Optical Analysis of Phosphor's Location for High-Power Light-Emitting Diodes

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Abstract—**High-power-light-emitting-diode (LED) packaging is crucial for the development of solid-state lighting. Phosphor's location could affect the LED packaging performance such as light extraction and correlated color temperature (CCT). This paper systematically analyzes first the effects of phosphor's location on LED packaging performance. A two-light-source step computation method based on the Monte Carlo theory is developed, and five different optical structures are discussed. Results show that the location of phosphor has small impact on light extraction but could greatly affect CCT. Remote phosphor location presents higher light extraction than proximate phosphor location. However, the increase is slight, and too remote location could reduce light extraction. A convex phosphor layer has higher light extraction but lower yellow–blue ratio than a plane phosphor layer. Considering the significant variation of CCT, it is suggested that an optical structure with plane and remote phosphor location should be a suitable choice for LED packaging.**

Index Terms—**Correlated color temperature (CCT), light-emitting diodes (LEDs), light extraction, packaging, phosphor.**

I. INTRODUCTION

RECENTLY, high-power light-emitting diodes (LEDs) have attracted great attention on the study and made remarkable progress [1]–[9]. With the improvement of internal quantum efficiency, external quantum efficiency, phosphor conversion efficiency, silicone materials, and packaging technology, the luminous efficiency of LEDs has increased to more than 100 lm/W with a drive current of 350 mA [4]. This performance can compete with that of the incandescent lamp, fluorescent lamp, and high-pressure sodium lamp. Therefore, taking into account the advanced characteristics of LEDs such as small size, long life, low power consumption, and high reliability, it has been widely accepted that solid-state lighting in terms of high-power LEDs will be the fourth illumination source [10].

Packaging is essential for the application of high-power LEDs. Packaging protects the chip from being damaged by the environment such as electrostatic discharge, enhances light extraction, and dissipates the generated heat to increase service life [11]. However, compared to the significant reduction of heat resistance, the improvement of light extraction needs to be given further efforts. This is mainly due to the fabrication technology of white LEDs. Nowadays, the generally accepted packaging method to generate white light is mixing the blue light emitted from the GaN chip with the broadband yellow light excited by YAG:Ce phosphor [12]. This is named phosphor-converted LED, which is first developed by Nichia in 1996 [13]. The phosphor is normally mixed with silicone and dispersed around the chip. To improve light extraction, corporations such as Cree, Lumileds, and Osram have developed various packaging structures and phosphor-dispersing technologies. The products of the three companies are shown in Fig. 1. The XLamp series from Cree utilizes a metal ring to mount the lens and coats the phosphor on chip by evaporating the solvent [14], [15]. Lumileds applies the conformal coating process to fabricate the phosphor layer in Luxeon K2 series, and the electrophoretic method to deposit phosphor particles on the circuit in Rebel type. Lumileds also proposes a new Lumiramic phosphor technology that utilizes a phosphor ceramic plate to be bonded on the thin-film flip-chip. This could improve color uniformity and stability and luminous efficiency [16]. The difference of Osram's products is that there is a reflector but without a lens to control the light distribution. Recently, Osram develops a new wafer-level technology by spin coating phosphor on a GaN wafer. This method could improve color distribution by controlling the thickness of the phosphor layer [17].

However, the aforementioned LEDs all disperse the phosphor directly on the chip surface. Researchers investigated the effects of phosphor's properties on the performance of LEDs by changing the location to be remote [18]–[22]. Narendran found that there was over 60% improvement in the light output compared to commercial LEDs by utilizing the scattered photon extraction (SPE) method. Based on the SPE method, Allen and Steckl applied the role of internal reflection on the packaging components to improve light extraction, and they found that the increase of efficiency was at least 26%. Luo *et al.* confirmed that remote phosphor location could increase light extraction, but the improvement of experimental results is only 7.8%. However, all these works mainly focus on some specific cases.

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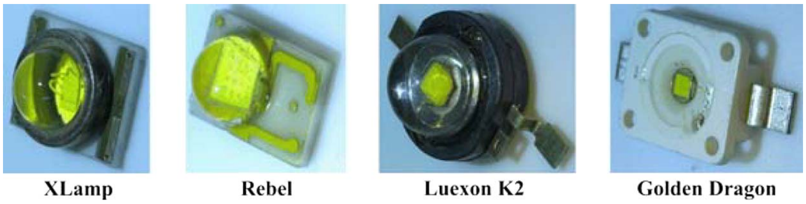


Fig. 1. Products of Cree (XLamp), Lumileds (Rebel and Luxeon K2), and Osram (Golden Dragon). It is clear that the phosphor is directly coated on chip.

It is not enough for understanding the influencing mechanism of phosphor's location. Therefore, more efforts are needed to systematically analyze the effects of phosphor's location on the packaging performance.

