The Impacts of Distance Between Phosphor Layers on Optical Properties of Triple-Layer Phosphor Structure

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Abstract. *One of the crucial goals often thought of in connection with remote phosphors is to make the emitted photon larger than other structures. However, the two biggest hurdles that make achieving the goals more challenging are color uniformity and Color Rendering Index (CRI). This is the reason why people have started to pay more attention to these issues in recent research papers. Thus, this study will present the idea of controlling the distance between phosphor layers to control the optical parameters of White light LED (WLED). Based on the Mie scattering theory, which is about absorption and scattering of plane electromagnetic waves by uniform isotropic particles of the simplest form (sphere, infinite cylinder) which are in a uniform and isotropic dielectric infinite medium, the results of the study are confirmed to be completely accurate and reliable. Specifically, when d = 0.64 mm, the flux can increase to 9.7 % compared to the original. Similarly, when d = 0.84 mm, the color uniformity can be double better meanwhile the CRI value is kept intact. Once fully calculated and substantiated, the paper will provide comparable results in practice for the production of higher quality WLED.*

Keywords

Color uniformity, Lambert-Beer law, luminous flux, Mie-scattering theory, triple-layer phosphor, WLED.

1. Introduction

Phosphor-converted white Light Emitting Diode (LED) is one of the factors with outstanding advantages for solving lighting problems and also the fourth potential source of light used to replace other conventional light sources. White light emitting diodes are becoming more and more popular and widely used in daily life, such as landscape and street lighting, backlighting, etc. Nevertheless, the light extraction efficiency and the angular homogeneity of correlated color temperature of white LED are always the challenging factors that restrict its development [1] and [2]. Due to the increasing demand of the market and its applications, more breakthroughs in lighting efficiency and color uniformity are needed to achieve higher illumination efficiency. One of the most common approaches for this problem is to generate white light based on the combination of blue light from the LED chip and the yellow light from the Ce^{3+}-doped $Y_3Al_5O_{12}$ phosphor ($YAG:Ce^{3+}$). Although this concept sounds unremarkable, the structure of the LEDs and the arrangement of the phosphor layers play an extremely important role in determining the luminous efficiency, especially the angular homogeneity. Some common phosphor coating methods are proposed for the manufacture of LEDs, such as dispensing coating and conformal coating [3], [4] and [5]. However, these structures do not bring out high luminous efficiency due to the degradation in light conversion of phosphor material, which is caused by the fact that the yellow emitting phosphor directly contacted with LED chip leads to the temperature increasing at the junction point of the LED and phosphor layer. Hence, reducing the effect of the heat would increase the phosphor performance and avoid the irreversible damage to the phosphor. Many studies have demonstrated that the remote phosphor structure, in which phosphor is placed far from the heat source (LED chip), can decrease the impact of heat considerably [6], [7], [8] and [9]. With that sufficient large distance of phosphor and LED chip, LEDs could reduce the backscattering and circulation of light inside them. This approach is an optimal solution to manage the heat of LED and thus it can improve the luminous efficiency as well as the color quality of LEDs. Still, the remote phosphor structure is good enough for regular lighting but may not meet different requirements of many illumination applications that are probably the reason for the next generation of LED. For further development, some novel structures of remote phosphor are proposed to minimize the backward scattering of the phosphor towards the chip and strengthen the luminous efficiency [10]. Another study employing 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 [11]. A patterned remote phosphor structure with a clear region in the perimeter area without coating phosphor on the surface surrounding could help achieve high uniformity of angular-dependent correlated color temperature and chromatic stability. 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. The remote phosphor structure has been proposed to improve the light output of LED [12]. Nevertheless, these structures still do not help achieve an optimized Correlated Color Temperature (CCT) uniformity with superior light efficiency.

