Modeling white light-emitting diodes with phosphor layers

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With a blue light-emitting diode and a phosphor layer to downconvert blue light to a second light, such as yellow, white light can be produced. The authors developed a one-dimensional model to describe the light propagating in the phosphor layer in terms of light absorption, conversion, and reflection. The parameters required for the model were determined from the data obtained by using multiple-layer phosphor films. The model predicts that, with a reflector between the diode and the phosphor layer that is blue-light transparent but reflects other visible light, the normalized white light intensity is above 0.9, higher than that of conventional packages (0.6–0.8). © *2006 American Institute of Physics*. [DOI: 10.1063/1.2400111]

Blue light-emitting diodes (LEDs) have been used as an excitation source for downconverting luminescent material, such as phosphor.[1,2] Mixing blue light with a downconverted light, such as yellow, white light can be produced. Unfortunately a portion of energy would be lost during the mixing processes in conventional packages. Reasons for such energy loss include chip absorption of backward light emitted from phosphor.[3] A remote-phosphor-package shown in Fig. 1 was first proposed in 1999 and such concepts have potential to reduce energy losses.[4] This work proposed a one-dimensional model to describe the light absorption, conversion, and reflection in LED-phosphor packages.

Shown in Fig. 2(a) is a small cross section of the phosphor layer with thickness Δz. The energy of the blue light emitted from the LED chip is lost during its propagating in the phosphor layer. The lost amount is proportional to the intensity of input blue light (Lambert-Beer's law[5]). Part of the energy loss of blue light is caused by its conversion to yellow. The converted light can propagate in the z direction or in the opposite direction.[3] The energy of the converted yellow light also dissipates during its propagation within the phosphor layer, following the Lambert-Beer's law.[5] In Fig. 2, PB represents the intensity of blue light, PY the intensity of yellow in the z direction, and PY^- that of yellow light in the opposite direction. By performing the energy balance, the following three equations were derived:

$$\mathrm{PB}|_{z+\Delta z} - \mathrm{PB}|_z = -\alpha_\mathrm{B} \times \Delta z \times \mathrm{PB}|_z, \tag{1}$$

$$\mathrm{PY}|_{z+\Delta z} - \mathrm{PY}|_z = -\alpha_\mathrm{Y} \times \Delta z \times \mathrm{PY}|_z + \frac{1}{2}\beta \times \Delta z \times \mathrm{PB}|_z, \tag{2}$$

$$\mathrm{PY}^-|_z - \mathrm{PY}^-|_{z+\Delta z} = -\alpha_\mathrm{Y} \times \Delta z \times \mathrm{PY}^-|_{z+\Delta z} + \frac{1}{2}\beta \times \Delta z \times \mathrm{PB}|_{z+\Delta z}, \tag{3}$$

where α_B and α_Y are parameters describing the fractions of the energy loss of blue and yellow lights during their propagations in the phosphor layer,[5] respectively, and β is the conversion coefficient for blue light converting to yellow. α_B, α_Y, and β are properties of the phosphor layer and dependent on the volume fraction of the phosphor particles in the layer, ρ_v. With Δz approaching zero, Eqs. (1)–(3) become

$$\frac{d\mathrm{PB}}{dz} = -\alpha_\mathrm{B} \times \mathrm{PB}, \tag{4}$$

$$\frac{d\mathrm{PY}}{dz} = -\alpha_\mathrm{Y} \times \mathrm{PY} + \frac{1}{2}\beta \times \mathrm{PB}, \tag{5}$$

$$\frac{d\mathrm{PY}^-}{dz} = \alpha_\mathrm{Y} \times \mathrm{PY}^- - \frac{1}{2}\beta \times \mathrm{PB}. \tag{6}$$

