Comprehensive Study on the Transmitted and Reflected Light Through the Phosphor Layer in Light-Emitting Diode Packages

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***Abstract*—In this study, we modeled the transmitted and reflected light of a phosphor layer in light-emitting diode packages by coupling the revised Kubelka-Munk and Mie-Lorenz theories. Through analyzing the transmitted and reflected light separately, it is found that the transmitted and reflected blue light vary monotonically with the changes of phosphor particle size, concentration and thickness. While the trends of the transmitted and reflected yellow light are non-monotonic, which are influenced by the interactions among the phosphor particle size, concentration and thickness. The light extraction efficiency through a phosphor layer was discussed. The reasons behind these phenomena were also presented.**

***Index Terms*—Light-emitting diodes (LEDs), phosphors, reflection, transmission.**

I. Introduction

CURRENTLY, high power blue gallium-nitride (GaN) light-emitting diodes (LEDs) are being used as the dominant excitation source to pump the down-converting phosphors to generate white light [1]–[5]. The light down-converting processes contain several sub-processes, i.e., light scattering, absorption, and conversion. Every time the light is scattered by a phosphor particle, light absorption and light conversion would happen consequently [6]. In the conversion sub-process, for the typical cerium-doped yttrium aluminium garnet (YAG:Ce) phosphors, a part of the blue light is absorbed by the phosphor particles and then converted to lower-energy yellow light emission due to the non-radiative relaxation process in the 4f- or 5d- energy level of the doping ions in phosphors [7], [8]. The ratio of converted yellow light to the absorbed blue light is dependent on the phosphor efficiency [9], [10]. The white light is obtained by mixing the transmitted blue light and transmitted yellow light from the phosphor layer inside the LED packages.

Since the white light of phosphor-converted LEDs (pc-LEDs) is generated by light mixing, the phosphor layer plays a significant role in determining the final light quality. As one of the most important components in pc-LEDs, phosphor layer witnesses the occurrence and supplies the sites of the whole light down-converting processes [11]–[14]. Moreover, the transmitted and reflected blue light and yellow light are usually mixed with each other, which increase the difficulties in the full understanding and accurate control of each light beam in light mixing. Comprehensively understanding the transmitted and reflected light properties of phosphor layer is therefore necessary and important. Meanwhile, the effects of phosphor parameters (particle size, concentration and thickness) on the transmitted and reflected blue and yellow light separately are complicated. Currently, the effects are not clear enough to be applied with accurate control.

As one of the most important criteria of LEDs, the light extraction efficiency, which is determined by the transmitted blue and yellow light, has attained plentiful interests from both researchers and engineers. Significant progress in pc-LEDs are strongly motivated by the advances in the high efficiency LEDs in the visible [15]–[24] and UV [25]–[27] spectral regimes, which serve as pump excitation sources for the phosphor in device configurations. The advances in high efficiency III-nitride LEDs has been achieved by using new types of active regions for improved spontaneous emission rate [15]–[19], new growth methods for dislocation density reduction [20]–[22], and new nano/micro photonics for improved efficiency [23], [24]. Recent works on UV-excitation phosphor materials have also been reported [28], and the availability of high efficiency deep/mid UV LEDs or lasers [25]–[27] is important as pumping excitation sources for this technology. In addition, recent works have also pointed out the possibility of employing UV-excitation phosphor materials for solid state lighting, where the availability of high performance deep/mid UV LEDs or lasers is important as pumping excitation sources for these phosphors.

In our previous study, we proposed a model to calculate the bidirectional scattering properties of phosphor layer in white LEDs [29]. The model was derived from Kubelka-Munk theory and we revised the theory by taking account of the light conversion process. The predictions of our model were much close to others' experimental data, thus our model was validated.