Based on the nonsequential Monte Carlo theory, this paper develops a two-light-source step computation method for the optical analysis. Past studies have proved that the Monte Carlo ray-tracing method is an effective tool for the simulation of LED packaging [20], [21], [23]–[25]. To better investigate the potential influences of phosphor's location, Section II illustrates the main objectives of this paper. Section III presents the numerical models for the optical analysis. Five optical structures are investigated, and the shape of the phosphor layer is changed from plane to convex. Sections IV and V discuss the effects of phosphor's location on the performance of LEDs from the simulation results.

II. PROBLEM STATEMENT

The basic optical elements in one LED module are chip, phosphor layer, and lens. Some modules may have a reflector. Although the performance of LED greatly depends on the initial light output of the chip, packaging elements are also important in the effort to achieve high-quality white LEDs.

Phosphor plays an important role in LED packaging. There are energy conversion and reemission, scattering, and absorption in the phosphor layer. When alternating the phosphor layer from being close to the chip to being remote, the propagation path and energy of light will be affected in terms of the scattering and absorption of phosphor, the reflection of reflector, the absorption of chip, the refraction of lens, etc. The absorption of phosphor and chip will influence the output optical power. The scattering of phosphor will disorder the light propagation. The directions of rays could be converged to central angles by the reflection of reflector and the refraction of lens or be changed to side angles. These will induce the variation of light extraction and correlated color temperature (CCT).

However, it is difficult to evaluate the effects of these factors on packaging performance experimentally, since the LED module is so compact that each element should be precisely controlled. Taking the fabrication of the phosphor layer and the dispersion of silicone as examples, the thickness of the phosphor layer is only 100 μm, but the flow of silicone and phosphor silicone is still uncontrollable because of the complicated viscoelasticity. Therefore, to fabricate the phosphor layer and silicone with the desired shape and location, further research and advanced techniques are needed.

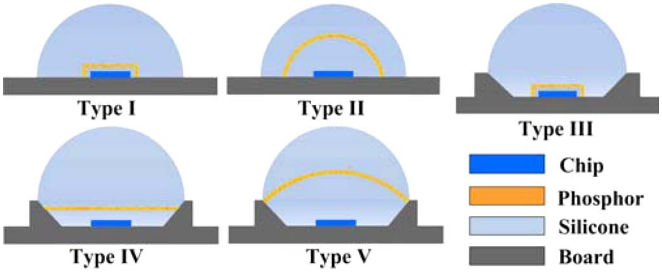


Fig. 2. Five optical structures for the analysis.

It is feasible to analyze the novel packaging design theoretically by computational simulation. As the first step to realize the importance of the phosphor layer, five numerical models are constructed. As a comparison, some models have a reflector, and some models have a convex phosphor layer. The phosphor layer is an independent material with uniform thickness. There is a distinct interface between the phosphor layer and other layers. As a result, Fresnel loss will be encountered when rays pass through the phosphor layer.

In this special investigation for the variation of phosphor's location, the objectives of this paper are as follows:

1) to investigate the effects of phosphor's location on light extraction;
2) to investigate the effects of phosphor's location on the variation of CCT;
3) to provide some suggestions on the packaging design.

III. NUMERICAL MODELS AND ANALYSIS

The correction and accuracy of results are mainly determined by the settings for the optical elements. It is assumed that there is no defect and delamination in the surface and the interface, and the attenuation of materials induced by heat and UV radiation is also not taken into account. The models do not consider smart structures such as the interconnections and gold wire. The optical properties of the chip and phosphor are represented with the refractive index, absorption, and scattering coefficient. In the following, a brief presentation for these models and analysis steps is given to facilitate the discussions of the predicted results.

A. Structures of Five Numerical Models

The five optical structures are shown in Fig. 2. To evaluate the impact of reflector on packaging performance, three numerical models in terms of types III, IV, and V have a reflector on each

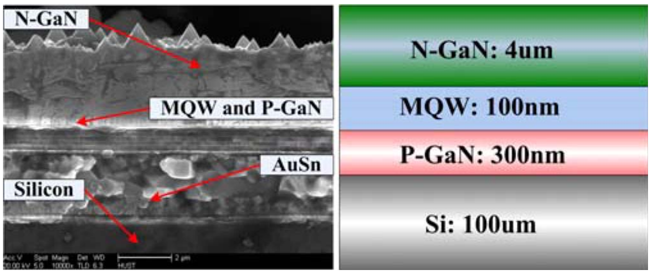


Fig. 3. Scanning electron microscope photographs of one Cree LED chip and the chip model for the simulation.

TABLE I
OPTICAL PROPERTIES OF THE CHIP

Item	N-GaN	MQW	P-GaN
Refractive Index	2.42	2.54	2.45
Absorption Coefficient (mm^{-1})	8	8	8

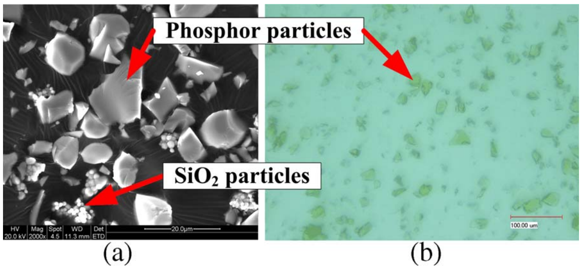
to compare other two nonreflector models of types I and II. The base diameter of the reflector is 3 mm, and the height is 2 mm. In order to minimize the effects of lens' size on light propagation, the radius of the lens in all types is large enough to be 4 mm. The optical parameters of the surface on the board and reflector are 85% perfect reflection, 5% scattering, and 10% absorption.