Figure 2(b) is a schematic illustration of a flip-chip structure of an LED chip with a phosphor layer thickness h. The intensity of blue light (PB) at $z=0$ is the light intensity from the blue LED, represented by PB_0. PY^-, the yellow light intensity traveling in the negative z direction, equals to zero at $z=h$. By assuming that there is no energy loss in the sapphire substrate, it is obtained that the yellow light intensity from the phosphor layer to the active layer is PY^- at $z=0$, denoted by $\mathrm{PY}^-(0)$. Part of the yellow light reaching the

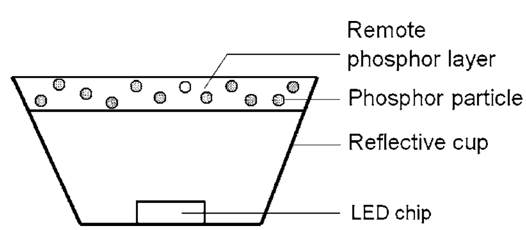

FIG. 1. Remote-phosphor package proposed by Chen (Ref. 4).

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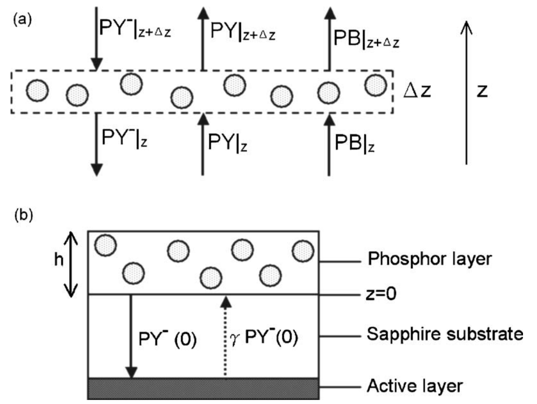

FIG. 2. (a) Schematic plot for a small section of phosphor layer (one-dimensional model) and (b) illustration of the boundary condition at $z=0$. A portion of backward yellow light, PY^-, is reflected by active layer back to the phosphor layer.

phosphor layer's bottom boundary is reflected back to the phosphor layer, with a yellow light reflection coefficient γ. Thus, the following boundary condition can be obtained $(PY(z=0)=\gamma PY^-(0))$. By further assuming that α_B, α_Y, and β are all constant, the solutions to Eqs. (4)–(6) can then be obtained, and the PB, PY, and PY^- at $z=h$ are expressed as

$$PB = PB_0 \times e^{-\alpha_B h}, \tag{7}$$

$$PY = \frac{1}{2}\frac{\beta \times PB_0}{\alpha_Y - \alpha_B}[e^{-\alpha_B h} - e^{-\alpha_Y h}] + \frac{1}{2}\frac{\gamma \times \beta \times PB_0}{\alpha_Y + \alpha_B}[e^{-\alpha_B h} - e^{-\alpha_B h - 2\alpha_Y h}], \tag{8}$$

$$PY^- = \frac{1}{2}\frac{\beta \times PB_0}{\alpha_Y + \alpha_B}[e^{-\alpha_B h} - e^{-\alpha_B h - 2\alpha_Y h}]. \tag{9}$$

In experiment, the PB and PY were measured at different phosphor layer thicknesses h. First we coated on a blue LED chip with a well-dispersed PMMA/phosphor powders/acetone solution. By the solvent evaporation method,[6] a 30 μm phosphor film was formed on the chip, and the blue and yellow light intensityies, PB and PY, were measured by an integrating sphere. A second 30 μm film was then coated on the top of the first layer and the light intensity for the chip with 60 μm film was measured again. We repeated five times the coating and measurement process with a constant ρ_v. Having a set of PB and PY data for different thicknesses h, the parameters α_B, α_Y, β, and γ were determined by curve fitting with Eqs. (7) and (8). Varying ρ_v and we performed the above experiments and data fitting for each ρ_v. Since the maximum phosphor thickness of our experiments is 150 μm, much smaller than the chip size, 1 mm, the one-dimensional approximation should still be valid. By experiment the parameters α_B, α_Y, β, and γ under different ρ_v values were obtained.