In this study, based on our model, we mainly analyzed the forward-scattering and backscattering properties of phosphor layer

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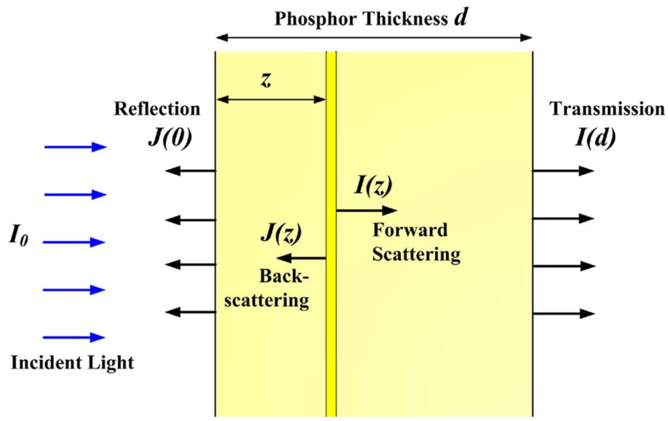

Fig. 1. Forward-scattering and backscattering functions with invasion depth z.

first. The effects of the phosphor parameters, such as phosphor particle size, concentration and thickness, on the transmitted and reflected light through the phosphor layer were discussed. The interactions between these phosphor parameters were presented.

II. Methodology

As shown in Fig. 1, for a phosphor layer with a thickness d, the forward-scattering function $I(z)$ and backscattering function $J(z)$ as the functions of the invasion depth z can be calculated as follows.

For blue light:

$$\begin{aligned} I_B(z) &= A(1-\beta)e^{\alpha z} + B(1+\beta)e^{-\alpha z} \\ J_B(z) &= A(1+\beta)e^{\alpha z} + B(1-\beta)e^{-\alpha z} \end{aligned} \tag{1}$$

For yellow light:

$$\begin{aligned} I_Y(z) &= C(1-\nu)e^{\mu z} + D(1+\nu)e^{-\mu z} \\ &\quad + \frac{2\eta a_B}{\nu(\mu^2-\alpha^2)}[A(\mu-\nu\alpha)e^{\alpha z} + B(\mu+\nu\alpha)e^{-\alpha z}] \\ J_Y(z) &= C(1+\nu)e^{\mu z} + D(1-\nu)e^{-\mu z} \\ &\quad + \frac{2\eta a_B}{\nu(\mu^2-\alpha^2)}[A(\mu+\nu\alpha)e^{\alpha z} + B(\mu-\nu\alpha)e^{-\alpha z}] \end{aligned} \tag{2}$$

with

$$\begin{aligned} \alpha &= 2\sqrt{a_B(a_B+2s_B)}, \beta = \sqrt{a_B/(a_B+2s_B)} \\ \mu &= 2\sqrt{a_Y(a_Y+2s_Y)}, \nu = \sqrt{a_Y/(a_Y+2s_Y)} \end{aligned} \tag{3}$$

where a and s are the absorption and scattering coefficients, respectively, and the corresponding subscripts B and Y denote the blue light and yellow light, respectively. η is the energy conversion coefficient from blue light to yellow emission. A, B, C and D are the undetermined constant coefficients, which can be solved with boundary conditions for blue light and yellow light, as shown in (4) and (5)

$$I_B(0) = I_0 + \gamma_B J_B(0), J_B(d) = 0 \tag{4}$$

$$I_Y(0) = \gamma_Y J_Y(0), J_Y(d) = 0 \tag{5}$$

where I_0 is the intensity of incident blue light from LED chip to the phosphor layer, d is the thickness of the phosphor layer.

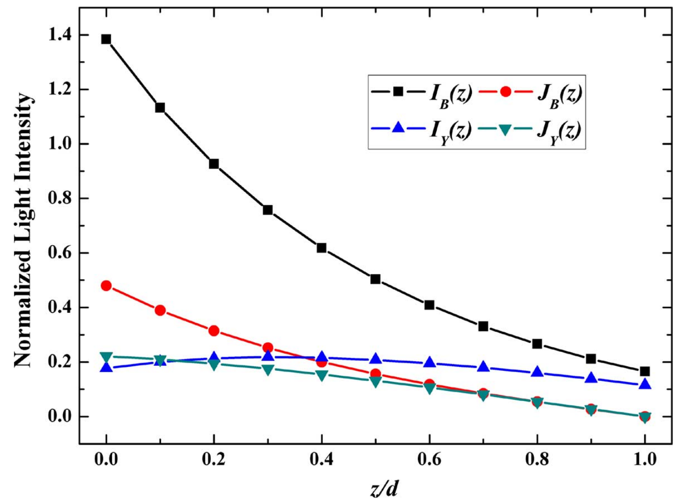

Fig. 2. Variation of normalized forward-scattering and backscattering light intensities with the increase of invasion depth in phosphor layer.