In types I and III, the phosphor layer is conformally coated on chip to replicate the square shape. The distance between the phosphor layer and the chip is altered from 0 to 0.1 mm. The case with 0-mm distance is called the direct-coating case. In types II and V, the model changes the location by increasing the radius of the phosphor layer. The second model fabricates the phosphor layer with a hemispherical film and increases the radius from 0.8 to 3.9 mm. The radius is increased from 4.25 to 10 mm in the fifth model. In type IV, the height of the phosphor layer is increased from 0.2 to 1.9 mm. The thickness of the phosphor layer is 0.1 mm in all cases.

B. LED Chip Model

The schematic diagram of the LED chip model is shown in Fig. 3, which is a simplified Cree LED chip with a size of 1 mm × 1 mm. The top surface of N–GaN is plane without considering the effects of roughness. The chip model defines the top surface of Si as a reflecting surface to represent the effects of the reflective metal film such as Ag. The optical properties of the surface are 80% perfect reflection, 5% scattering, and 15% absorption.

We consider that the light emits uniformly from the MQW layer, since the direction of photons that are excited by the combination of electrons and holes in MQW is arbitrary. Considering that the area of the top and down surfaces is much larger than that of the side surfaces, the model defines these two plane surfaces as the light sources by ignoring the side-emitting lights. The optical properties of the chip are illustrated in Table I [26].



(a) (b)

Fig. 4. Photographs of phosphor particles. (a) SEM photograph. The sizes of phosphor particles are irregular. The study normally applies the average radius to represent the dimension of phosphor particle. SiO_2 particles are used to enhance scattering. (b) 1000× photograph for phosphor particles embedded in silicone.

The light extraction efficiency of the chip $(\eta_{\mathrm{chip-extraction}})$ is calculated for the following analysis of packaging efficiency. $\eta_{\mathrm{chip-extraction}}$ is expressed as

$$\eta_{\mathrm{chip-extraction}} = \frac{P_{\mathrm{chip-extraction}}}{P_{\mathrm{electrical-power}}\,\eta_{\mathrm{injection}}\,\eta_{\mathrm{internal}}} \qquad (1)$$

where $P_{\mathrm{chip-extraction}}$ is the extracted optical power from the chip, $P_{\mathrm{electrical-power}}$ is the consumed electrical power, which is 1 W in this paper, $\eta_{\mathrm{injection}}$ is a measure of the efficiency of converting total current to carrier transport in a p-n junction, and η_{internal} is the ratio of emitted photon numbers to carrier numbers passing through the junction. This paper defines that both $\eta_{\mathrm{injection}}$ and η_{internal} are 100%. The computational result shows that $\boldsymbol{\eta}_{\mathrm{chip-extraction}}$ is around 14.54%.

C. Absorption and Scattering Model for Phosphor

The average radius of a phosphor particle is 5–8 μm, as shown in Fig. 4. Generally, the number of particles is 10 000–100 000/mm^3 in the mixture of phosphor silicone. Therefore, there may be millions of phosphor particles in the phosphor layer. This induces that light will encounter many particles in the propagation path and thus be scattered many times before it transmits through the phosphor layer. During the multi-scattering process, blue light energy will be weakened gradually by absorption, whereas the converted yellow light energy will be increased for each scattering. Therefore, the ratio of yellow/blue light output is determined by phosphor properties.

Since the optical behavior of rays in the phosphor layer is so complicated, simplifying the optical properties is necessary. Considering the phosphor layer as a bulk scattering material, it is an effective method that applies the scattering and absorption coefficients to represent the total effects of phosphor particles on light propagation. Therefore, when a beam of rays passes through the phosphor layer, the transmitted light energy can be expressed as

$$I(x) = I_0 e^{-(\mu_\alpha + \mu_s)x} \qquad (2)$$

where I_0 is the initial power of the incident light, I_x is the residual optical power after passing through the phosphor layer, μ_α and μ_s are the absorption and scattering coefficients, and x is the thickness.

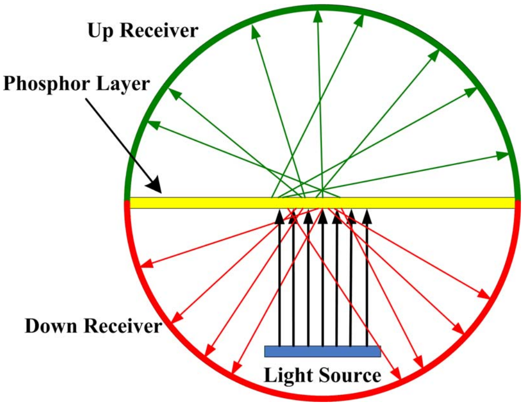


Fig. 5. Optical model for the verification of the definitions of phosphor properties.

