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Trapped whispering-gallery optical modes in white light-emitting diode lamps with remote phosphor

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Three-dimensional ray tracing simulations show that a significant fraction of the phosphorescence emitted in high-power white light-emitting diode lamps with a remote phosphor is trapped as whispering-gallery modes propagating along the circumference of the encapsulant. The whispering-gallery modes, which are a significant optical loss mechanism and occur for multiple shapes of the encapsulation dome, are shown to be sensitively dependent on the diffusivity of the reflector cup employed in the lamp. By employing a diffuse reflector cup, up to 86% of the trapped modes is extracted out from the encapsulant. In addition, it is experimentally demonstrated that the phosphorescence efficiency is improved by up to 12.2% as the diffusivity of the reflector increases. The experimental results are consistent with theoretical ray tracing simulations. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2221747]

White light can be generated by combining a short wavelength light-emitting diode (LED) with a phosphor wavelength converter.[1,2] In order to develop high-power white LED lamps for general illumination applications, new packaging technologies with low optical loss as well as high photon out-coupling efficiency are needed.[3,4] The placement of the phosphor, the geometry of the encapsulation dome, and the reflector cup influence the optical loss, and hence the device efficiency. Recently, it has been demonstrated that a large separation between the phosphor and the primary LED emitter, which we refer to as *remote phosphor* arrangement, enhances the phosphorescence extraction by reducing the optical power absorbed by the LED chip.[5,6]

In this letter, the occurrence of trapped optical modes inside the package propagating along the circumference of the encapsulant, i.e., whispering-gallery modes,[7,8] is identified to be a significant loss mechanism. Using ray tracing simulations, optical modes inside packages having a specular reflector cup are compared to modes inside packages with a diffuse reflector cup. It is found that the percentage of trapped modes and thus the phosphorescence efficiency are sensitively dependent on the diffusivity and specularity of the reflector cup. A diffuse reflector cup can reduce deterministic whispering-gallery modes, and thus enhance light extraction. It is experimentally shown that the phosphor efficiency of dichromatic LED lamps is enhanced by 12.2% by employing a diffuse reflector cup.

Three-dimensional ray tracing simulations have been performed for white LED lamps with remote phosphor. Figure 1(a) shows a truncated-cone shaped reflector cup filled with an encapsulant ($n_{encapsulant}=1.6$). Three different encapsulant geometries, namely, a "flat" (no cap), "convex" (spherical cap with height $h=r/2$), and "hemispherical" ($h=r$) top surface, are used in the simulations. The 3-mm-high cup has a sidewall tilt of 45° and a bottom surface diameter of 1.4 mm. The reflectance is 95% for both, the specular and the diffuse reflector cup. For specular reflection, the angle of reflectance equals the angle of incidence. For diffuse reflec-

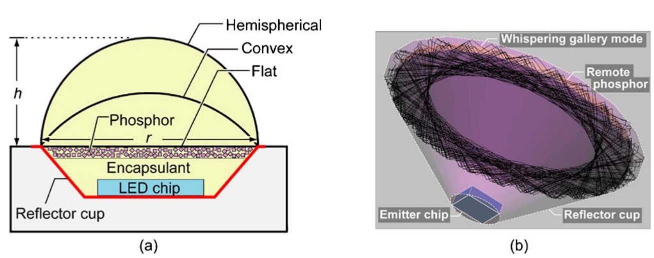

FIG. 1. (Color online) (a) Schematic cross-sectional view of dichromatic white LED lamps with remote phosphor and flat ($h=0$), convex ($h=r/2$), and hemispherical ($h=r$) encapsulant domes. (b) Trace of a single ray inside the LED lamp with remote phosphor, illustrating a trapped whispering-gallery mode.