The γ_B and γ_Y are the reflection coefficients of blue light and yellow light on the boundaries.

It is seen that the forward-scattering and backscattering functions for both blue light and yellow light cannot be totally solved unless the necessary absorption and scattering coefficients of phosphor particles are obtained in advance. These coefficients are the intrinsic characteristics of the phosphor particles and they are difficult to be measured actually. In this study, we adopted the Mie-Lorenz theory to calculate the necessary coefficients since the theory is valid for all possible ratios of particle radius to the wavelength [30]. According to Mie-Lorenz theory, the extinction efficiency $Q_{\rm ext}$, the scattering efficiency $Q_{\rm sca}$, and the absorption efficiency $Q_{\rm abs}$ are normally calculated by the following equations [30], [31] :

$$Q_{\rm ext} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1){\rm Re}(a_n+b_n) \tag{6}$$

$$Q_{\rm sca} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2+|b_n|^2) \tag{7}$$

$$Q_{\rm abs} = Q_{\rm ext} - Q_{\rm sca} \tag{8}$$

where a_n and b_n are the expansion coefficients with even symmetry and odd symmetry, respectively, which can be determined by

$$a_n = \frac{m^2 j_n(mx)[xj_n(x)]' - j_n(x)[mxj_n(mx)]'}{m^2 j_n(mx)\left[xh_n^{(1)}(x)\right]' - h_n^{(1)}(x)[mxj_n(mx)]'} \tag{9}$$

$$b_n = \frac{j_n(mx)[xj_n(x)]' - j_n(x)[mxj_n(mx)]'}{j_n(mx)\left[xh_n^{(1)}(x)\right]' - h_n^{(1)}(x)[mxj_n(mx)]'} \tag{10}$$

where $j_n(x)$ and $h_n^{(1)}(x)$ are the Bessel function and first kind of Hankel function, respectively. x is the size parameter, which is calculated by (11). m is the complex refractive index of the particle relative to the ambient medium. In the LED packaging, the ambient medium of phosphor particles is silicone gel, thus

