

Using flat phosphor layer in dual-layer remote phosphor configuration to improve luminous efficacy

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ABSTRACT

The phosphor layer shape and components distances are the subjects proposed to advance the quality of WLEDs in this article. The two distances, between phosphor layers (d_1) and between the phosphor layer and the LED chip (d_2) in Flat dual-remote phosphor (FDRP) and Concave dual-remote phosphor (CDRP) were examined by experiments to determine their impacts on WLEDs lighting performances. The results suggest that FDRP is a better option than CDRP for lighting performance. In each respective structure, the distances influence the lighting capacity and color output whenever they fluctuate. Therefore, to effectively control and study this phenomenon, the correlated color temperature is maintained at 8500 K, and the concentration of phosphor material is altered while the distances are changing. When d_1 and d_2 are at the starting value of 0, the recorded lumen output and chromatic performance of lighting devices are the lowest and begin to increase as d_1 and d_2 expand. Bigger d_1 and d_2 mean bigger scattering area and better chromatic light integration, which leads to higher color quality. Detailed results present that optimal values of d_1 or d_2 for the highest lumen output of 1020 lm are 0.08 mm or 0.63 mm, respectively. Meanwhile the lowest color deviation is accomplished with $d_1=0.64$ mm or $d_2=1.35$ mm.

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1. INTRODUCTION

Recently, the luminescence industry is taken by solid state lighting, a lighting solution that applies non-polluting materials, better than conventional method in terms of efficiency and durability [1]. Out of many solid-state lighting options from organic light-emitting diode (OLED), quantum-dot light-emitting diode (QLED) to carbon-dot light-emitting diode (CLED), the light-emitting diode (LED) is always the optimal solution owing to better optical properties and therefore being applied in many different lighting applications [2]. Much like every other lighting solution, LED is constantly making changes to adapt to higher application demands of the industry, although the process is stagnant due to obstacles in color quality and light output enhancement [3]. To solve the problem, many researches have proposed placing a distance between the blue light source and yellow light source of WLEDs. The idea is implemented in remote phosphor structure, which was reported as a positive reinforcement on the lumen output and durability of LEDs lighting

devices [4, 5]. Despite being an advanced solution and currently widely applied, the remote phosphor structure still experiences reduced lighting efficiency due to the discrepancy of emission spectra in LED chip and phosphor materials. The issue was studied through intensive research and many solutions that suggest changing the configuration or particles setting for better light output were proposed. These solutions include applying phosphor with pattern or molded with particular shape [6], adding more phosphor layers into the structure [7], blending with other substances such as nanoparticles [8], and using other innovative phosphor with distinct traits [9]. Others try to achieve enhanced emitted light through LEDs alteration with the reflector [10]. The mechanism of structures that employ remote phosphor as optical properties enhancer is presented in a few notable research [11-13]. A study attempted to boost the lighting capacity with inner reflection enhancing setup that requires half a spherical shell lens made of polymer and a layer of phosphor dispersed inside [14]. Another one altered the device structure by planting a space to deflect the emitted light in the desired direction and increase light output [15]. Beside the structure configuration that hugely affects the outcome of light, the attention should also be on the amount of phosphor materials presents in the device. Evidently, the light loss that damages the lighting efficiency and often appears in low CCTs WLEDs increases with the concentration of phosphor material [16]. Other possible causes for reduced luminous flux that have been pointed out by other research are high scattering and reflecting. From this issue, it is apparent that improving the yellow and blue lights emission and simultaneously limiting light loss from any sources are the most practical solutions. As mentioned, lighting output is one of the essential optical traits that draws in lots of effort from researchers while multi-layer phosphor structure, namely the remote configuration with two phosphor layers, is the most effective and frequently used tool to achieve the goal [17-21]. Even when the target and tool are determined, choosing a specific setup for the lighting device is still complicated considering there are many other options that have different references and can be useful in distinct scenario. Therefore, we include the two most notable options, flat dual-layer remote phosphor configuration (FDRP) and concave dual-layer remote phosphor configuration (CDRP), for research. Our results show that FDRP is the better choice because FDRP WLEDs is more responsive to the changes of d_1 and d_2 . In particular, the distances between phosphor layers and phosphor layer with LED chip are more influential to the scattering properties in FDRP, which improves the light output. On the other hand, CDRP WLEDx with arched shape phosphor layers does not show much changes when these distances fluctuate, which makes lighting enhancement more difficult. Moreover, the fact that shaped phosphor layers in CDRP are not easily manufactured allows FDRP to stand out as the best option for lumen output with the suitable amount of yellow phosphor YAG:Ce³⁺.

