A new structure of multi-layer phosphor package of white LED with high efficiency

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The applications of white light-emitting diodes (LEDs) have become more and more wide recently, while the low light-extraction efficiency of white LED limits its development. In this letter, a new structure of multi-layer phosphor package of white LED is proposed to improve the light-extraction efficiency. It is illustrated that the thickness of phosphor layer plays an important role in improving the light-extraction efficiency of LED. The light-extraction efficiency of LED is improved by double-layer or multi-layer phosphor package structures.

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The applications of white light-emitting diodes (LEDs) have become more and more wide but the light-extraction efficiency of white LED is always the main factor that limits its development. Further applications need higher light-extraction efficiency. Some ways of improving the light-extraction efficiency of white LED have been reported. For example, it can be improved by an omni-directional reflector consisting of GaN, a quarter-wave layer of SnO_2 nanorod and a Ag layer[1] or by the surface gratings and the encapsulation of a polymer[2]. The packaging technology is another way to improve the efficiency. The combination of a phosphor wavelength converter with a short-wavelength primary emitter is a common method for LED-based white-light sources[3]. Typical structures of the phosphor arrangement in dichromatic white LED are shown in Figs. 1 and 2. Figure 1, whose phosphor layer replicates the contour of the LED chip, shows a conformal phosphor distribution[4] and Fig. 2 shows a uniform distribution of phosphor within the reflector cup, which we refer to as "phosphor-in-cup". However, they both limit the light-extraction efficiency of LEDs.

The placement and arrangement of phosphor have significant effects on the light-extraction efficiency of white LEDs. A large portion of light emitted by the phosphor impinges on the LED chip and can be absorbed severely. So the conformal and phosphor-in-cup distributions limit the efficiency of white LED. The structure whose phosphor is placed at a sufficiently large distance from the LED chip is called remote phosphor configuration[5,6], as shown in Fig. 3. This kind of structure improves not only the efficiency but also the lifetime of LEDs. For the phosphor layer away from the LED chip, the heat generated by the LED chip only transfer to the substrate[7] instead of the phosphor. The probability of a light ray emitted by the phosphor hitting the low reflective LED chip directly is small. However, there is still a large probability of a light ray reflected by the reflector cup to be re-absorbed by the LED chip, as shown by rays 1 and 3 of Fig. 3.

In this letter, a new structure of multi-layer phosphor package, as illustrated in Fig. 4, is presented. The multi-layer phosphor configuration can increase the transmitted light (ray 3) and reduce the reflected light that directly impinges on the absorptive LED chip, thus improve the LEDs efficiency.

The absorption coefficient, the scattering coefficient and the thickness of the phosphor layer all affect the transmission of light. The first parameter has a much larger effect than the second one. Increasing the thickness has the same effect as increasing both of the absorption

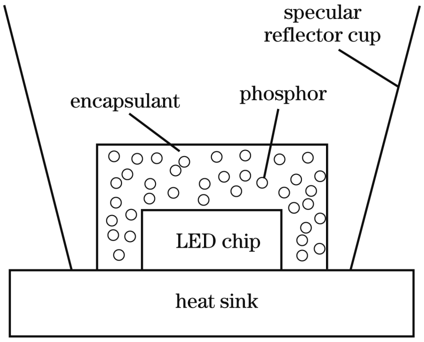

Fig. 1. Conformal distribution directly on LED chip.

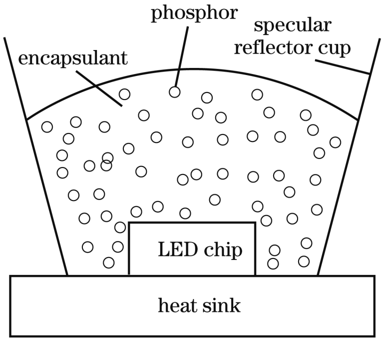

Fig. 2. Uniform distribution in reflector cup (phosphor-in-cup).

coefficient and the scattering coefficient[8]. If the absorption coefficient increases, the blue light reduces quickly but the yellow light increases slightly. So the bigger the absorption coefficient is, the lower the conversion efficiency will be. Therefore, the thickness of the phosphor layer should be reduced properly to improve the efficiency.