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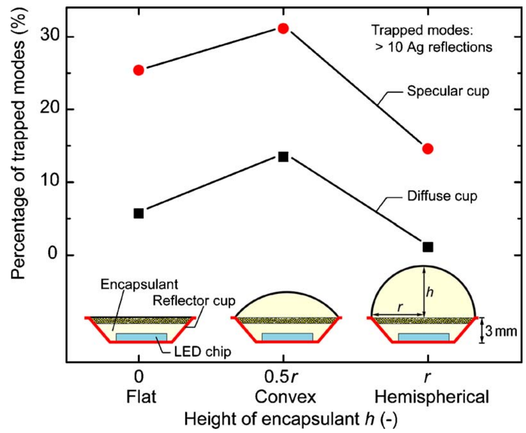

FIG. 2. (Color online) Simulated percentage of trapped modes (>10 Ag reflections) inside the white LED lamps with remote phosphor for flat, convex, and hemispherical encapsulant domes.

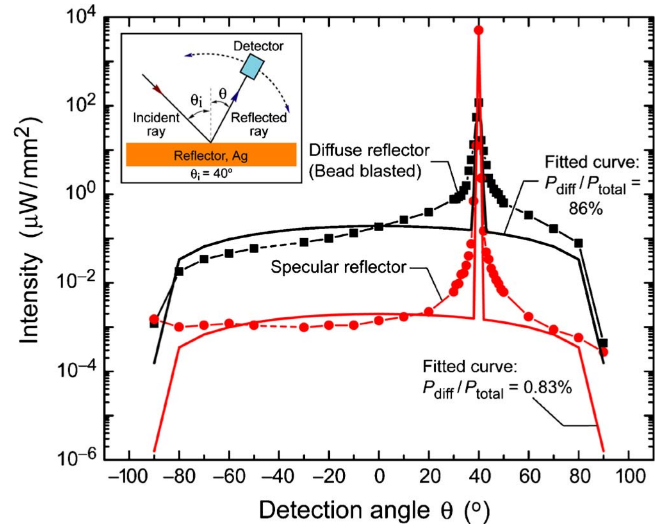

FIG. 3. (Color online) Measured angular dependence of reflectivity for a specular and a bead-blasted Ag reflector. Fitting the experimental data to the theoretical model gives diffuse-to-total-reflected-power ratios of 0.83% and 86% for the specular and the roughened Ag reflector, respectively.

tion, the reflected light has a Lambertian distribution with intensity $I \propto \cos\theta$,[9] irrespective of the incident angle, where θ is the angle with respect to the surface normal. The square-shaped LED chip with dimensions of $1\ \text{mm} \times 1\ \text{mm} \times 300\ \mu\text{m}$ and reflectivity of 50% (Ref. 10) is located at the center of the cup's bottom surface. The remote phosphor, emitting at 550 nm, is assumed to be a uniform cylindrical light source with thickness of 0.2 mm, immersed in the encapsulant at the top of the reflector cup. Both the encapsulant and phosphor are assumed to be transparent at 550 nm. Scattering by the phosphor can be neglected in the simulations for two ideal cases: (i) a small or negligible difference in the phosphor refractive index and encapsulant refractive index and (ii) for nanophosphors in which the phosphor-particle size is much smaller than the wavelength. The number of rays used in the simulation is sufficiently large to obtain ergodicity.

It is found that a significant fraction of rays is trapped inside the packages with a specular Ag reflector cup, irrespective of the encapsulant geometry. Figure 1(b) shows the trace of a single whispering-gallery ray inside a lamp package, in which multiple reflections occur. However, trapped modes, which we define here as modes having more than ten Ag reflections (ten reflections by the Ag reflector cup), are found to significantly decrease in lamp packages with diffuse reflector cup. Assuming a Ag cup with reflectivity of 95%, the power of the ray decreases to 60% after only ten reflection events, indicating that multiple reflection events greatly limit the phosphorescence efficiency.

