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Analysis of high-power packages for phosphor-based white-light-emitting diodes

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An optimized packaging configuration for high-power white-light-emitting diode (LED) lamps that employs a diffuse reflector cup, a large separation between the primary emitter (the LED chip) and the wavelength converter (the phosphor) and a hemispherically shaped encapsulation is presented. Ray tracing simulations for this configuration show that the phosphor efficiency can be enhanced by up to 50% over conventional packages. Dichromatic LED lamps with phosphor layers on the top of a diffuse reflector cup were fabricated and studied experimentally. The experimental enhancement of phosphor efficiency is 15.4% for blue-pumped yellow phosphor and 27% for ultraviolet-pumped blue phosphor. Those improvements are attributed to reduced absorption of the phosphorescence by the LED chip and the reduction of deterministic optical modes trapped inside the encapsulant.
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With the rapid development of high-power white-light-emitting diodes (LEDs) and its potential for general illumination applications, there is a need for new high-power packaging technologies with low thermal resistance, compact size, and high efficiency.[1] The combination of a phosphor wavelength converter with a short-wavelength primary emitter is a common method for LED-based white-light sources. For example, a GaInN blue LEDs pumping a yellow YAG:Ce phosphor can generate dichromatic white light by mixing the two complementary colors. High photon outcoupling efficiency is particularly important for high-power LED lamps. The reflector cup, the placement of the phosphor, and the geometry of the encapsulation dome strongly influence the efficiency of the lamps.

In common configurations, the phosphor is either distributed uniformly in the reflector cup[2] or located in a layer replicating the contour of the LED chip (conformal phosphor distribution).[3] These "phosphor-in-cup" arrangements limit the phosphor efficiency because a portion of light generated by the phosphor is emitted toward the absorptive LED chip. Separating the phosphor from the LED chip by a large distance[4,5] reduces the probability of the phosphorescence being absorbed by the chip and thus improves the phosphor efficiency. For improving the extraction of light emitted by the LED chip and the phosphor out of the lamp package, encapsulations with different geometries have been employed. However, trapped optical modes inside the lamp package can occur, especially for high-power LED packages with compact size and relatively small encapsulant domes. Diffuse reflector cups can help to reduce deterministic optical modes trapped in the package and optical losses due to multiple reflections.[4]

In this letter, the influence of reflector cup surface roughness, phosphor placement, and geometry of the encapsulant on phosphor efficiency are studied, theoretically and experimentally. An optimized packaging configuration with a diffuse reflector cup, a large separation between the phosphor and the LED chip and a hemispherical encapsulant dome is demonstrated to have very favorable properties. The phosphor efficiency is enhanced by up to 50% in simulations and 27% in experiments for dichromatic LED lamps compared with conventional packaging configurations.

The high-power LED packages shown in Fig. 1 have two different phosphor arrangements, namely "phosphor-in-cup" and "phosphor-on-top". We assume that the surface of the reflector cup is either specular or diffuse. For a specular reflector cup, the angle of reflectance equals the angle of incidence. For a diffuse reflector cup, the reflected light I has a Lambertian distribution with an intensity $I \propto \cos\,\theta$, irrespective of the incident angle, where θ is the angle with respect to the surface normal. In addition, three different encapsulant geometries, shown in Fig. 1, are considered, namely a "flat" (no cap), a "convex" (spherical cap with height $h = r/2$), and

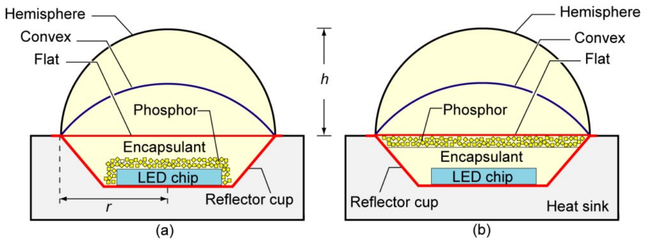

FIG. 1. Schematic cross-sectional view of the dichromatic white LED lamps with (a) phosphor-in-cup arrangement and (b) phosphor-on-top arrangement. Three different geometries of the encapsulation dome, flat ($h = 0$), convex ($h = r/2$), and hemispherical ($h = r$), are shown (color online only).