Kang *et al.* proposed a one-dimensional (1D) model to describe the light absorption, conversion, and reflection in LED-phosphor packages[9]. The 1D model is a schematic illustration of a LED chip with single phosphor layer thickness of h. The intensities of blue light (PB) and yellow light (PY) are the light intensity from the blue LED, represented by PB_0. α_B and α_Y are parameters describing the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer, respectively, and β represents the conversion coefficient for blue light converting to yellow light. The reflection coefficient γ shows the yellow light reflected from the LED chip. Light transmission can be expressed as

$$\mathrm{PB} = \mathrm{PB}_0 \times \mathrm{e}^{-\alpha_\mathrm{B} h}, \tag{1}$$

$$\begin{aligned}\mathrm{PY} = {} & \frac{1}{2}\frac{\beta \times \mathrm{PB}_0}{\alpha_\mathrm{Y} - \alpha_\mathrm{B}}(\mathrm{e}^{-\alpha_\mathrm{B}\mathrm{h}} - \mathrm{e}^{-\alpha_\mathrm{Y}\mathrm{h}}) \\ & + \frac{1}{2}\frac{\gamma \times \beta \times \mathrm{PB}_0}{\alpha_\mathrm{Y} + \alpha_\mathrm{B}}(\mathrm{e}^{-\alpha_\mathrm{B} h} - \mathrm{e}^{-\alpha_\mathrm{B} h - 2\alpha_\mathrm{Y} h}).\end{aligned} \tag{2}$$

Because the secondary transmitted light is much smaller than the directly transmitted light[10], we make $\gamma = 0$. Then, Eq. (2) becomes

$$\mathrm{PY} = \frac{1}{2}\frac{\beta \times \mathrm{PB}_0}{\alpha_\mathrm{Y} - \alpha_\mathrm{B}}(\mathrm{e}^{-\alpha_\mathrm{B}\mathrm{h}} - \mathrm{e}^{-\alpha_\mathrm{Y}\mathrm{h}}). \tag{3}$$

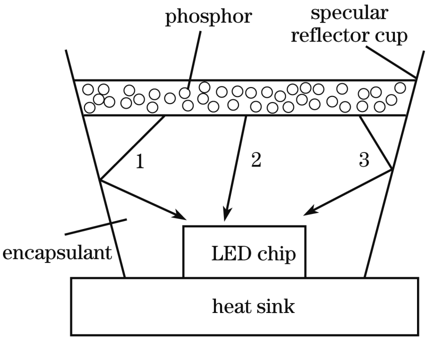

Fig. 3. Remote phosphor configuration.

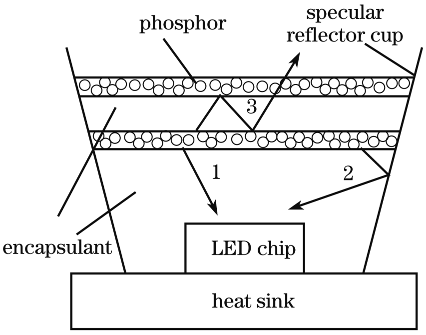

Fig. 4. Double-layer phosphor configuration.