The scattering distribution function is used to generate the random directions of the scattered light rays. The function is based on the Henyey–Greenstein model

$$p(\theta) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos\theta)^{3/2}} \tag{3}$$

where g is called the anisotropy factor. In the phosphor layer, since the scattering of light by the particles is isotropic, g is zero.

The numerical model assumes that the absorption and scattering coefficients are 8 and 11.85 mm^{-1} for the blue light, respectively. Phosphor is considered to be transparent when the incident light is in the yellow–green spectrum. Therefore, the absorption coefficient is defined as 0 mm^{-1} for the yellow light. Because of nonabsorption, the yellow light will be scattered more than the blue light. This means that the yellow light will be exhausted later in the propagation process and presents higher scattering coefficient, which is 16.25 mm^{-1}.

This paper defines that the refractive index of the phosphor layer is 1.7. The conversion efficiency of the phosphor is 80%, which is obtained by multiplying the Stokes efficiency (85%) with the quantum efficiency (95%).

D. Verification for the Definitions of the Phosphor Model

To verify the correction of the aforementioned phosphor assumptions, a simple optical model is constructed to compare the simulation results with the testing results. The model is shown in Fig. 5. One parallel beam of the incident rays enters the phosphor layer vertically, and two receivers are used to collect the forward-scattered light and the backscattered light. The thickness of the phosphor layer is 0.1 mm. The radius of the phosphor layer is large enough to ensure that no rays are emitted from the side surface. The ray-tracing method, which is also applied in the following numerical models, is based on the Monte Carlo theory. The Monte Carlo theory is a technique for computing the outcome of the random process.

The forward power and backward power are 14.74% and 11.04% for the blue light 52.92% and 45.81% for the yellow light, respectively. The power ratios of forward to backward are 1.335 and 1.155 for the blue and yellow lights, respectively, which are close to 1.2 and 1.024 in the testing results [27]. The difference is the phosphor that is not in plane shape in the test. Therefore, the aforesaid definitions of the phosphor layer are feasible in the numerical analysis.

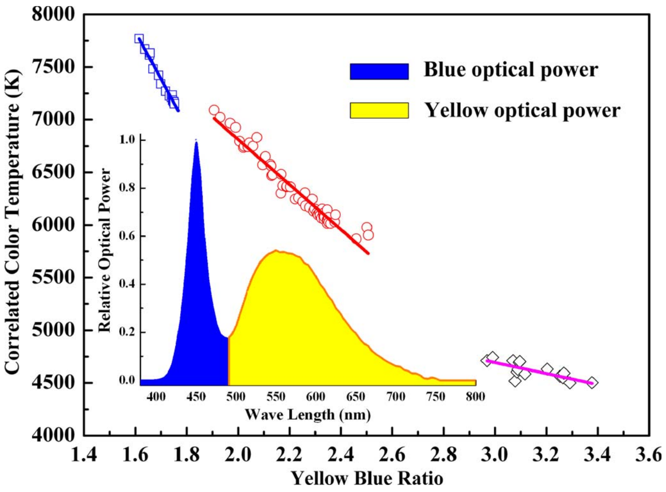


Fig. 6. Spectrum of LEDs and the relationship between YBR and CCT.

E. Silicone Materials

Silicone materials used to encapsulate LEDs are normally divided into three categories: gel, elastomer, and resin. Gel is suitable for chip sealing and inner encapsulation. Elastomer and resin are suitable for lens molding and overmolding. The numerical model does not distinguish the optical differences of the three materials, and defines that the refractive indexes are all 1.5 and that the absorption coefficient is 0 mm^{-1}.

F. Analytical Method

This paper develops a new analytical method that is named two-light-source step computation. The procedure is illustrated in the following:

1) defining the material properties of each layer;
2) defining the top and down surfaces of the MQW layer as the light sources and then inputting the optical power;
3) ray tracing and collecting the simulation data;
4) redefining the material properties of each layer;
5) redefining the top and down surfaces of the phosphor layer as the light sources, the power of which is calculated from the absorbed blue light;
6) ray tracing and collecting the simulation data;
7) calculating the simulation results of each case.

The energy of light is calculated by optical power in watts. The blue light output and yellow light output are computed separately to easily investigate the impact of phosphor's location on CCT. CCT can be represented by the yellow–blue ratio (YBR):

$$\text{Yellow blue ratio} = \frac{\text{Yellow optical power}\,(490-780\ \text{nm})}{\text{Blue optical power}\,(380-490\ \text{nm})}. \tag{4}$$

Higher YBR normally induces lower CCT. As noticed in Fig. 6, the test results of a dozen LED modules confirm that YBR could illustrate the variation of CCT.