The relationship between the parameters and ρ_v is depicted in Fig. 3. A trend can be observed that with more phosphor in the film, the film would lose more blue and yellow lights and also downconvert more blue light to yellow light. On the other hand, the reflection coefficient ranges between 0.6 and 0.8 and is independent of ρ_v, which is reasonable since γ is a property of the phosphor layer's boundary only. We used linear equations to describe the dependence of α_B, α_Y, and β on ρ_v. Substituting them into Eqs. (7) and (8), PB and PY can be calculated for a given γ at different film thicknesses. The calculated results for $\gamma=0.7$ and experimental data are presented in Fig. 4.

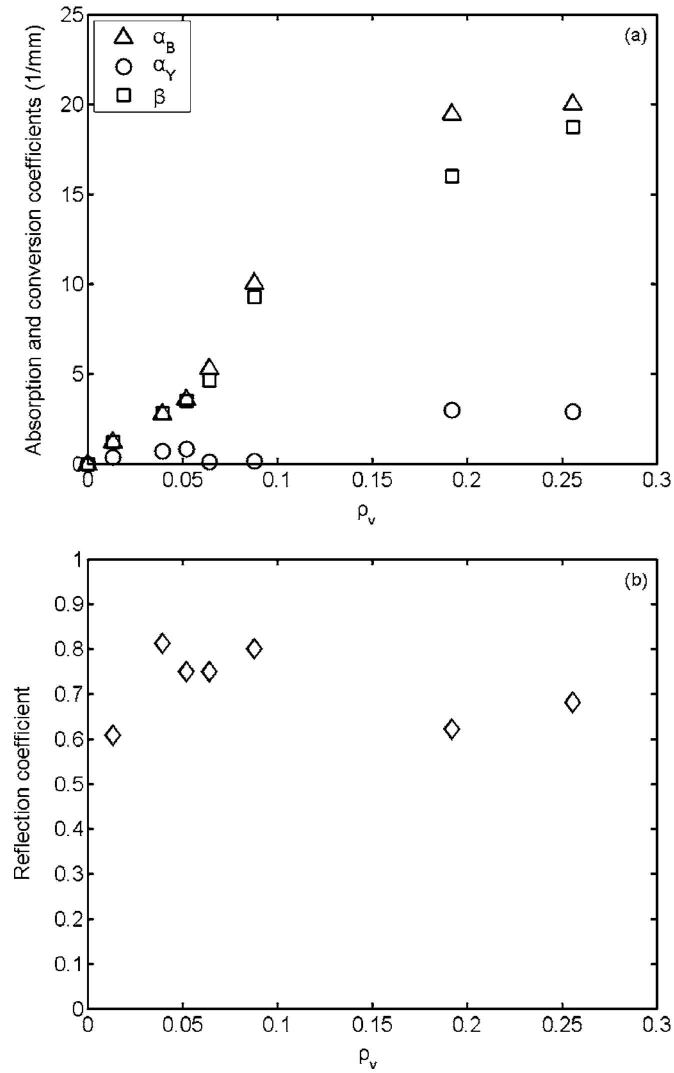

FIG. 3. (a) Dependence of absorption and conversion coefficients on the volume fraction of phosphor in the film and (b) relationship between the reflection coefficient and the volume fraction of phosphor in the film. The absorption coefficient is zero when ρ_v equals to zero because the absorption coefficient of PMMA is effectively zero compared to phosphor particles (Ref. 7).

According to Eqs. (7) and (8), the blue and yellow light emitted from a diode with a phosphor layer are functions of α_B, α_Y, β, γ, and h. Since α_B, α_Y, and β are functions of ρ_v only, the model parameters can be reduced to ρ_v, h, and γ. Figure 4 shows the dependence of the normalized total light intensity $((PB+PY)/PB_0)$, the same definition as the extraction efficiency, on ρ_v and h. By replotting the normalized intensity versus yellow light fraction $(PY/(PB+PY))$, the calculated results shown in Fig. 4 collapse into a single curve in Fig. 5. The results in Fig. 5 show that, for a specific yellow light fraction, the normalized total light intensity increases with increasing reflection coefficient. With $\gamma=1.0$, the normalized total intensity is above 0.9.