2. COMPUTATIONAL SIMULATION

2.1. Constructing the WLEDs configuration

To construct the dual-layer phosphor WLEDs that is suitable for the experiments, we used the LightTools software and simulated the 8500 K lighting device with 3-D ray tracing [22, 23]. The simulated product can be view in Figure 1, with Figure 1 (a) demonstrating the physical model containing all the components placed on the structure. Figure 1 (b) shows the arrangement of 9 blue chips implanted into gaps within the structure. These gaps are 2.07 high and each 8-mm-diameter reflector contains a 1.14x0.15 mm in size, 1.16 W in lighting energy, and 453 nm in highest emission wavelength of blue chip. This setup of blue chips is applied in FDRP and CDRP, which are expressed by Figures 1 (c) and (d), respectively. In particular, Figure 1 (c) presents that d_1 and d_2 , are the indicators for distances between phosphor layers and from the phosphor layer to chips surface, while in Figure 1 (d), these distances are represented by r_1 and r_2 . Besides the difference that FDRP has straight phosphor layers and CDRP has bended phosphor layers, other components are the same from the blue chips, reflector cup, silicone gel, to the fixed 0.08 mm of phosphor thickness. The phosphor particles in WLEDs are in circular shape with diameter around 14.5 μm . The experiments will measure the optical properties of WLEDs in both FDRP and CDRP with the distances constantly changing. We assess the performance of phosphor layers and WLEDs in each case and then apply them to the comparison between FDRP and CDRP. The results are utilized to evaluate the best structure and distances for lighting performance. To keep the WLEDs at a stable condition to conduct experiment while changing other factors, the concentration of phosphor must be adjusted. For example, in Figures 2 (a) and (b), d_1 and d_2 vary from 0 to 0.6 mm and from 0.2 to 1.4 mm, respectively, causing the concentration of YAG:Ce³⁺ to change with them in the range of 14-26% wt.

In order to achieve the highest values of optical properties including the luminescence efficiency and color quality, it not only requires the changes in d_1 and d_2 but also the suitable phosphor adjustment to maintain color temperature at 8500 K. The case of CDRP is also similar, with a fixed 16 mm r_1 and tunable r_2 , CDRP also needs phosphor concentration adjustment to operate properly. The relation between the changes of r_2 can be best observed in Figure 2 (c), where YAG:Ce³⁺ concentration continuously plunges when r_2 goes from 16 to 16.6 mm and begins to rise as r_2 increases toward 16.9 mm. The YAG:Ce³⁺ phosphor concentrations

presented in Figure 2 are the values needed to correspond to distance changes and maintain 8500 K color temperature in WLEDs. The comparison between CDRP and FDRP shows that YAG:Ce³⁺ phosphor is less affected by the distance changes occurring in CDRP. This result suggests that CDRP is not the most effective tool to adjust scattering properties, and the enhancement in light output is not noticeable. Another factor is CDRP phosphor layer is harder to construct than FDRP one, which makes FDRP better than CDRP in both application and proficiency. Therefore, it is advisable to use FDRP for the purpose of tuning distances and getting the desired optical values.

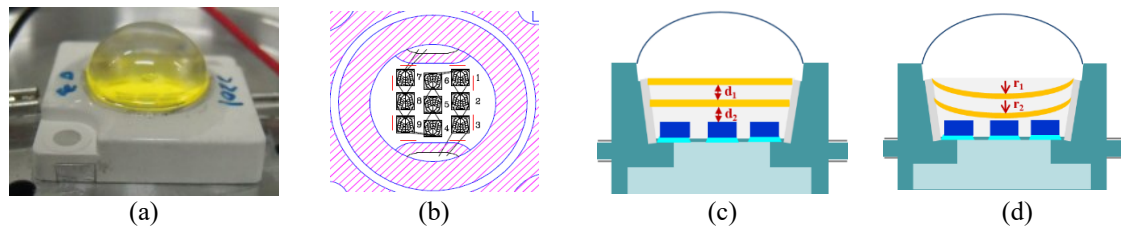


Figure 1. Photograph of WLEDs setup: (a) actual WLEDs, (b) bonding diagram, (c) illustration of FDRP, and (d) illustration of CDRP