When the thickness is $2h$ (Fig. 3), the subscript "1" is used to describe it, then Eqs. (1) and (3) become

$$\mathrm{PB}_1 = \mathrm{PB}_0 \times \mathrm{e}^{-2\alpha_{\mathrm{B}1} h}, \tag{4}$$

$$\mathrm{PY}_1 = \frac{1}{2}\frac{\beta_1 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}}(\mathrm{e}^{-2\alpha_{\mathrm{Y}1}\mathrm{h}} - \mathrm{e}^{-2\alpha_{\mathrm{B}1}\mathrm{h}}). \tag{5}$$

When the package is the double-layer phosphor structure and the thickness of each layer is h, the subscript "2" is used to describe it.

$$\begin{aligned}\mathrm{PB}_2 &= \mathrm{PB}_0 \times \mathrm{e}^{-\alpha_{\mathrm{B}2} h} \times \mathrm{e}^{-\alpha_{\mathrm{B}2} h} \\ &= \mathrm{PB}_0 \times \mathrm{e}^{-2\alpha_{\mathrm{B}2} h},\end{aligned} \tag{6}$$

$$\begin{aligned}\mathrm{PY}_2 &= \frac{1}{2}\frac{\beta_2 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}2} - \alpha_{\mathrm{Y}2}}(\mathrm{e}^{-\alpha_{\mathrm{Y}2}\mathrm{h}} - \mathrm{e}^{-\alpha_{\mathrm{B}2}\mathrm{h}}) \times \mathrm{e}^{-\alpha_{\mathrm{Y}2}\mathrm{h}} \\ &\quad + \frac{1}{2}\frac{\beta_2 \times \mathrm{PB}_0 \times \mathrm{e}^{-\alpha_{\mathrm{B}2} h}}{\alpha_{\mathrm{B}2} - \alpha_{\mathrm{Y}2}} \times (\mathrm{e}^{-\alpha_{\mathrm{Y}2} h} - \mathrm{e}^{-\alpha_{\mathrm{B}2} h}) \\ &= \frac{1}{2}\frac{\beta_2 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}2} - \alpha_{\mathrm{Y}2}} \times (\mathrm{e}^{-2\alpha_{\mathrm{Y}2} h} - \mathrm{e}^{-2\alpha_{\mathrm{B}2} h}).\end{aligned} \tag{7}$$

The variation of the transmitted blue light is

$$\mathrm{PB}_2 - \mathrm{PB}_1 = \mathrm{PB}_0 \times (\mathrm{e}^{-2\alpha_{\mathrm{B}2} h} - \mathrm{e}^{-2\alpha_{\mathrm{B}1} h}). \tag{8}$$

The variation of the transmitted yellow light is

$$\begin{aligned}\mathrm{PY}_2 - \mathrm{PY}_1 = {} & \frac{1}{2}\frac{\beta_2 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}2} - \alpha_{\mathrm{Y}2}} \times (\mathrm{e}^{-2\alpha_{\mathrm{Y}2}\mathrm{h}} - \mathrm{e}^{-2\alpha_{\mathrm{B}2}\mathrm{h}}) \\ & - \frac{1}{2}\frac{\beta_1 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}} \times (\mathrm{e}^{-2\alpha_{\mathrm{Y}1} h} - \mathrm{e}^{-2\alpha_{\mathrm{B}1} h}).\end{aligned} \tag{9}$$

Because the thickness h and the particle density ρ_v have the same effect on the parameters α_B, α_Y and β, it can be concluded from Refs. [8] and [9] that α_B increases significantly with the thickness, but α_Y only grows a little and is close to 0. The reason for the growth of the conversion coefficient β is that the yellow transmitted light increases steadily with the growth of α_B. So we can get $\alpha_{\mathrm{B}2} < \alpha_{\mathrm{B}1}, \beta_2 < \beta_1$ and $\alpha_{\mathrm{Y}1}$ being close to $\alpha_{\mathrm{Y}2} (\alpha_{\mathrm{Y}2} < \alpha_{\mathrm{Y}1})$. For $\frac{\beta_1}{\alpha_{\mathrm{B}1}} < \frac{\beta_2}{\alpha_{\mathrm{B}2}}$, and α_Y much smaller than α_B, it can be concluded that

$$\frac{\beta_1}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}} < \frac{\beta_2}{\alpha_{\mathrm{B}2} - \alpha_{\mathrm{Y}2}}.$$