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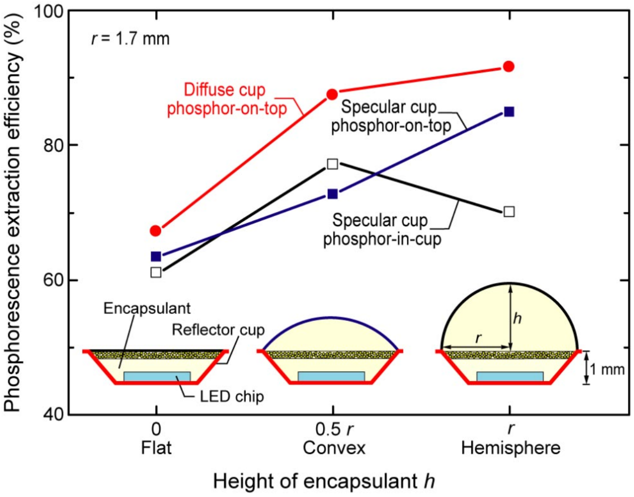

FIG. 2. Extraction efficiency of phosphorescence calculated by ray tracing for different package configurations (color online only).

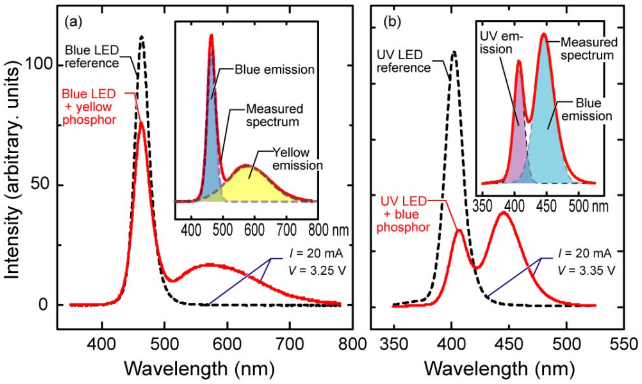

FIG. 4. Emission spectra (solid line) of a blue-pumped white LED lamp with yellow phosphor and a UV-pumped dichromatic LED lamp with blue phosphor. The dashed lines show the emission from reference LEDs packaged without phosphor. Deconvolution of the spectra into emission from the LED chip and emission from the phosphor is shown in the inset (color online only).

a "hemispherical" (spherical cap with height $h=r$) top surface.

Three-dimensional ray-tracing simulations have been performed for different types of white LED lamp structures including the phosphor-in-cup and phosphor-on-top arrangements, and for specular and diffuse reflector cups. In the simulation, we assume a truncated-cone-shaped reflector cup filled with an encapsulant ($n_{\text{encapsulant}}=1.6$). The cup with a 45° tilted sidewall is 1 mm high and its diameter at the bottom and top is 1.4 mm and 3.4 mm, respectively. The reflectance of the cup is assumed to be 95% ($R_{\text{reflector}}=95\%$) for both, the specular reflector cup and the diffuse reflector cup. The square-shaped LED chip, 1 mm × 1 mm, 300 μm thick, is located at the center of the cup bottom surface. The reflectance of the chip is assumed to be 50% ($R_{\text{LED chip}}=50\%$).[6] The phosphor emitting at $\lambda=550$ nm assumed to be a uniform cylindrical source with thickness of 100 μm immersed in the encapsulant. The phosphor is placed at the top of the reflector cup for the phosphor-on-top configuration and conformally on the chip for the phosphor-in-cup configuration. Both the encapsulant and phosphor are assumed to be transparent at 550 nm. The parameters used for the ray-tracing simulation are fully consistent with experimentally determined parameters. The number of rays used in the simulation is sufficiently large to obtain ergodicity.

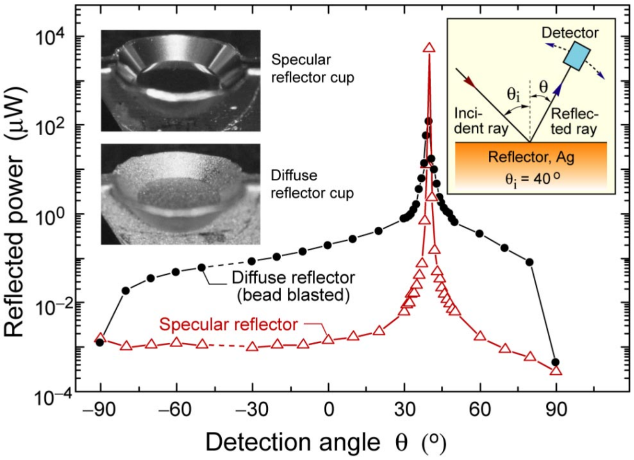

FIG. 3. Angular dependence of reflected power for a diffuse Ag reflector, which is roughened by bead blasting, and a specular Ag reflector (color online only).