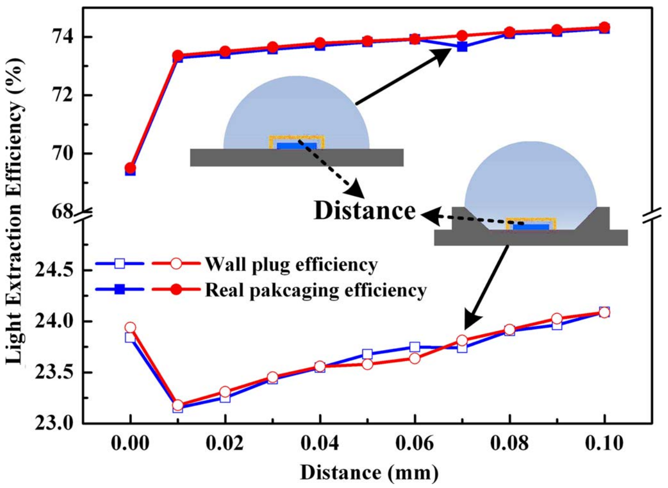


Fig. 7. Effects of phosphor's location on the light extraction efficiencies of types I and III.

To evaluate the effects of phosphor's location on light extraction, this paper applies the wall plug efficiency ($\eta_{\rm WPE}$), nominal packaging efficiency ($\eta_{\rm NPE}$), and real packaging efficiency ($\eta_{\rm RPE}$) to show the differences. They are expressed in the following:

$$\eta_{\rm WPE} = \frac{P_{\rm module-extraction}}{P_{\rm electrical-power}} \tag{5}$$

$$\eta_{\rm NPE} = \frac{\eta_{\rm WPE}}{\eta_{\rm chip-extraction}} \tag{6}$$

$$\eta_{\rm RPE} = \frac{P_{\rm module-extraction}}{P_{\rm electrical-power}\eta_{\rm injection}\eta_{\rm internal} - P_{\rm chip-absorbed}} \tag{7}$$

where $P_{\rm module-extraction}$ is the optical power that is extracted from the module and $P_{\rm chip-absorbed}$ is the optical power absorbed by the chip.

IV. RESULTS AND DISCUSSION

In this section, simulation results are displayed in the following figures, and discussions will be applied to analyze the fundamental effects of phosphor's location on LEDs. From the definitions of $\eta_{\rm WPE}$ and $\eta_{\rm NPE}$, it can be found that the tendencies of $\eta_{\rm WPE}$ and $\eta_{\rm NPE}$ will be the same. Substituting $\eta_{\rm WPE}$ and $\eta_{\rm chip-extraction}$ in (6) with (5) and (1), $\eta_{\rm NPE}$ is changed to

$$\eta_{\rm NPE} = \frac{P_{\rm module-extraction}/P_{\rm electrical-power}}{P_{\rm chip-extraction}/P_{\rm electrical-power}\eta_{\rm injection}\eta_{\rm internal}} = \frac{P_{\rm module-extraction}}{P_{\rm chip-extraction}} \tag{8}$$

where $P_{\rm chip-extraction}$ is constant. Therefore, it is enough to apply $\eta_{\rm WPE}$ and $\eta_{\rm RPE}$ to evaluate the affections of phosphor. $\eta_{\rm NPE}$ will be displayed in a single picture for all cases.

The numerical results of light extraction efficiency for types I and III are shown in Fig. 7. It is clear that real packaging efficiency and wall plug efficiency increase slightly when the phosphor layer is changed to a remote place from 0.01 to 0.1 mm. However, there is a sudden variation if phosphor is directly dispersed on the chip surface. The variation is strange since the wall plug efficiency is significantly higher than those cases with small distances, but the real packaging efficiency is obviously lower.

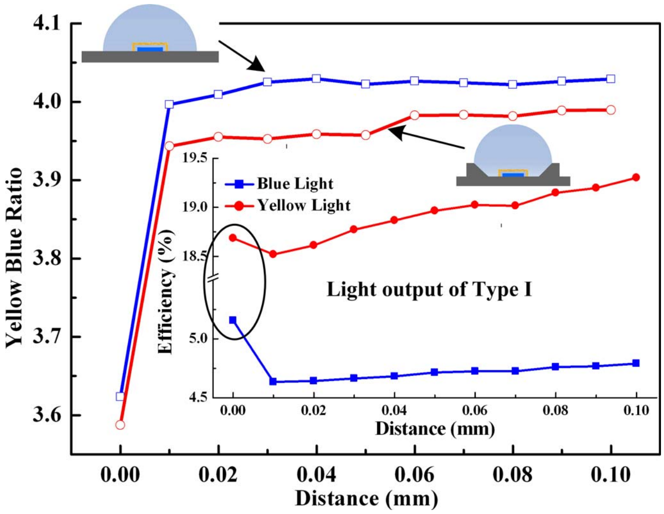


Fig. 8. Effects of phosphor's location on the YBR (CCT) of types I and III, and blue light output and yellow light output of type I.