In this paper, for the first time, a study about three-layer phosphor's effect on the performance of phosphor converted White LED (pc-WLED), including lumen efficiency and CCT angular uniformity, is investigated and presented. The simulation is conducted by moving two phosphor layers between the first layer and the LED chip and then choosing the most appropriate distance to obtain higher lumen output and higher color quality. The simulation results show that with the highest lumen output, the angular uniformity can be achieved at the distance of 0.7 mm among these phosphor layers. The backscattered photons can be extracted and the overall light output, as well as the luminous efficacy, can dramatically go up. The objective of the study presented here is to understand how the three-layers phosphor affects the final performance result of a remote-phosphor white LED in terms of light output and color properties.

2. WLED Modelling

The influence of using two-layer phosphor on the performance of pc-LEDs at the Correlated Color Temperature (CCTs) of 5600 K to 8500 K is carried out by utilizing 3-D ray tracing simulation with LightTools software. As can be seen from the model structure, the components of a WLED include the blue LED chips, three-layer phosphor, a reflector cup, and a silicone layer. The structure of WLED model with a dome-lens is used for simulation from the real model of WLED, as shown in Fig. 1(a) and Fig. 1(d).

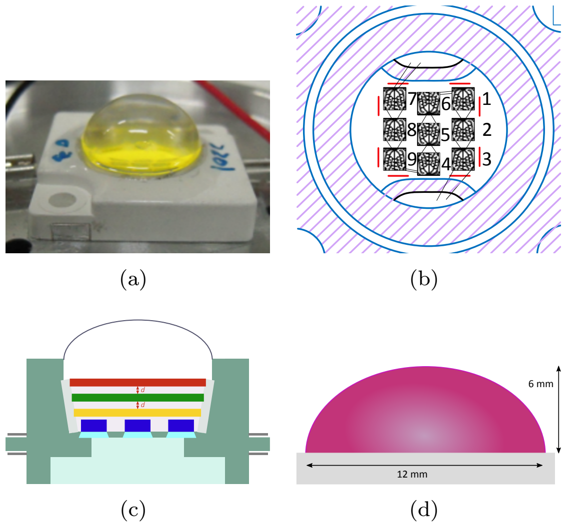

Fig. 1: Photograph of WLED structure: (a) Actual WLED, (b) Bonding diagram, (c) Illustration of pc-WLED model, (d) Simulation of WLED using LightTools commercial software.

A reflector has a height of 2.07 mm and a bottom length of 8 mm, which is boned with these chips. In addition, every factor of each blue chip which is attached to the reflector has carefully been designed to get the best results, where 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, as shown in Fig. 1(b). Besides, Fig. 1 also depicts that the chips were covered with a 0.08 mm thick phosphor layer. In order to clarify the effect of using three-layer phosphor, the optical simulation process is conducted with a variation of distance among phosphor layers with 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 WLED, the two layers are separated by a space called d, as illustrated in Fig. 1(c), where d is adjusted from 0.24 to 0.84 mm. By varying d, the luminous flux can reach to the highest value as well as the color deviation can receive the smallest index. To maintain color temperature of WLED, the concentration of phosphor is varied corresponding to the distance of phosphor layers, as shown in Fig. 2.

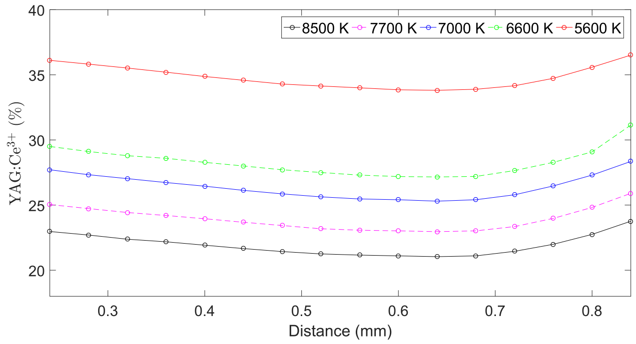

Fig. 2: The concentration of yellow YAG:Ce^{3+} phosphor as a function of d.

