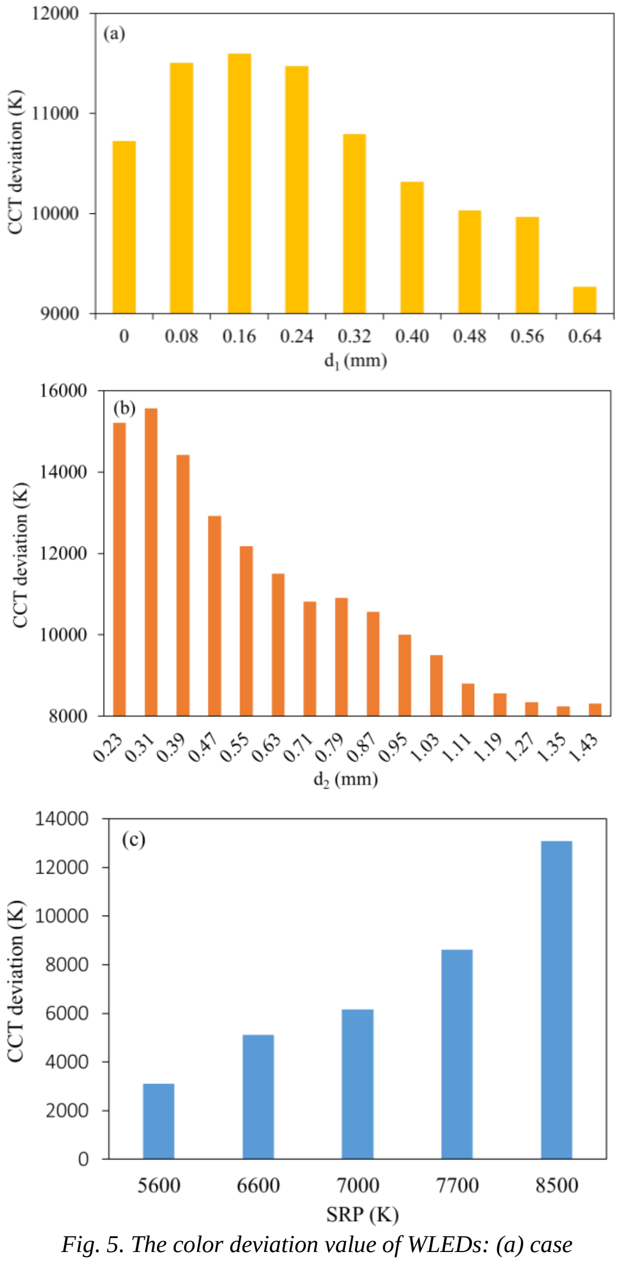

Fig. 5. The color deviation value of WLEDs: (a) case of d_1; (b) case of d_2, (c) case of SRP (color online)

Similar to the luminous flux, the color deviation increases dramatically when d_1 = 0.08 mm and maintained to 0.24 mm. It means the increase of d_1 in this range will negatively affect the color uniformity of WLEDs, as shown in Fig. 5 (a). The color deviation is determined by the scattering in the phosphor layer and this has been confirmed in many recent studies [18-22]. When d_1 increases, the space where the scattering events occur extents, which causes more rays to be mixed and more homogeneous. As a result, the color quality becomes better. Therefore, when d_1 continues to increase to 0.64 mm, the color deviation will be minimized to the smallest value. Similarly, the color difference increases slightly when d_2 = 0.31. Yet if d_2 keeps going up, the color deviation can be halved from the original when d_2 = 1.35 mm, as shown in Fig. 5 (b). In conclusion, as can be seen from Fig. 5, the influence of d_2 on color homogeneity is much greater than d_1's.

The color deviation of SRP structure is 13084 K, and it is hard to adjust this deviation as the optical parameters of this structure are nearly optimal. Fig. 5 (c) shows that the color deviation of the 8500 K package is the largest, compared to the other packages. Thus, this package is the one that need to be improved. In this research, we decided to choose the LED package having CCT of 8500 K to make an advance and prove the effectiveness of this dual-layer structure, especially when the enhancement of LEDs with 8500 K still remains a difficult task. Based on the results demonstrated in Fig. 5 (a) and Fig. 5 (b), the color deviation of DRP structure can be changed significantly when extending d_1 and d_2. In other words, DRP structure exhibits a superior decrease in color deviation than the SRP. In short, the results of Fig. 5 are valuable references for improving the color quality of LED not only with dual-layer remote phosphor in particular but also remote phosphor structure in general.

4. Conclusions

To sum up, this research analyzes and demonstrates in detail the influence of the distances d_1 (between two phosphor layers) and d_2 (between the phosphor layer and the LED surface) on the optical characteristics of remote phosphor package. The researched results revealed that the appropriate position of phosphor layer in remote phosphor package will significantly improve the luminous flux and color uniformity of WLEDs. The luminous flux remarkably rises and reaches the maximum value when d_1 = 0.08 mm or d_2 = 0.63 mm, while the color uniformity value reduces in both cases. Meanwhile, if $d_1 > 0.08$ mm or $d_2 > 0.63$ mm, the lumen output and the color deviation have a slump trend. This is due to the effect of the increase in the trapping, the absorption, and the re-scattering of light in LED package and the chemical transformation of the heated phosphor layer. Hence, studying a suitable distance between phosphor layers in remote phosphor package is a chief factor in designing high efficiency pc-LEDs.

Acknowledgements

This work was supported by the Ministry of Science and Technology of the Republic of China, project 108-2622-E-992-013 -CC3.

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