From (7), the variation is mainly due to the fact that the chip absorption of the direct-coating case is relatively lower. Since the refractive index of the phosphor layer is higher than that of silicone materials, when phosphor is directly coated on chip, the critical angle is bigger than those cases with silicone coated on chip first. Therefore, less blue light will be confined in the chip and emitted out. This induces the lower $P_{\rm chip-absorbed}$.

As noticed in Fig. 8, the blue light output for the direct-coating case is obviously higher than that for other cases, which indicates that the effect of refractive index is great. Another important factor is the absorption of phosphor for the blue light. Simulation results show that when phosphor is directly coated on chip, the totally absorbed blue light by phosphor is 32.49%, but the distance of 0.01 mm is 25.397%. There is at least 8% difference in the absorption of blue light. As a result, the yellow light output could be also higher in the direct-coating case after phosphor's conversion. Consequently, the extracted power from the module is higher, but the real packaging efficiency is lower.

It can be found that the increase of yellow light output is not as significant as that of blue light in the direct-coating case, and the yellow light output is increased slowly with the increase of distance in Fig. 8. This is mainly due to the conversion loss of phosphor and the high absorption of chip. Since the conversion efficiency is 80%, there will be more energy loss if more blue light is converted. Taking the cases of direct coating and 0.01-mm distance as examples, the difference between the absorbed blue light and the converted blue light is reduced from 7.09% to 5.67%.

When phosphor is directly coated on chip, all of the backscattered yellow light must pass through the chip and loses most of the power. However, when there is a gap between the phosphor and the chip, part of the backscattered yellow light can be emitted out without being absorbed by chip. The distance is farther, and the phenomenon is more significant. This induces

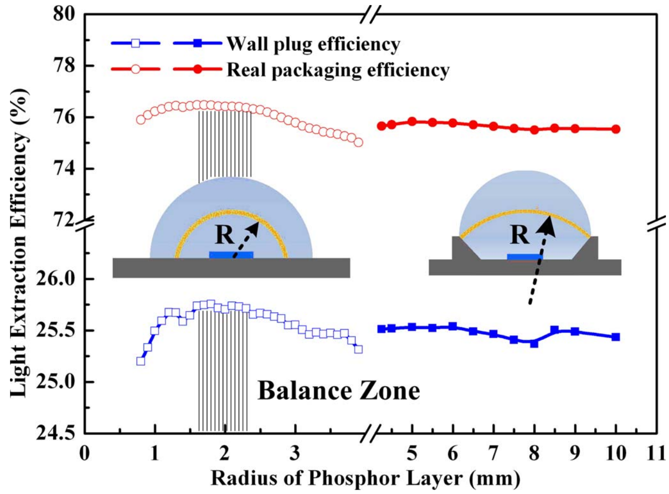


Fig. 9. Effects of phosphor's location on the light extraction efficiencies of types II and V.

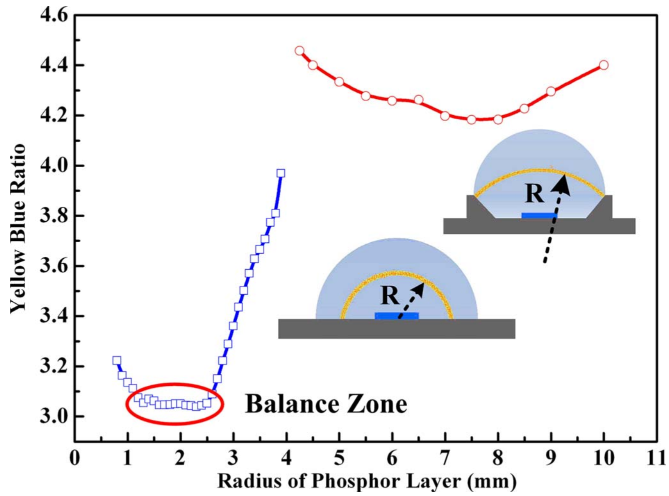


Fig. 10. Effects of phosphor's location on the YBR (CCT) of types II and V.

that the remote phosphor location could finally exhibit a higher light extraction.

As noticed in Fig. 8, the relatively higher blue light output and lower yellow light output also induce the sudden reduction of YBR in the direct-coating case. Because of the increased yellow light output for remote location, the color of LEDs should tend to become warm white.

From Figs. 7 and 8, it can be found that the trend and value of light extraction efficiency and CCT in the third numerical model are similar to that in the first model. This may be caused by the size of the reflector. Since the angle of the cone is 102.6°, this may indicate that most of the lights are directly emitted out without being reflected. However, if the angle of the cone is small enough and the height of the reflector is bigger, the affection on the light propagation may be significant and thus distinguish the difference between two types. The small difference of YBR indicates that the reflector could change the color to cooler.

The simulation results for the two structures with convex phosphor layer are shown in Figs. 9 and 10. It demonstrates that the influences on light extraction are small when the location is remote enough. The fluctuations for wall plug efficiency and real packaging efficiency are no more than 0.56% and 1.45%, respectively. However, the influences on YBR are significant. This could change the color of light and luminous efficiency.