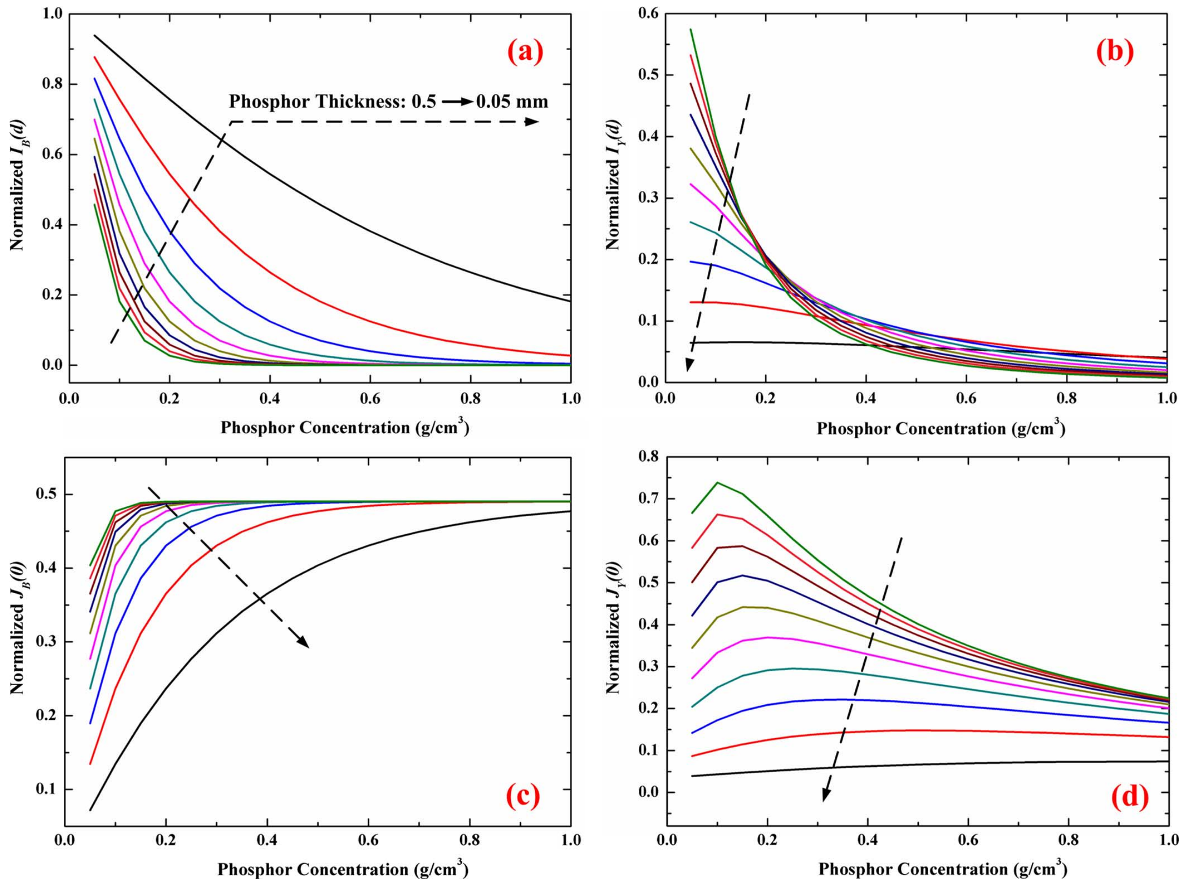

Fig. 3. Effects of phosphor concentration and thickness on the transmitted and reflected blue and yellow light.

the complex refractive index of phosphor particle is calculated by (12) as

$$x = krn_{\text{sil}} = \frac{2\pi n_{\text{sil}}}{\lambda} r \tag{11}$$

$$m = n_{\text{phos}}/n_{\text{sil}} \tag{12}$$

where k is the wave number, r is the equivalent sphere radius, λ is the wavelength. n_{phos} and n_{sil} are the refractive index of phosphor and silicone gel, respectively.

Then the light scattering and absorption coefficients can be calculated as follows in (13) [32]:

$$\mu_{\text{sca}} = Q_{\text{sca}} A V_d$$
$$\mu_{\text{abs}} = Q_{\text{abs}} A V_d \tag{13}$$

where A is the geometrical cross area of the particle $(= \pi r^2)$ and V_d is the volume density of phosphor particles.

Therefore, the forward-scattering and backscattering functions $I(z)$ and $J(z)$ for both blue and yellow light with any invasion depth could be calculated completely by coupling the revised Kubelka-Munk theory and Mie-Lorenz theory.

III. Results and Discussions

With the above methodology, we analyzed the forward-scattering and backscattering functions with the increase of invasion depth. And then the effects of phosphor parameters on the transmitted and reflected light were discussed.

A. Forward-Scattering and Backscattering Functions

The variations of the forward-scattering and backscattering intensities for both blue and yellow light with the invasion depth z were calculated and plotted in Fig. 2. It is seen that with the increase of $z, I_B(z)$ decreases greatly, while $I_Y(z)$ has a trend of rise at first and a drop at last. It is also seen that both $J_B(z)$ and $J_Y(z)$ decrease when the light invades the phosphor layer deeper, and when the light penetrates the phosphor layer, both $J_B(z)$ and $J_Y(z)$ vanish. The reasons may include: 1) with the increase of z, more blue light is absorbed and scattered along with light invasion, thus $I_B(z)$ decreases; 2) when z increases at first, more yellow light is converted and $I_Y(z)$ increases slightly; when z increases further, the effects of yellow light absorption and scattering overweigh the increase of the yellow light intensity, thus $I_Y(z)$ decreases; and 3) as shown in Fig. 1, with the increase of z, both the blue and yellow light are backscattered by thinner phosphor layer ($d - z$ part), and the backscattered blue and yellow light components reduce, thus $J_B(z)$ and $J_Y(z)$ decrease.