As can be seen from Fig. 2, the concentration and particle size of the two layers of red phosphor and green phosphor are fixed. Meanwhile, the concentration and size of the yellow phosphor layer are changeable. Compared to the two in-cup phosphor and conformal phosphor structures, it is much more difficult for the remote phosphor structure to bring better result. Thus, the idea of coating the red phosphor layer aims to increase the CRI for the LED, and cover the green phosphor layer to increase the optical and color uniformity. To make it more convincing, the study utilized WLED with four different CCTs in the range from 5600 K to 8500 K.

However, the studies mentioned above were conducted in the case that the subjects were single-chip WLED and the color temperature was less than 7000 K. Still, if CCTs is greater than 7000 K, the study will become more complicated due to the effect of the scattering and absorption of phosphoric layers. It is easy to recognize the obvious difference in CCT concentration here. The higher the color temperature is, the lower the phosphor concentration gets. Moreover, the change in concentration and distance also has a huge effect on luminosity and color quality. In addition, it is impossible to measure the impact of the red phosphor layer and green phosphor layer mentioned above. The results and further discussion will be put into Sec. 3.

3. Results and Discussion

Figure 3 indicated the dramatic influence of d on the flux of WLED. When d climbed from 0.24 to 0.64 mm, the photon tended to increase and reach a peak of 968 lm at $d = 0.64$ mm. This can be explained by Eq. (1), Eq. (2) and Eq. (3). As d rose, light transmission became easier between layers, resulting in increased luminosity. However, when $d > 0.64$ mm, the yellow phosphor concentration YAG:Ce^{3+} also enhanced, leading to a decline in the optical flux of WLED. Specifically, the discrepancy of the WLED corresponding to the values of d is shown in Tab. 1.

Tab. 1: The luminous flux as a function of d with the average CCTs.

CCTs (YAG:Ce^{3+} %)	0.24 mm	0.64 mm	0.84 mm
5600 K (36.11 %)	560 lm	622 lm	482 lm
6600 K (29.5 %)	730 lm	801 lm	627 lm
7000 K (27.71 %)	777 lm	853 lm	669 lm
7700 K (25.04 %)	850 lm	917 lm	729 lm
8500 K (22.97 %)	905 lm	968 lm	781 lm

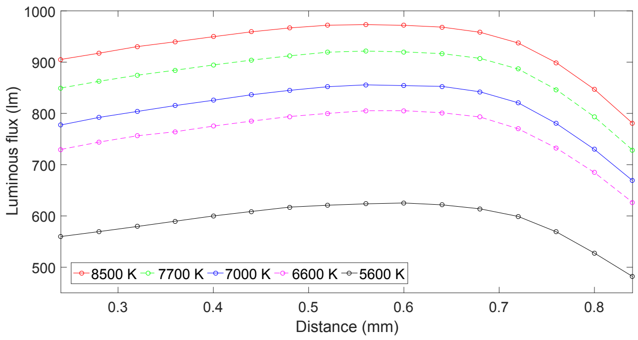

Fig. 3: The luminous output of WLEDs as a function of d.

There are two reasons for the improvement in brightness: the presence of large green phosphors, and the appropriate distance d leading to optimization of light transmission. When choosing $d = 0.64$, the flux could go up to 71 lm compared to the original distance ($d = 0.24$ mm). This means that the flux could increase by about 9.7 % compared to the original one.