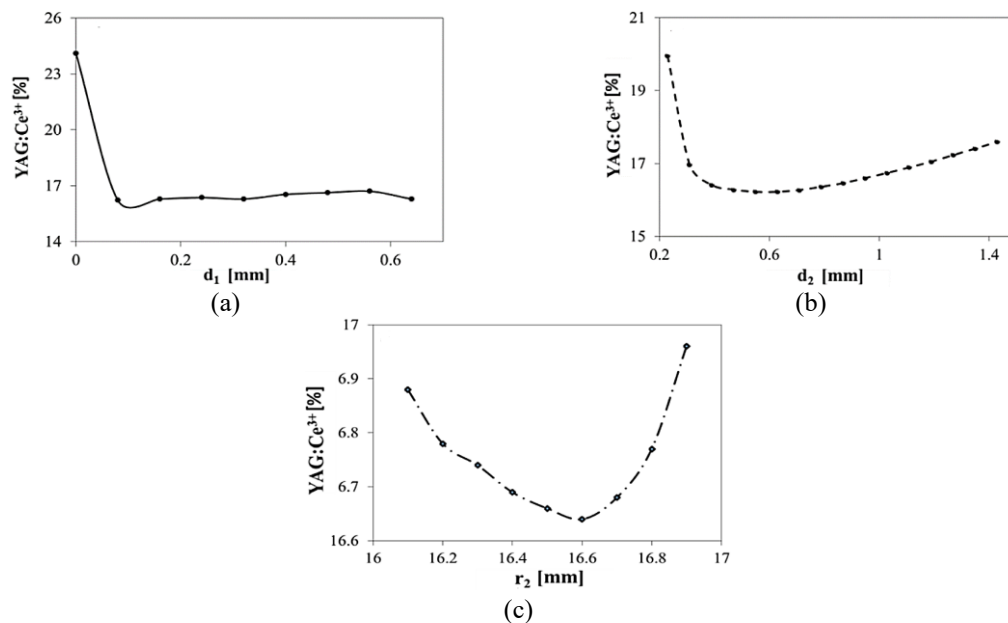


Figure 2. The concentration of yellow phosphor in case of: (a) d_1 , (b) d_2 , and (c) r_2

The graphs of Figure 2 show the changes needed to be made in phosphor concentration to respond to the gap changes in WLEDs. This is a compulsory adjustment to maintain the correlated color temperature (CCT) because the color temperature is influenced by many scattering factors of device configuration and cannot retain a consistent value unless alterations are made. By analyzing the graphs, we can see that as the distance expands the concentration decreases. Although at some points the concentration of phosphor slightly rises and falls, the idea is to lower phosphor concentration to stabilize CCTs. The decrease of phosphor concentration is most noticeable at the beginnings, in which cases the concentration values dipped to the lowest points in the whole graph at 16.22% when $d_1=0.08$ mm in Figure 2 (a) and 16.22% when $d_2=0.55$ mm in Figure 2 (b). As the d_1 and d_2 move away from 0.08 mm and 0.55 mm, the phosphor concentration stops declining and even begins to rise in the case of d_2 although it cannot reach the value at the beginning. These results confirm that the distances such as d_1 and d_2 have influences on the performance of phosphor in terms of scattering properties, which can support WLEDs enhancement if they are utilized correctly.

2.2. Computing the transmission of light

The mathematical equation to calculate the blue and yellow light yielded from WLEDs with two phosphor layers is presented in this part. The results provide valuable information for better understanding of

WLEDs mechanism and enhancing methods. The amount of emitted blue light and modified yellow light in a LED package of single phosphorus layer with $2h$ phosphor density is shown in (1) and (2) [22-25].