B. Effects of Concentration and Thickness

For a phosphor layer, the transmission and reflection intensities of blue light and yellow light are most concerned because they determine the light extraction efficiency (LEE) and light quality. When the thickness of phosphor layer is d, the transmitted blue light and yellow light are $I_B(d)$ and $I_Y(d)$, respectively; the reflected blue light and yellow light are $J_B(0)$ and $J_Y(0)$, respectively. To observe the interactions among the

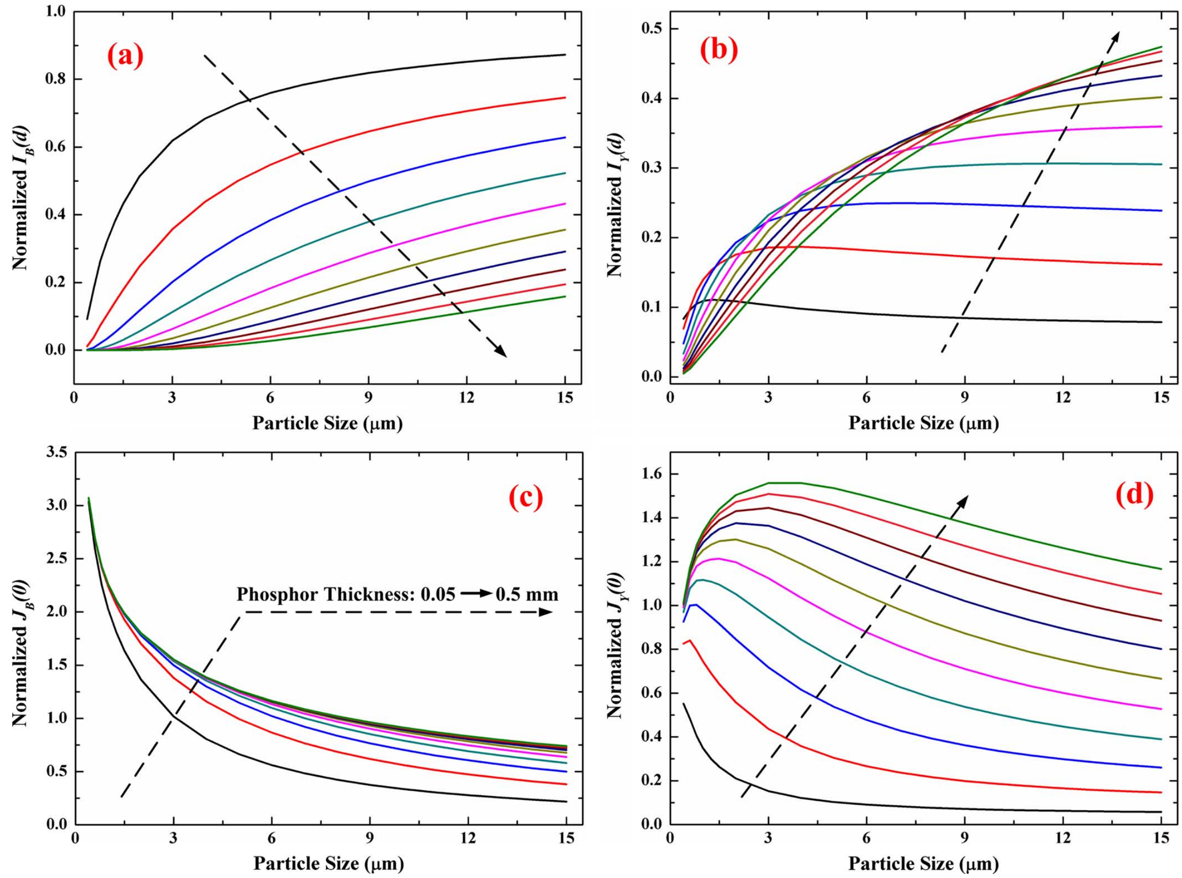

Fig. 4. Effects of phosphor particle size and thickness on the transmitted and reflected blue and yellow light.

light scattering, reabsorption and conversion inside phosphor layer, the variation of $I_B(d)$, $J_B(0)$, $I_Y(d)$, and $J_Y(0)$ with the change of phosphor concentration and thickness d are calculated and plotted separately in Fig. 3.