In practical application, for a one-dimensional package geometry, as described in Fig. 2, an increase in γ without affecting the blue light emission can be accomplished by placing a yellow light reflector,[8] transparent to blue light, between the phosphor film and the LED chip. For complicate

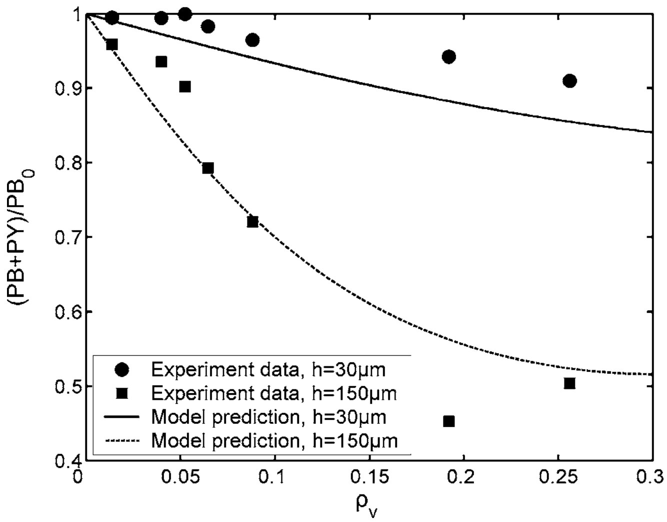

FIG. 4. Relationship between the normalized total intensity ($(PB+PY)/PB_0$) and the volume fraction of phosphor in film (ρ_v)—comparison between calculated results (given $\gamma=0.7$) and experiment data.

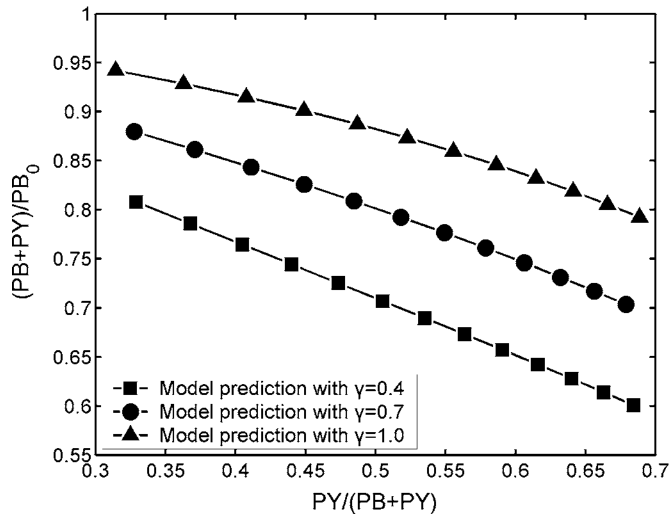

FIG. 5. Model calculated results to depict effects of reflection coefficient γ at any given phosphor-layer thickness by plotting normalized total intensity vs yellow light fraction, $PY/(PB+PY)$.

package geometry, the design of the package geometry and the reflectivity of the package material would also contribute to the value of γ in our model. When the package surface has higher reflectivity than the chip surface, the remote-phosphor package should have higher γ than the conventional one because the area involved in reflection is higher, which is believed to be the reason why it has higher light extraction. Details about how to estimate γ for complicated package geometry will be published in a subsequent paper.

In summary, with the model presented in this letter, we can predict the blue and yellow light intensities for a LED-phosphor package, as long as the phosphor layer's thickness, phosphor particle characteristic parameters, α_B, α_Y, and β, and the boundary's yellow light reflectivity are known. We suggest that higher light intensity can be achieved with any method to improve boundary reflectivity for yellow light.

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