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

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

In dual-phosphor remote WLEDs with an h phosphor density, the amount of emitted blue lights and modified yellow rays are expressed as:

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

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

The h denotes phosphor density (mm). The subscript “1” indicates WLEDs with single phosphor structure and “2” indicates WLEDs with dual-phosphor remote structure. The β stands for the rate of internal conversion of blue rays transforming to yellow rays. The yellow-light reflection coefficient is illustrated by γ . The radiation intensities of LED chip including the blue light intensity (PB) and yellow light intensity (PY) are represented by PB_0 . The blue and yellow light energy lost during the spreading process in the phosphor layer are indicated by α_B ; α_Y , respectively. The WLEDs in double-layer phosphor structures have their luminous efficacy improved significantly in comparison with the single layer structures:

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

The emission spectra of the dual-layer remote phosphor are measured and presented in Figure 3 for comparison. In the cases demonstrated in Figures 3 (a) and (b), the light emission capacity receives an improvement as the distances expand. Particularly, in Figure 1 (a), the light emission of WLEDs according to $d_1 > 0$ shows an increase in comparison to the one at $d_1 = 0$. The spectrum improvement is most noteworthy in wavelength bands of 380 to 480 nm and 480 to 580 nm. The emitted fluxes of WLEDs responding to d_2 in Figure 3 (c) are also similar, the light output gradually increases as the d_2 grows over the default index of 0.23 mm. Regarding the light extraction of phosphor structure, it is safe to assume that using multi-layer structure will results in more light radiation than single-layer structure.

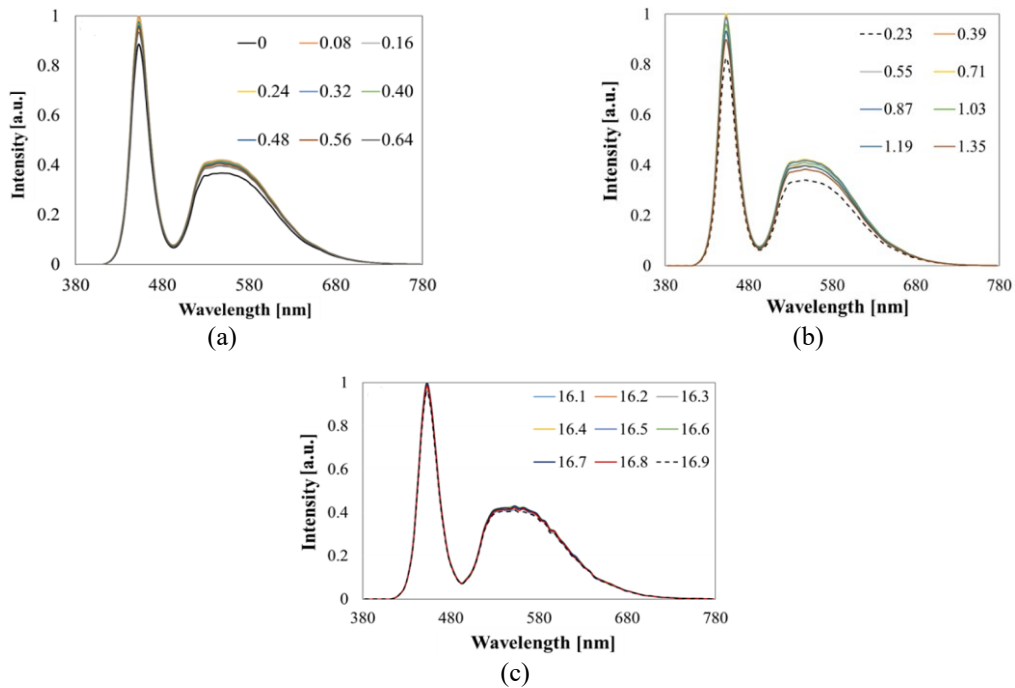


Figure 3. Emission spectra of dual-layer phosphors case of: (a) d_1 ; (b) d_2 , and (c) r_2

3. RESULTS AND ANALYSIS

The graphs illustrated in Figure 4 are about the light output of remote WLEDs with the distances between components fluctuating through different values. Figure 4 (a), which refers to the gap between the layers of phosphor d_1 , shows that the luminous flux is benefited from the increasing d_1 at the range from 0 mm to 0.08 mm. d_2 in Figure 4 (b) exhibits the same result when the luminous flux increases at the starting values of d_2 , from 0.23 mm to 0.63 mm. Considering the results in FDRP and CDRP configurations, the distances of FDRP are smaller, with d_1 equal to 0.08 mm or d_2 equal to 0.63 mm, when luminous flux of this configuration reaches the highest value of 1020 lm, while in CDRP cases the distances are much wider, with $r_2=16$ mm and $r_2=16.6$ mm, yet the best value of achievable luminous flux stops at 894 lm, see Figure 4 (c). In the process where the light from the LED chip is produced and blended with the yellow phosphor, a part of the total emitted light is lost due to backscattering, absorption, and reflection that happen during the scattering process. Therefore, the distance between these components ensures the converted light are at the highest when passing through the remaining phosphor layer.