For the triple-layer phosphor package, the mathematical model of the transmitted blue light and converted yellow light is presented and demonstrated. As a result, a great improvement in LED efficiency can be obtained in this mathematical model. The transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of h is expressed by following:

$$PB = PB_0 \cdot e^{-\alpha_B h}, \tag{1}$$

$$PY = \frac{1}{2} \frac{\beta \cdot PB_0}{\alpha_Y - \alpha_B} \left(e^{\alpha_B h} - e^{\alpha_Y h} \right), \tag{2}$$

where 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. αB; αY are parameters describing the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer, respectively. We can put the Mie-scattering theory [2] and [13] into practice to derive the relationship of luminous output to the phosphor weight rigorously. The transmitted light power can be calculated by the Lambert-Beer law:

$$I = I_0 e^{-\mu_{ext} L}. \tag{3}$$

In this formula, I_0 is the incident light power, L is the phosphor layer thickness (mm) and μ_{ext} is known to be the extinction coefficient, which can be expressed as: $\mu_{ext} = N_r \cdot C_{ext}$, where N_r is as the number density distribution of particles (mm^{-3}). C_{ext} (mm^2) is the extinction cross-section of phosphor particles. Using MATLAB, the extinction cross-section C_{ext} (mm^2) of particles is computed as:

$$C_{ext} = \frac{2\pi a^2}{x^2} \sum_{n=1}^{\infty} (2n+1)\,\mathrm{Re}\,(a_n + b_n)\,, \tag{4}$$

$$a_n(x,m) = \frac{\psi_n'(mx)\,\psi_n(x) - m\psi_n(mx)\,\psi_n'(x)}{\psi_n'(mx)\,\xi_n(x) - m\psi_n(mx)\,\xi_n'(x)}, \tag{5}$$

$$b_n(x,m) = \frac{m\psi_n'(mx)\,\psi_n(x) - \psi_n(mx)\,\psi_n'(x)}{m\psi_n'(mx)\,\xi_n(x) - \psi_n(mx)\,\xi_n'(x)}, \tag{6}$$

where the particle size parameter is defined as $x = \pi D/\lambda$, a_n is the expansion coefficient with even symmetry, b_n is the expansion coefficient with odd symmetry, D is the diameter of phosphor particle, m is the refractive index, λ is the calculated wavelength, and $\psi_n(x)$ and $\xi_n(x)$ are the Riccati - Bessel functions.

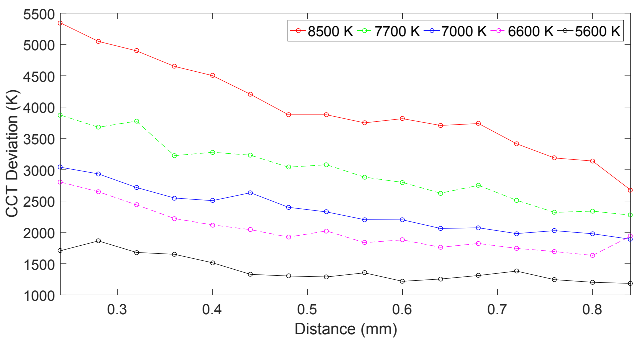

Fig. 4: The color deviation value of WLEDs as a function of d.

As can be seen from Fig. 4, the adjustment of the distance d not only provides higher luminosity but also sharply reduces color deviation. When lengthening d, the light transmission will become more convenient between the layers. Besides, the scattering will also climb up by increasing the scattering space. The scattering variation when modifying d is shown obviously in Tab. 2 from which it can be easy to see that the largest decrease in CCT of 8500 K falls by almost 50 %, which means that the shade white light is double better. The definition of the CCT deviation is calculated as follows: D-CCT = $\mathrm{CCT}_{(\max)} - \mathrm{CCT}_{(\min)}$. Where $_{(\max)}$ and $_{(\min)}$ represent the maximal CCT at the zero degrees of viewing angle and minimal CCT at the 70 degrees of viewing angle, respectively. The scattered light of each particle in pc-LEDs is different, resulting in varying the optical properties of WLEDs. If the scattered blue light is enhanced enough, the CCT deviation can be reduced significantly. Conversely, the CCT deviation should be increased with lack or redundancy of the scattered blue light in WLEDs. The scattered blue light not only combines with the converted yellow but also combines the yellow ring for emitting white light, resulting in reduction of yellow ring phenomenon of WLEDs.