Figure 2 shows the fraction of trapped modes for different encapsulation geometries and reflector cups. For lamp packages with a specular reflector cup, 25%, 32%, and 14% of the emission rays are trapped, i.e., have more than ten Ag reflections, in flat, convex, and hemispherical encapsulations, respectively. By employing a totally diffuse reflector cup, the fraction of trapped modes is significantly reduced, irrespective of the encapsulant geometry, as shown in Fig. 2. The percentage of trapped modes decreases to 5.2%, 13.6%, and 1.9% for flat, convex, and hemispherical encapsulations, respectively. Diffuse reflector cups randomize the trapped rays and thus increase the extraction probability. 58% and 86% of trapped modes are extracted out into free space by employing a totally diffuse reflector cup for convex and hemispherical encapsulation shapes, respectively. The simulation clearly demonstrates that the diffuse reflector cup effectively eliminates whispering-gallery trapped modes.

Surface-roughened reflectors have a diffuse as well as a specular reflection component. We refer to such reflectors as *partially diffuse reflectors*. To investigate the influence of partially diffuse reflector cups on the phosphor efficiency, it is desirable to quantify the specularity and diffusivity of roughened reflector cups. The intensity of the reflected light can be expressed as

$$I(\theta,\phi) = I_{\text{diff}}\cos(\theta) + I_{\text{spec}}\cos(\theta)\frac{1}{\sigma^2 2\pi} \times \exp\left[-\frac{1}{2}\left(\frac{\theta-\theta_i}{\sigma}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{\phi-\phi_i}{\sigma}\right)^2\right], \quad (1)$$

where ϕ and θ are the azimuthal and polar angles and ϕ_i and θ_i are the corresponding angles of incidence, respectively. I_{diff} is the maximum intensity for diffuse reflection and $1/(2\pi\sigma^2)I_{\text{spec}}\cos\theta_i$ is the maximum intensity for specular reflection. The diffuse reflection intensity, given by the first summand on the right-hand side of the equation, follows the Lambertian distribution. The second summand describes the specular reflection intensity, which is assumed to be broadened as a Gaussian function. Fitting Eq. (1) to experimental data will give us the I_{diff}, I_{spec}, and σ. The diffuse and specular reflection powers (P_{diff} and P_{spec}) are obtained by integrating the first and second summands of the equation over space, i.e., over $0° \leqslant \theta \leqslant 90°$ and $0° \leqslant \phi \leqslant 180°$.

The angular dependent reflectivity of a specular and a bead-blasted roughened Ag reflector was measured by a He–Ne laser (632 nm), as shown in Fig. 3. The incident angle was 40° and the reflected intensity was measured from −90° to 90°, as illustrated in the inset. Compared with the specular reflector, the diffuse reflector shows a two orders of magnitude higher diffusely reflected power. Fitting Eq. (1) to the experimental data gives diffuse-to-total-reflected-power ratios $P_{\text{diff}}/P_{\text{total}}$, i.e., $P_{\text{diff}}/(P_{\text{spec}}+P_{\text{diff}})$, (subsequently called "diffusivity") of 86% for the bead-blasted Ag reflector and of 0.83% for the specular Ag reflector.