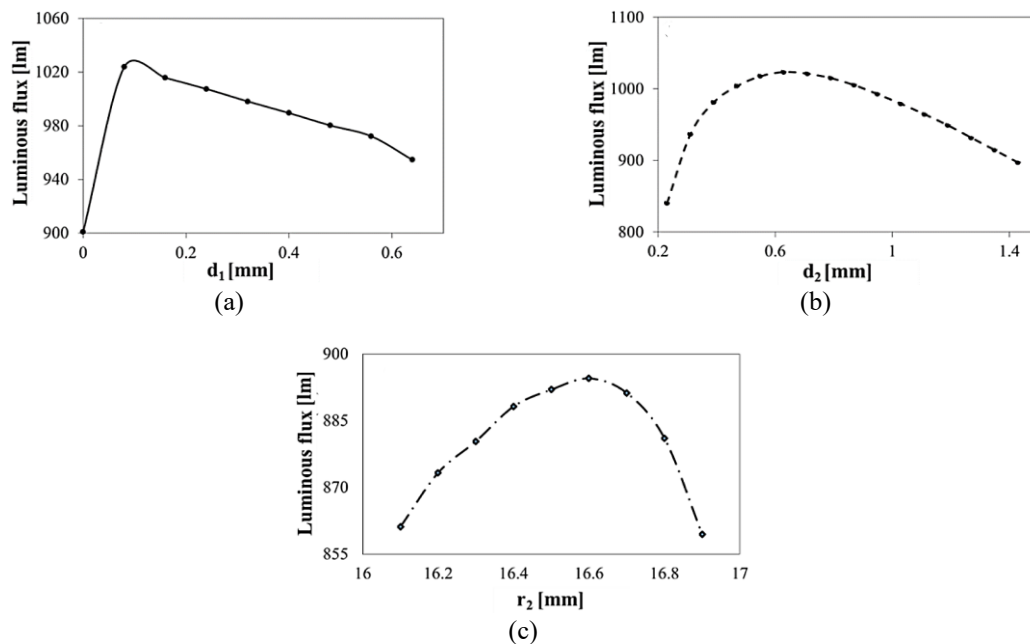


Figure 4. The luminous output of WLEDs at the same CCT in cases of (a) d_1 , (b) d_2 , and (c) r_2

This also explains why if there are no distances and the components contact directly with each other the generated heat at the junction goes up and damages the luminous flux. These results prove that the distances are deciding factors to the light conversion efficiency of WLEDs. In phosphor structure with bended phosphor layers such as CDRP, the layer texture induces the backscattering effect and leads to more light loss from this event. As a result, higher r_2 means lower luminous flux, which is most recognizable as the r_2 reaches 16.9 mm pushing the backscattered light to the highest value. The fact that backscattering events in CDRP structure take place at the gap between LED chip and phosphor layer as well as between the phosphor layer and the remaining part of the structure, making the reduced scattering efficiency more visible when r_2 is higher than 16.6 mm. In cases where r_2 is in between 16.1 and 16.9 mm, the expanded distance between phosphor layers reduces back scattered energy and aids the light transmission in the structure, leading to better radiation capacity. However, the more r_2 increases beyond this point the worse the lighting ability of WLEDs becomes due to the LED chip and lower part of first phosphor layer being pushed closer together.

4. CONCLUSION

The purpose of this research is to measure the influences of the distances between the two phosphor classes and from the phosphor class to the LED chip, depicted as d_1 and d_2 , on the performance of phosphor converted lighting devices. From the results of experiments, it can be concluded that FDRP is better for the development of luminous flux in WLEDs, which is because of the light moving more freely in FDRP than in CDRP. The influences of the distances d_1 and d_2 and phosphor content on lighting performances are also

confirmed by the highest light output achieved when d_1 at 0.08 mm or d_2 equal to 0.63 mm; however, the color performance of WLEDs with these distances are not ideal. In other cases, when d_1 or d_2 are lower than the value that allows the highest light output, the color performance becomes increasingly better because the absorption, backscattering inside the structure, and thermal performance are enhanced. So, FDRP is the prominent choice between two shaped phosphor layer structures, while the distances of d_1 and d_2 depend more on the production requirements or manufacturers decision in making the desired high quality WLEDs.

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