Tab. 2: The color deviation (D-CCT) as a function of d with the average CCTs.

CCTs (YAG:Ce^{3+} %)	0.24 mm	0.64 mm	0.84 mm
5600 K (36.11 %)	1707 K	1255 K	1185 K
6600 K (29.5 %)	2803 K	1762 K	1939 K
7000 K (27.71 %)	3040 K	2062 K	1939 K
7700 K (25.04 %)	3872 K	2625 K	2275 K
8500 K (22.97 %)	5344 K	3706 K	2676 K

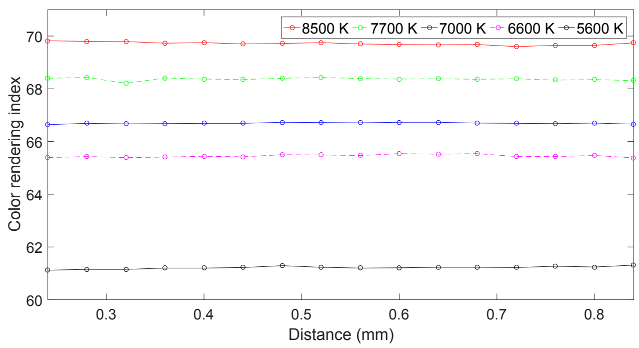

Fig. 5: The color rendering index of WLEDs as a function of d.

Actually, the smaller the color deviation is, the better the white light can achieve. This is the chief goal of the study. At all CCTs values, the deviation gets the lowest value when $d = 0.84$ mm. When d increases, the color uniformity is also better due to the following reasons: the scattering in WLEDs increases with the green and red phosphor layers, which are also the main influences of color uniformity, leading to the increase of the scattering space as well as the mixing of light rays, resulting in a reduced color deviation.

Therefore, choosing wisely the appropriate increase is the vital key to increasing the optical and uniformity color of WLEDs.

In addition, the CRI results are also shown in Fig. 5. It is easy to see that CRI is not affected by changing the distance (d). So what is the effect of red phosphor? Normally, when red phosphor is added into the compound, the CRI will go up while the flux falls down. In this case, however, it is interesting to note that the CRI results are stable while luminosity and color uniformity are higher. For further understanding, look back to the structure of WLEDs in which the red phosphor layer is on the top. It can be seen that much of the light passing through the green phosphor layer was white. Hence, the absorption capability of red phosphor with white light is very poor. This means that the red phosphor layer just has a slight impact on enhancing the CRI as an initial target. However, the presence of this red phosphor layer will increase the scattering in the LED, which is beneficial for color uniformity. Remaining the CRI unchanged while the luminescent and color enhancers increase is also a better outcome.

4. Conclusion

In conclusion, the influences of the distance d on the optical parameters of WLEDs were presented in detail in this research paper. The Mie scattering theory is also applied here to confirm the results. According to experimental results, the flux could increase by 70 lm, equivalent to 9.7 % when $d = 0.64$ compared to the distance $d = 0.24$. However, when $d > 0.64$ mm, the concentration of YAG:Ce^{3+} phosphor increased, resulting in reduced transmission of light through the yellow phosphor layer as well as negligible lumen loss. Therefore, if the goal is to enhance the quality of flux, the manufacturers can choose the phosphor in which $d = 0.64$ mm. In addition, color uniformity was considered as the second objective of the study. Particularly, the color deviation could reduce by 50 % compared to the original distance, which means that the color may be twice as good as that when $d = 0.84$ with a CCT of 8500 K. This is an important reference for the manufacturers in terms of color uniformity. Furthermore, the third objective of the study was CRI. Because the red phosphor layer on the top is poorly capable of absorbing white light, this red phosphor layer has slight effect on CRI. Thus, it can be seen that CRI stayed remain when d increased. Nevertheless, this red phosphor layer could increase the scattering in the LED and also stabilize the CRI value. In summary, this article has provided valuable reference information for the production of better WLEDs.

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