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Influence of Dual-layer and Triple-layer Remote Phosphor Package on Optical Properties of White LEDs

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Abstract

In this paper, the influence of the distance between phosphor layers in the dual-layer and triple-layer remote package on luminous flux and color rendering property is presented and analyzed. During the simulation, it is recognized that an appropriate distance can produce higher quality of the multi-chip white LED (MCW-LEDs) through adjusting the distance between two and three phosphor layers. According to the research results, 0.1mm is the outstanding distance between two phosphor layers so that the performance of MCW-LEDs can be accomplished the best optimal effect. In addition, the simulation results show that the dual-layer structure yielded higher optical properties than the triple-layer structure in relation to the distance. The highest lumen output of triple layer-structure can be achieved at the distance of 0.6 mm and dual-layer structure is 0.1 mm. Meanwhile, the color rendering index (CRI) changes insignificantly when the distance increases. Triple layer package is not practical for high power white LEDs due to high cost and low conversion efficiency. Dual-layer remote phosphor package with the distance between two phosphor layers of 0.1mm is an optimal structure of LEDs in improving the luminous efficiency and the color quality.

***Keywords**: dual-layer structure, triple-layer structure, remote phosphor package, luminous flux, color rendering index*

1. Introduction

Phosphor converted white light emitting diodes (pc-LEDs) tend to become a promising lighting source and have many opportunities to compete with the traditional lighting sources in a number of applications [1, 2]. However, some available pc-LEDs still have some restrictions such as low conversion efficiency, color rendering ability and poor color uniformity, hence it must to be optimized and improved. In most current white LED structures, yellow emitting phosphor is directly applied onto LED chip surface; the thermal degradation of phosphor material will appear, thus resulting in the reduction of reliability of products [3].

Narendran et al demonstrated that more than half of the down-converted light was backscattered and reflected by phosphor in most LEDs, that leads to the reduce of the overall light output [4]. To minimize the trapping phenomenon of rays inside the LEDs, a new technology, in which the phosphor layer separated far away from the LED chip that is called remote phosphor package, is introduced. With this technology, LEDs can extract the backscattered photons and improves further luminous efficacy [5]. Because of an air-gap between LEDs and phosphor layer in the remote phosphor package, the impact of heat can be reduced during the optical performance process. It leads to more blue and yellow rays be converted and transmitted toward the LED surface than the conventional cases, thus it can get better optical properties. Although this solution is an effective approach in reducing the thermal impact inside the LEDs, it is still facing with the difficulties for varying requirements and

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increasing demand of applications in the commercial LED lighting market. As a development, a next generation of remote phosphor configuration is proposed, in which the dual-layer structure is employed in the remote phosphor package to enhance luminous efficiency of pc-LEDs.

A study with applying a thin silicone layer into dual-layer remote phosphor structure can yield 5% higher lumen output than a conventional remote phosphor package at the same CCT [6]. Similarly, there are some approaches focusing on the phosphor structure proposed to reduce the probability of the backward light from the phosphor layer to the absorptive LED chip such as remote phosphor package with the hemispherical dome [7], employing a double remote micro-patterned phosphor film into pc-LEDs [8] as well as ring remote phosphor structure [9]. A different propose also demonstrated that an air-gap layer embedded in the remote phosphor package offers advantages in luminous flux and chromatic stability [10]. Besides, the different phosphor material arrangement has a significant role for improving the phosphor converted efficiency.

A two-layer remote phosphor structure in which a SrO.3B2O3:Sm2+ red phosphor layer above a yellow phosphor layer can achieve more than 17% in lumen compared to the mixed red and yellow phosphor package [11]. However, these phosphor layers in this structure are placed adjacent to each other at a random distance with LED chip in remote phosphor package and in these studies, the specified distance between phosphor layers is not determined so it should be suggested to achieve the best optical performance.

In this research, we study the effect of the distance between phosphor layers and LED chip on the optical properties of both dual-layer and triple layer structures. The luminous efficiency, the color rendering ability in two and three-layer remote phosphor package versus distance between phosphors are investigated and presented. We try to look into a best position of phosphor layers within LEDs and hope to achieve an optimized design of the high efficiency LEDs. As I know, in the previous papers, authors demonstrated that the dual-layer structure can improve the efficiency of LED but they haven’t found the appropriate distance to achieve the best efficiency.The obtained results of this paper indicate that the highest overall light output, lumen efficiency as well as better color quality of LEDs can be achieved at the distance between two phosphor layers of 0.1mm for dual-layer structure and 0.6mm for triple layer structure. The enhancement of efficiency was due to the improving in the utilization of blue, yellow rays within the LEDs. The simulation results show that the LED with the two-layer remote phosphor package exhibits the light extraction, color rendering ability better than triple-layer remote phosphor package. Illustration of MCW-LEDs structure as shown in Figure 1.