From Figs. 3(a) and (c), it is seen that with the increase of concentration, $I_B(d)$ decreases while $J_B(0)$ increases greatly. Meanwhile, the thicker the phosphor layer is, the lower the phosphor concentration is when $I_B(d)$ gets its minimum value or $J_B(0)$ gets its maximum value. These phenomena can be understood as follows: 1) when phosphor concentration or thickness increases, more blue light is absorbed and scattered, it becomes harder for blue light to penetrate the phosphor layer, thus $I_B(d)$ decreases; 2) when phosphor concentration or thickness increases, more blue light is backscattered, thus the reflected blue light $J_B(0)$ increases. Since the blue light is scattered into all the directions, the further increase of concentration or thickness contributes nothing to the enhancement of $J_B(0)$ at the incident surface, and $J_B(0)$ tends to be a stable maximum value.

From Figs. 3(b) and (d), the increase of concentration leads to a trend of gradual decrease of $I_Y(d)$, but $J_Y(0)$ witnesses a rise at first and a trend of decrease in the end. When comes to the thickness, it is seen that the increase of thickness results in the increase of $I_Y(d)$ at low concentration, but the situation is just the opposite at large concentration. But $J_Y(0)$ increases along with the increase of thickness. When concentration is low, thicker phosphor layer can absorb more blue light and emit more yellow light, thus $I_Y(d)$ and $J_Y(0)$ increases; but when concentration is large, yellow light scattering and absorption overweigh yellow emission in thicker layer, thus $I_Y(d)$ and $J_Y(0)$ drops instead. The thicker the phosphor layer is, the more phosphor particle would participate in the light backscattering and more yellow light would be scattered, thus $J_Y(0)$ increases along with the thickness.

The concentration and thickness are important parameters in affecting the transmitted and reflected light. The concentration and thickness almost play the similar role that they mainly influence the amount of phosphor particles which participate in the light scattering, absorption and conversion.

C. *Effects of Particle Size and Thickness*

The phosphor particle size is also an important parameter [33], [36]. With the similar method, we calculated the variations of the transmitted and reflected blue or yellow light along with the phosphor particle size and thickness, as shown in Fig. 4. The phosphor concentration in the whole calculation is 0.2 g/cm^3. From this figure, we can see that the increase of particle size may result in the gradual increase of $I_B(d)$ and $I_Y(d)$, the sharp decrease of $J_B(0)$. But $J_B(0)$ has a small rise at first, and a gradual drop afterward. According to electromagnetic field theory, when the particle is illuminated by light, the total scattered field is obtained by superposing the scattered wavelets on the incident wave. When the particle radius is small, all the secondary wavelets are approximately in phase and there were no much variation of scattering with direction. As the particle radius increases, the number of possibilities for

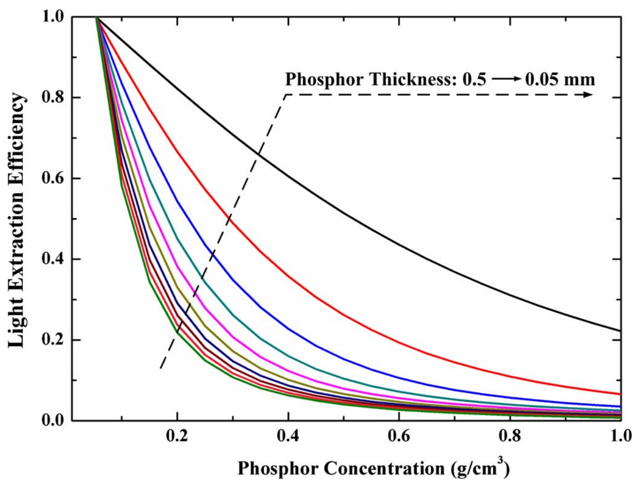

Fig. 5. Trends of light extraction efficiency with phosphor concentration and thickness.