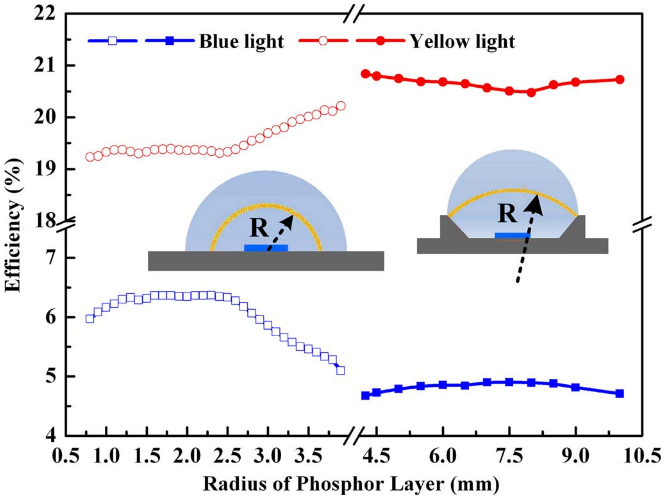


Fig. 11. Blue light output and yellow light output in types II and V with the increase of radius.

In the second structure, the efficiency is increased at the beginning but reduced at the end. Inversely, the tendency of the YBR curve descends and then ascends. The same characteristic is that there exists one balance zone around the radius of 2 mm, which is half of the lens' radius. This is mainly due to the fact that the power ratio between the forward-scattered light and the backscattered light is changed with the location. Three factors are considered effective. They are the size and surface area of phosphor layer, the reflection loss, and the absorption of chip. As Fig. 11 shows, the blue light output and yellow light output could illustrate the influencing mechanism of these factors.

In the second structure, the determining factor is the absorption of chip when the location is small. An increased gap between the phosphor layer and the chip could reduce the absorption of chip, since part of the rays could be reflected and emitted out. Therefore, there is a slight increase of light output. However, the influence on the blue light is more significant. Blue light is emitted from the chip, which is in the center of hemispherical phosphor layer. As a comparison, the direction of yellow light is random and disordered. Therefore, the absorbed power of yellow light is higher than that of blue light.

However, with the increase of radius, the absorption and scattering of enlarged phosphor layer and reflection loss will be the main factors. The effect of chip's absorption should be weakened gradually. This results in the phenomenon of balance zone. At last, the enlarged phosphor layer absorbs more blue light and emits more yellow light. The reduced gap between the lens and phosphor enhances the vibration of blue light and thus will be absorbed by phosphor. The backscattered blue light should also be reflected many times by the board or reflector and finally loses most of the energy in reflection and phosphor layer.

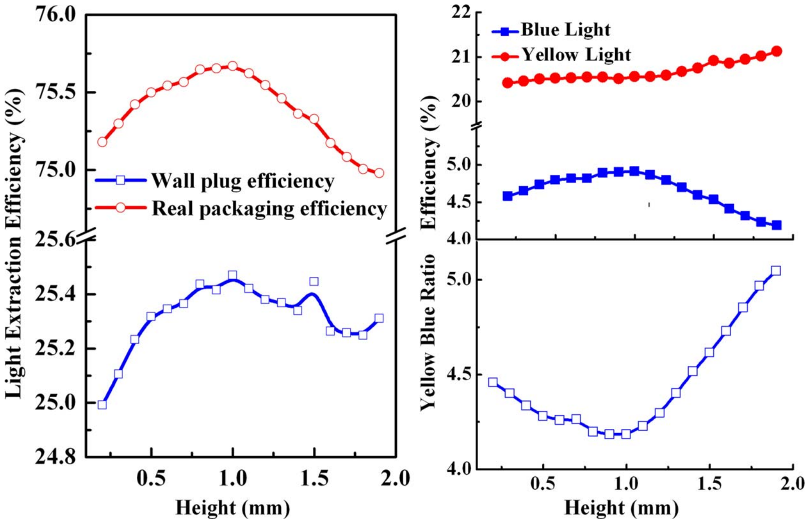


Fig. 12. Effects of phosphor's location on the packaging performance of type IV.

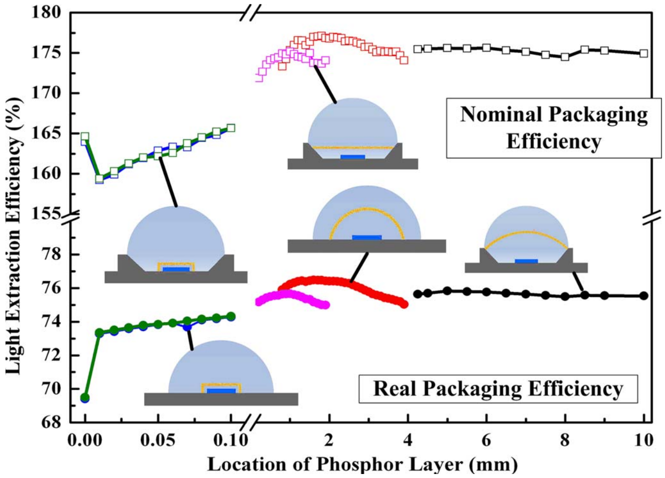


Fig. 13. Effects of phosphor's location on the light extraction efficiencies for all cases.