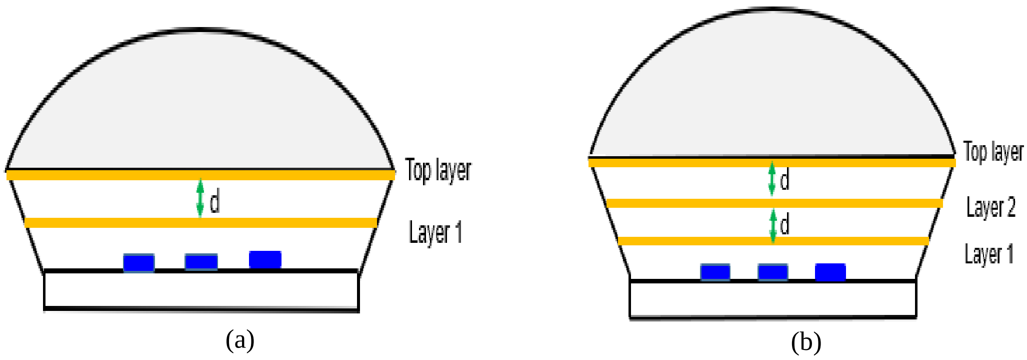

Figure 1. Illustration of MCW-LEDs structure: (a) a dual-layer structure of the remote phosphor package and (b) triple-layer structure of the remote phosphor package

2. Simulation Model

The effect of the distance between phosphor layers with LED chip on the light output of pc-LEDs is examined by using 3-D ray tracing simulation with LightTools software. Remote phosphor package, in which a thin phosphor layer is separated far away from the LED chip by a layer of a transparent material, is carry out simulation on the various distance. To perform simulation about the effect of distance between phosphor layers on the optical characteristics for two different configuration packages of LED, a 3-D model for each one was built by using

LightTool software. Each blue LED chip with radiant flux of 1.16W at emission wavelength 455nm and a dimension of a height of 0.15mm, a square base of 1.14mm is resided in the cavity of reflector.

The refractive index of phosphor particles is 1.8 at all wavelengths of emitted light. The shape of phosphor particle is spherical and the average diameter is 14.5µm. The reflector has a height of 2.07mm and a bottom length of 8 mm. Each package has a convex lens boned on the top surface of the phosphor layer. The refractive index of the material for the convex lens is equal to 1.46 at the excitation wavelength of 460nm. Since the CCT value of simulated pc-LEDs is 8500K, the concentration of phosphor in both dual-layer and triple-layer package is continuously varied to maintain the same CCT of white LEDs during the simulation process as shown in Figure 2. It can be seen in Figure 2, the phosphor concentration in the dual-layer package has upward trend with the distance from 0 to 0.1 mm and this value stays the same afterward. Meanwhile, the concentration of the triple-layer package rapidly increases in ranging from 0.2 to 0.4 mm and slightly decreases when the distance continuously increases to 0.7 mm. The concentration and the thickness of phosphor layers for two cases of structures are set up the same. For multi-layer phosphor package, Li presented a mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure and demonstrated a great improvement of LED efficiency for proposed mathematical model [12]. The transmitted blue light and conveted yellow lightfor single layer remote phosphor package with the phosphor layer thickness of 2h.

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

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

The transmitted blue light and convetedyellow light for double layer remote phosphor package with the phosphor layer thickness of h.

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

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

$$+\frac{1}{2}\frac{\beta_2 \times PB_0 \times e^{-\alpha_{B2}h}}{\alpha_{B2} - \alpha_{Y2}}(e^{-\alpha_{Y2}h} - e^{-\alpha_{B2}h}) = \frac{1}{2}\frac{\beta_2 \times PB_0}{\alpha_{B2} - \alpha_{Y2}}(e^{-2\alpha_{Y2}h} - e^{-2\alpha_{B2}h}) \tag{5}$$

Where h is the thickness of each layer, the subscript “1” and “2” are used to describe single layer and double layerremote phosphor package, β represents the conversion coefficient for blue light converting to yellow light, γ is reflection coefficient of the yellow light, ρ_v is the particle density; PB, PY are the intensities of blue light and yellow light respectively. α_β; α_y are parameters describing the fractions of the energy loss of blue and yellow lights. And the paper demonstrated that the lighting efficiency of pc-LEDs with the double-layer phosphor structure enhances compared to single layer structure.