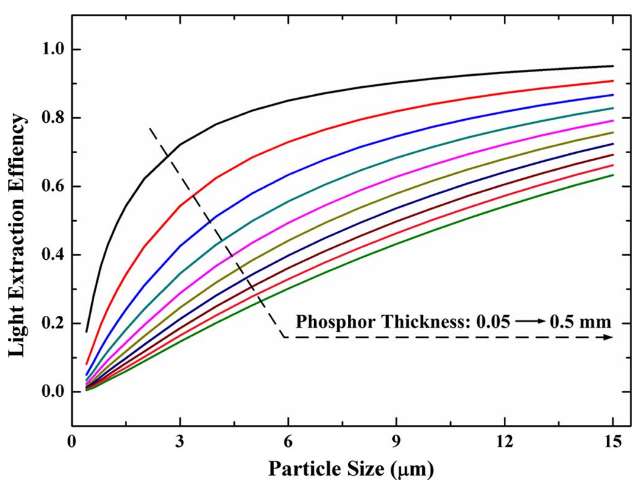

Fig. 6. Trends of light extraction efficiency with phosphor particle size and thickness.

mutual enhancement and cancellation of the scattered wavelets increase. The larger the particle is, the more peaks and valleys of the superposing wave in the scattering pattern are, therefore the larger the variation of scattering in directions is. Large particle means strong forward scattering, thus $I_B(d)$ and $I_Y(d)$ increase, $J_B(0)$ and $J_Y(0)$ decrease. Since the concentration in the calculations is all the same, large particle means smaller number of particles that participate in the down-converting processes. The reasons for the small increase of $J_Y(0)$ lie in the interaction between the particle size and particle number. The effects of thickness and its causes are similar to those in Fig. 3, not repeat here.

After comprehending the transmitted and reflected light respectively, some optical phenomena can be understood. Light extraction efficiency (LEE) through a phosphor layer is an important evaluation parameter. It is determined by the transmitted blue and yellow light. Therefore, it can be normalized as [35], [36]

$$\eta_{\rm LEE} = (I_B(d) + I_Y(d))/I_0 \tag{14}$$

The trends of LEE with varying phosphor concentration and thickness are shown in Fig. 5. It is seen that LEE decreases with the increase of concentration and thickness. According to (14), the results can be understood with Fig. 3(a) and (b) and are consistent with [35].

The variations of LEE with changing phosphor particle size and thickness are pictured in Fig. 6. It is seen that the increase of particle size results in the increase of LEE, while the thicker phosphor layer may cause a drop of LEE. The phenomena can be understood by referring to Figs. 4(a) and (b). These results reach a consensus with [33], [34].

IV. Conclusion

In this study, the forward-scattering and backscattering functions of a phosphor layer were modeled based on the revised Kubelka-Munk and Mie-Lorenz theories. The effects of phosphor parameters (particle size, concentration and thickness) on the transmitted and reflected blue and yellow light were analyzed, respectively. It is found that the transmitted and reflected blue light vary monotonically with changes of phosphor particle size, concentration and thickness. While the trends of the transmitted and reflected yellow light are non-monotonic, which are influenced by the interactions among the phosphor parameters. The light extraction efficiency through a phosphor layer was also discussed. The light extraction efficiency increases with the increase of particle size and the decrease of concentration and thickness. The reasons behind these phenomena were easy to understand by analyzing the trends of the transmitted blue light and yellow light respectively.

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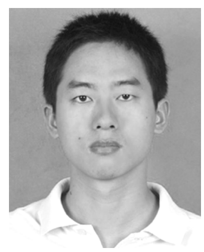

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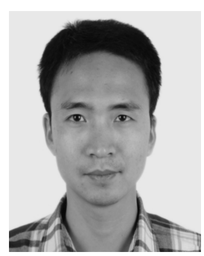

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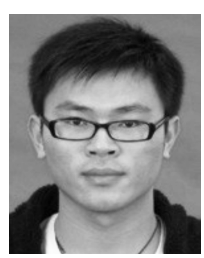

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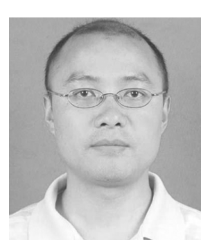

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