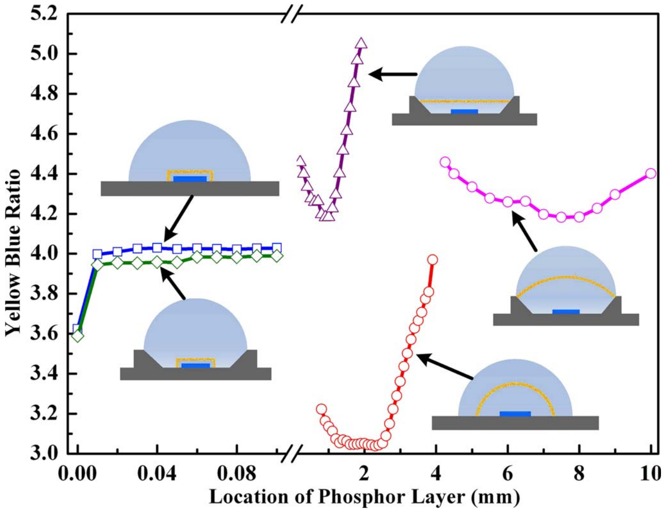


Fig. 14. Effects of phosphor's location on the YBR (CCT) for all cases.

Compared with the obvious change by location in type II, the variation of type V is relatively small. This may be because the location is too remote. However, the change of curvature still has limited impact on CCT.

As shown in Fig. 12, the light extraction and CCT in type IV have similar tendency as that in type II. This indicates that remote phosphor location has similar influencing mechanism for packaging. However, this case does not present the phenomenon of balance zone. Therefore, the manufacturing tolerance is relatively lower.

To further discuss the simulation results and obtain more useful conclusions, the light extraction efficiency and YBR for all cases are shown in one figure. Fig. 13 shows the tendency of nominal packaging efficiency and real packaging efficiency. Fig. 14 is about the variation of CCT. Compared to the significant variation of CCT, the impact of phosphor's location on efficiency is small. The fluctuations are no more than 6.5% for NPE and 4.9% for RPE. The variations of efficiency tend to become slower and smoother with the increase of location. Results also confirm that remote phosphor location presents higher light extraction than proximate phosphor.

It can be found that the light extraction efficiency of the convex phosphor layer is normally higher than that of the plane phosphor layer, such as in type IV. This may be due to the fact that convex surface could improve the critical angle for some random light rays and provide more chances to let these rays be extracted from the surface by reducing the times of multiscattering. This affection is limited because most of the rays are disordered by phosphor's scattering. Specifically, this affection plays a role in structures with light source in the center of convex surface. For example, the blue light emitted from the chip should have relatively higher blue light output in type II, while the yellow light emitted from the phosphor layer should present higher yellow light output in type IV. Therefore, the YBR of type II is lower than that of type IV, as shown in Fig. 14.

It should be noted that the calculation of efficiency is based on the optical power, not the luminous flux. Luminous flux is related to visual sensitive function, which is based on wavelength. Human's eyes are more sensitive to yellow light. Therefore, more yellow light output normally generates higher luminous flux. From Figs. 13 and 14, although the variation of optical power output is small, the great change of YBR could influence the luminous flux significantly. Finally, the type IV with remote and plane phosphor layer is predicted to have the highest luminous flux.

V. CONCLUSION

Based on the Monte Carlo ray-tracing method, five numerical models are discussed in this paper. This paper develops a two-light-source step computation method to calculate the models. Wall plug efficiency, nominal packaging efficiency, real packaging efficiency, and YBR are applied to evaluate the effects of phosphor's location. Simulation results show that the location of phosphor layer has low impact on light extraction, except for the structure with phosphor directly coated on chip. This is mainly due to the chip's absorption. The fluctuations are no more than 6.5% for nominal packaging efficiency and 4.9% for real packaging efficiency. This indicates that the scattering of phosphor could effectively weaken the change of optical elements in structure. Results confirm that remote phosphor location presents higher light extraction than proximate phosphor location, which has been discussed by other researchers but not systematically analyzed. With the increase of location, the variations of efficiency tend to become slower and smoother. Therefore, the location of phosphor should not be too remote to avoid the potential reduction in light output.

CCT greatly depends on the structure and location of phosphor layer. Small variation of location could induce a significant change of YBR. Except for that of types I and III, the YBRs of other cases have inverse tendency to light extraction. Results show that the convex phosphor layer presents higher light extraction but lower YBR than the plane phosphor layer. Finally, considering the sensitivity of human's eyes for different spectra, it is suggested that an optical structure with plane and remote phosphor location should be a suitable choice for LED packaging.

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