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

The simulation result and the theoretical calculation verify that the transmitted light increases and the backscattering light (by the phosphor layer) degrades in double-layer package, thus it improves the light-extraction efficiency of white LEDs.

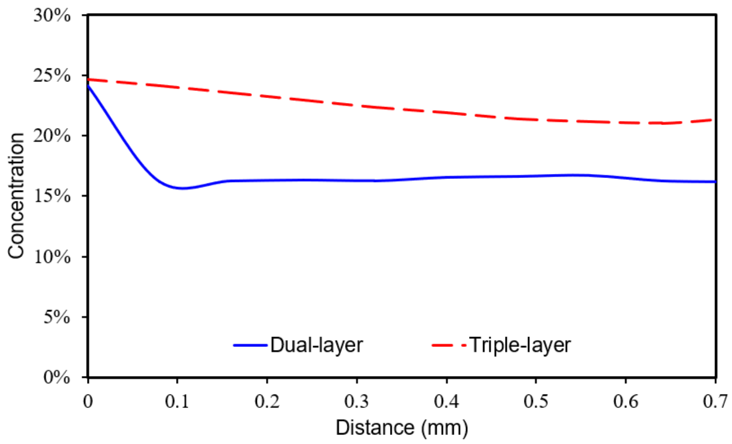

Figure 2. The concentration of yellow phosphor with different distance between two phosphor layers at the same CCT of LEDs

3. Simulation Results and Discussion

In order to strengthen the luminous efficiency, improve color quality of LEDs and bring the benefit for the thermal management of remote phosphor layer, a simulation model of remote phosphor is developed. This model allows adjusting the phosphor location to find the best optimal distance between phosphor layers that can determine the optical characteristics of LEDs.In simulation process; we adjust the position of the middle phosphor layers and fix the position of the top phosphor layer to LED chip. However, the placement and arrangement of phosphor layers in both dual-layer and triple-layer package can produce the significant 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 in this research, the phosphor concentration needs to be varied to the distance between two phosphor layers in pc-LEDs as shown in Figure 2.

The phosphor concentration of dual-layer package tends to decrease with range within 0-0.1 mm and to be unchanged afterward. It can be attributed that two phosphor layers closely placed withthe short distance range within 0-0.1 mm seemly like a single phosphor layer which has double large thickness compared to a conventional phosphor layer. Increasing the phosphor layer thickness can enhance both the scattering, the absorption, the reflection according to the previous study, thus it causes a high color correlated temperature inside LEDs [12]. Considering these facts, it can be deduced that the concentration of phosphor needs to be reduced to ensure that this package has the same CCT during the simulation process. For the case of dual-layer structure, the concentration of yellow phosphor is still keeping the same when the distance rises more than 0.1 mm. Meanwhile, the phosphor concentration of triple-layer package is different from dual-layer package. The concentration is about 25% bigger than dual-layer structure and slightly reduce from 0 to 0.7 mm. The phosphor concentration of triple layer package insignificantly varies with the distance ranging from 0 to 0.7 mm.

Figure 3 depicts the influence of the distance between phosphor layers and LED chip of remote phosphor package on the lumen output. The simulation results show that the variation of the distance has a significant impact on the light extraction. For the dual-layer package, the lumen output dramatically enhances and gets the peak value with ranging from 0 to 0.1 mm. Conversely, it tends to drop when the distance of phosphor layers continuously increases further. When the distance d varies from 0 to 0.1 mm, it means that these two phosphor layers are separated further away, the probability of light trapped in the gap between two phosphor layers will reduce. The reflected light which directly impinges on the absorptive LED chip could decrease and the transmitted light through phosphor layers can be increased, thus this improves the LED efficiency. With distance range within 0-0.1 mm, the heat generated by the LED chip only transfers to the substrate instead of the contact surface of two phosphor layers. The increase of the distance between these phosphor layers can offer not only the high luminous flux, but also produce the temperature stability of this multilayer phosphor configuration. This leads to more light be transmitted and extracted through the phosphor layers. For the distance ranging from 0.2 to 0.7 mm, the drop of the luminous flux is attributed by the weakened photon extraction and the heat effect of phosphor. The blue light from LED chip will encounter the first phosphor layer and be converted to the yellow light. However, some portion of light is lost inside the LEDs due to the backscattering, absorption and reflection, the other portion is converted to yellow light and transmitted through the second phosphor layer.