The simulation results, presented in Fig. 2, show that the phosphor-on-top configuration with a diffuse cup has the highest extraction efficiency, irrespective of the encapsulation geometry. The phosphor efficiency is enhanced by 50% compared with that of the phosphor-in-specular-cup configuration with flat encapsulation. This improvement is mainly due to two reasons. First, the diffuse reflector cup introduces a chaotic component, which allows the extraction of the deterministic optical modes trapped in packaging structures with specular reflector cups. Second, the phosphor-on-top arrangement reduces absorption of phosphorescence by the LED chip. Figure 2 also shows that the shape of the encapsulant influences the phosphor efficiency. To minimize the total internal reflection losses, a spherical encapsulation with the light source in the center point is the best configuration. For the phosphor-in-cup distribution with a convex cap, the phosphor is closest to the center point of the spherical cap, which results in a high extraction efficiency. For the phosphor-on-top arrangement, the hemispherical encapsulation shows the best phosphor efficiency for the same reason. With the hemispherical encapsulant geometry, the phosphor-on-top and diffuse cup configuration shows a 27% improvement compared with phosphor-in-specular-cup case and an 8% improvement compared with phosphor-on-top and specular cup case.

Dichromatic LED lamps comprising a UV GaInN LED ($\lambda=400$ nm) with a blue phosphor and a blue GaInN LED ($\lambda=470$ nm) with a yellow phosphor were fabricated with different phosphor arrangements and reflector cups. For diffuse reflector cups, the sidewall of the reflector cup is roughened by bead blasting to achieve the diffuse reflection. Figure 3 shows the measured angular dependence of the reflectivity for a diffuse Ag reflector and a specular Ag reflector. The incident angle of He–Ne laser was 40° and the reflected power was measured from −90° to +90° as shown in the inset. The roughened Ag reflector shows a more than two orders of magnitude higher diffusely reflected power compared with the specular Ag reflector. The LED chips were

TABLE I. Phosphor power conversion efficiency for dichromatic LED lamps with different reflector cups and phosphor configurations.

	Phosphor power conversion efficiency (%)	
	UV LED + blue phosphor	Blue LED + yellow phosphor
Specular cup and phosphor-in-cup	67.9 (−)	59.9 (−)
Specular cup and phosphor-on-top	76.8 (13.1%)	64.6 (7.8%)
Diffuse cup and phosphor-on-top	86.2 (27.0%)	69.4 (15.4%)

die-bonded to the bottom of the reflector cups followed by wire bonding. For the phosphor-in-cup configuration, the phosphor was uniformly mixed into an epoxy resin and filled into the reflector cup. For the phosphor-on-top configuration, the reflector cups first were filled with transparent epoxy resin (without phosphor) and subsequently cured. A layer of phosphor containing epoxy resin was spread on the top of the already cured epoxy. After the phosphor containing epoxy was cured, reflector cups containing LED chips and phosphor were encapsulated by standard LED packaging technology.

Figure 4 shows the emission spectra of the reference primary LED emitters and of the dichromatic lamps operating at 20 mA in an integrating sphere. As illustrated in the inset, the spectra of dichromatic lamps were deconvoluted into two parts, the emission from the LED primary emitter and the emission from the phosphor. The optical power of each part can be determined by integrating the deconvoluted spectra. The phosphor power conversion efficiencies, shown in Table I, were calculated by dividing the experimental optical power from the phosphor by the difference in optical power between the reference emission of the LED (without phosphor) and the emission from the LED chip in the dichromatic configuration. For the dichromatic white lamp using the blue-pumped yellow phosphor, the phosphor conversion efficiency was improved by 7.8% for the phosphor-on-top with a specular cup configuration, and by 15.4% for the phosphor-on-top with a diffuse cup configuration over the phosphor-in-specular-cup configuration. As for the UV-pumped blue phosphor, the enhancement of power conversion efficiency is even higher. A 27% improvement is obtained for the phosphor-on-top and diffuse cup configuration compared with phosphor-in-specular-cup configuration. Because the luminous efficiency depends linearly on the phosphorescence efficiency, an improvement in phosphorescence efficiency directly translates into an improvement in luminous efficiency. The experimental results are fully consistent with the ray-tracing simulation, confirming the enhancement of phosphor efficiency by employing diffuse reflector cups and a large separation between primary emitter and wavelength converter.

In summary, an efficient packaging configuration consisting of a diffuse reflector cup, a phosphor spatially separated from the primary emitter, and a hemispherical encapsulant cap is presented. Ray-tracing simulations show a 50% improvement in phosphor efficiency compared with the phosphor-in-specular-cup configuration with a flat encapsulation. Dichromatic LED lamps with different phosphor placements and reflector cups were fabricated and compared with standard lamps. The phosphor conversion efficiency of the optimized phosphor-on-top arrangement and diffuse reflector cup is improved by 15.4% for blue-pumped yellow phosphor and 27% for UV-pumped blue phosphor, confirming the simulation results. This improvement is attributed to the reduced absorption of phosphorescence by the LED chip and the reduction of deterministic optical modes trapped inside the lamp encapsulant.

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