Therefore, Eq. (9) becomes

$$\mathrm{PY}_2 - \mathrm{PY}_1 > \frac{1}{2}\frac{\beta_1 \times \mathrm{PB}_0}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}} \times (\mathrm{e}^{-2\alpha_{\mathrm{B}1}\mathrm{h}} - \mathrm{e}^{-2\alpha_{\mathrm{B}2}\mathrm{h}}). \tag{10}$$

The total transmitted-light change is

$$\begin{aligned}(\mathrm{PB}_2 - \mathrm{PB}_1) + (\mathrm{PY}_2 - \mathrm{PY}_1) > {} & \mathrm{PB}_0(\mathrm{e}^{-2\alpha_{\mathrm{B}2} h} - \mathrm{e}^{-2\alpha_{\mathrm{B}1} h}) \\ & \times \left(1 - \frac{1}{2}\frac{\beta_1}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}}\right).\end{aligned} \tag{11}$$

Under the same ρ_v and thickness, $\alpha_{\mathrm{B}1}$ is much larger than $\alpha_{\mathrm{Y}1}$ and β_1[9], so we can get

$$\frac{1}{2}\frac{\beta_1}{\alpha_{\mathrm{B}1} - \alpha_{\mathrm{Y}1}} < \frac{1}{2}.$$

Therefore,

$$(\mathrm{PB}_2 - \mathrm{PB}_1) + (\mathrm{PY}_2 - \mathrm{PY}_1) > \frac{1}{2}\mathrm{PB}_0[\mathrm{e}^{-2\alpha_{\mathrm{B2}}h} - \mathrm{e}^{-2\alpha_{\mathrm{B1}}h}]. \tag{12}$$

For $\alpha_{\mathrm{B2}} < \alpha_{\mathrm{B1}}$, the right-hand side of Eq. (12) is positive. The efficiency of the double-layer phosphor structure increases:

$$\frac{(\mathrm{PB}_2 + \mathrm{YP}_2) - (\mathrm{PB}_1 + \mathrm{PY}_1)}{(\mathrm{PB}_1 + \mathrm{PY}_1)} > \frac{\mathrm{e}^{-2\alpha_{\mathrm{B2}}h} - \mathrm{e}^{-2\alpha_{\mathrm{B1}}h}}{\mathrm{e}^{-2\alpha_{\mathrm{Y1}}h} - \mathrm{e}^{-2\alpha_{\mathrm{B1}}h}} > 0. \tag{13}$$

To verify the theory on the double-layer phosphor structure, the three-dimensional (3D) ray-tracing was simulated with a commercial software. In the simulation, two configurations shown in Figs. 3 and 4 were designed, and the extraction light from the phosphor directly transfered into the receiver not through the optical lens. It was assumed that the square-shaped LED chip with the size of 0.8×0.8×0.3 (mm) was located at the center of the cup bottom surface and the power of the chip, which emitted light through five surfaces except the bottom surface, was 1 W. The reflectances of the cup and the LED chip were assumed to be 95% and 50%, respectively, and the refractive index of the encapsulant filled in the cup was 1.6. The thickness of the single phosphor layer immersed in the encapsulant was 0.1 mm and the particle density was 2.2×10^6 mm^{-3}. The simulation results show that the power of double-layer structure is 0.399 W with the correlated color temperature (CCT) of 6279 K, and the power of the single-layer structure is 0.381 W with the CCT of 6283 K. The efficiency improves by 4.72%, which accords with the result of 5% deduced in the theory.

In conclusion, the theoretical calculation and the ray-tracing simulations, verify that the transmitted light increases and the reflected light (by the phosphor layer) reduces in the structure of double-layer package, which improves the light-extraction efficiency of white LED. With higher efficiency and higher power, LED will dominate in the fields of Urban landscape lighting, display, stadiums, and so on. The most attractive aspect is that it will bring a breakthrough in the field of general lighting. So the prototype of the multi-layer phosphor package should be studied more in the future.

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