The further increasing of the distance makes phosphor layer move closer to LED chips, and thus more light is trapped and reflected inside the gap between the first phosphor layer and LED chips. This causes the junction temperature rise of phosphor layers and LED chips which may produce the low conversion efficiency. For the triple-layer structure, the process of the light propagation inside LEDs has similar tendency. Luminous flux also increases with the distance range within 0-0.6 mmand reduces at the position of the distance range within 0.6-0.7 mm. The lumen of triple layer structure reaches the highest value at the distance of 0.6 mm. The simulation results show that the case of the dual-layer package has a better enhancement than the case of the triple-layer package at the beginning (see Figure 3). In other words, the dual-layer configuration produces a higher percentage of extracted photons to the total light energy than triple-layer configuration.

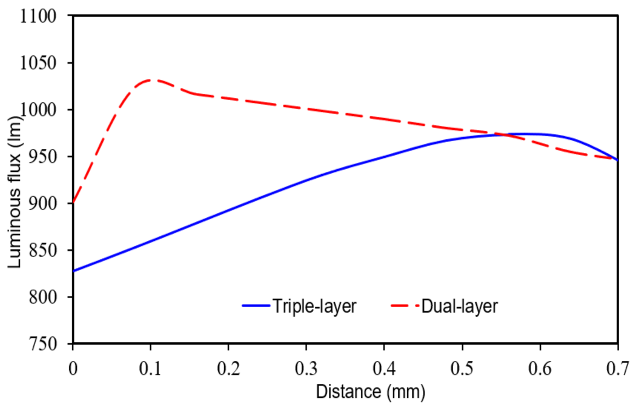

Figure 3. The luminous output of MCW-LEDs at the same CCT with different distance between phosphor layers

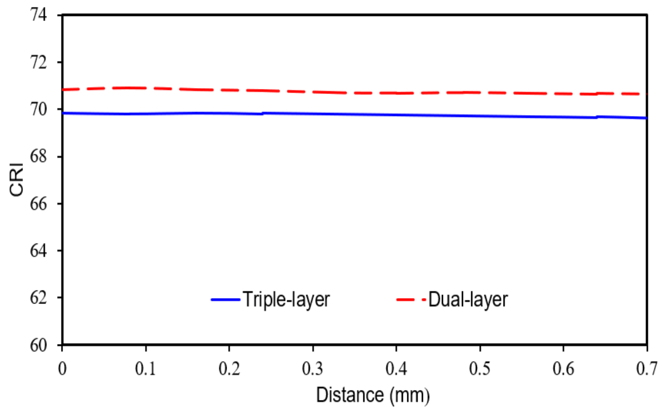

Figure 4. The color rendering index (CRI) value of MCW-LEDs with different distance between phosphor layers

Additionally, the effect of the distance between two phosphor layers on color rendering index is investigated (see Figure 4). For both two types of multi-layer configurations, when the distance is suitable, the probability of the transmitted blue light and the converted yellow light rises. The heat generated by the LED chip usually transfers to the substrate instead of the phosphor, thus it avoids chemical degradation of phosphor as well as the thermal damage of LEDs. This offers a wider emitted spectrum at this position of phosphor layer and the color quality of LEDs becomes better, thus the CRI grows. When the distance is so large, it means that the first phosphor layer is so close to LED chip, blue rays are backscattered and trapped further inside the LED package.

The consequence is that the quality of light becomes poorer, and thus the obtained color rendering index is low. Although the trend of CRI for both two cases of multi-layer phosphor configuration is same. But we can observe that CRI of the dual-layer phosphor configuration is better than triple-layer one. As a conclusion, the variation of the position as well as the number of phosphors layers in remote phosphor package significantly influences on luminous flux, CRI. The best luminous flux and CRI can be achieved at the optimal distance of 0.1 mm between two phosphor layers for the dual-layer remote phosphor package. The dual-layer package offers great advantages in yielding high luminous flux and CRI. The phenomena may be due to the fact that the blue light and yellow light have to transfer through three phosphor layers in triple-layer package, and thus there is still a large probability of rays lost inside these three phosphor layers.

4. Conclusion

In this research, the influence of the distance between phosphor layers as well as the number phosphor layers on the optical characteristics of remote phosphor package at the same CCT is analyzed and demonstrated in detail. The researched results revealed that the appropriate position of phosphor layer in remote phosphor package significantly improves the luminous flux and color rendering index of LEDs. The luminous flux remarkably enhances and achieves the maximum value at the distance of 0.6 mm for the case of trial-layer package and 0.1 mm for dual-layer package. Meanwhile, with the distance ranging from 0.1 mm to 0.7 mm of dual-layer package, the lumen output and the color quality of LEDs have slightly downward tendency. The reason of this issue is due to the increase of the trapping, the absorption, the re-scattering of light in LED package and the chemical change of the heated phosphor layer. Therefore, finding a suitable distance between phosphor layers in remote phosphor package is a key factor in designing high efficiency pc-LEDs.

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