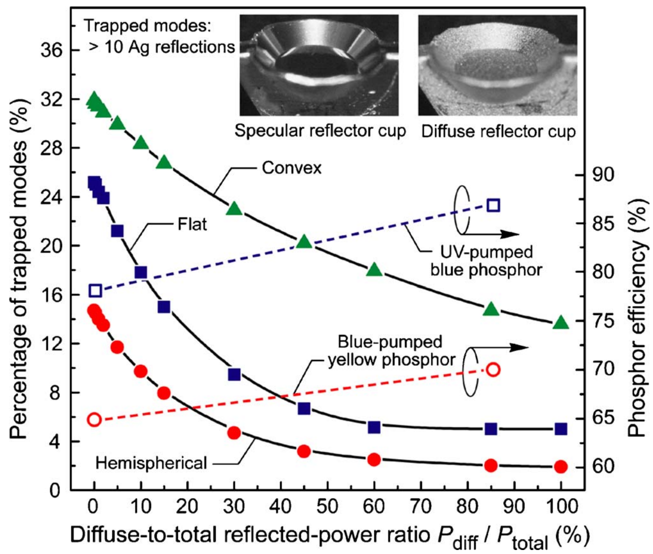

FIG. 4. (Color online) Experimental phosphorescence efficiency (open symbols) measured on dichromatic LED lamps employing a specular and a bead-blasted roughened reflector cup. Simulated dependence (solid symbols) of trapped modes (>10 Ag reflections) on the diffuse-to-total-reflected-power ratio is also shown. The inset shows photos of a specular and a bead-blasted reflector cup.

Figure 4 shows the simulated dependence of the trapped modes on P_{diff}/P_{total}, i.e., $P_{diff}/(P_{spec}+P_{diff})$, for partially diffuse reflector cups. The number of the trapped modes decreases with increasing diffuse component for the flat, convex, and hemispherical encapsulations, indicating the improvement of phosphorescence extraction efficiency. For a reflector cup with diffusivity of 86%, the percentage of trapped modes decreased to 4.8%, 14.7%, and 2.0% for flat, convex, and hemispherical encapsulants, respectively. Accordingly, the extraction efficiency for the phosphorescence, the power of phosphorescence extracted into the free space divided by the power of phosphorescence generated inside the package, is improved by 20% for flat encapsulant, 19% for convex encapsulant, and 13% for hemispherical encapsulant. The simulation thus shows that efficient LED lamp packages with remote phosphor require a highly diffuse reflector cup.

Using specular and bead-blasted Ag reflector cups, dichromatic LED lamps with remote phosphor were fabricated. Ultraviolet (UV) GaInN LEDs ($\lambda=400$ nm) pumping blue phosphor and blue GaInN LEDs ($\lambda=470$ nm) pumping yellow phosphor were employed. Primary LED lamps of UV GaInN LED and blue GaInN LED (both without phosphor) were fabricated as a reference to determine the phosphor conversion efficiency. The emission spectra of the LED lamps were measured using an integrating sphere. For dichromatic lamps, the emission spectra can be deconvoluted into two parts, the emission from the LED primary emitter and the emission from the phosphor. Integrating of the deconvoluted spectra gives the optical power of each part.[5,6] The phosphor conversion efficiency, shown in Fig. 4, was determined by dividing the experimental emission 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. The phosphor efficiency is improved by 7.4% for blue-pumped yellow phosphor and 12.2% for UV-pumped blue phosphor by substituting the specular reflector cup by the diffuse reflector cup. Both reflector cups are shown in the inset of Fig. 4. This improvement is attributed to diffuse reflector cups, which introduce a chaotic diffuse reflection pattern and thus enhance the extraction of trapped modes and reduce the reabsorption of phosphorescence by the LED chip. In the experiments, the scattering by the phosphor is not negligible, which also can help to randomize and extract the trapped modes. This is one of the reasons that the experimental enhancement of phosphor efficiency when employing a diffuse reflector cup is smaller than that obtained in simulations.

In conclusion, trapped whispering-gallery rays are shown to be a major loss mechanism for white LED lamp with remote phosphor. Trapped modes can be significantly reduced by increasing the diffusivity of the reflector cup. By employing a diffuse cup, the percentage of trapped modes reduced from 25%, 32%, and 14% to 5.2%, 13.2%, and 1.9% for flat, convex, and hemispherical encapsulants, respectively. Up to 86% of trapped modes are extracted out into free space by employing a diffuse reflector cup for hemispherical encapsulant. Dichromatic LED lamps with remote phosphor were fabricated using specular and diffuse reflector cups. A 7.4% and a 12.2% enhancement of phosphor efficiency for blue-pumped yellow phosphor and UV-pumped blue phosphor are found, respectively, when employing a diffuse reflector cup. The experimental results are fully consistent with the ray tracing simulation results.

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