Exploring packaging efficiency in phosphor-converted white LEDs

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Modeling and analyzing power losses at the packaging level enables improved efficiencies for various types of white LED.

Phosphor-converted white LEDs (pcW-LEDs) have ever more important roles in modern lighting, since their high efficiency and luminous efficacy make them suitable replacements for both traditional and specialized light sources. Using a well design, with a low-cost substrate such as sapphire, the technology demonstrates luminous efficacy as high as 150 lumens/W operated at 1W. By combining internal quantum- and light-extraction efficiencies (IQE and LEE), the external quantum efficiency (EQE) of a blue die for a pcW-LED can be as high as 80%. However, to achieve this we need to consider the packaging efficiency (PkE): the ratio of the emitted light power of a pcW-LED to the blue light power escaping from the die to the packaging volume. Currently there is a shortage of detailed analysis of PkE, making it difficult to determine pcW-LED luminous efficacy limits in terms of correlated color temperature (CCT).

Here, we analyze possible power losses at the packaging level. We establish the total packaging loss (PkL) by summing up three kinds of power reductions. First, the phosphor material’s limited quantum efficiency in wavelength conversion causes phosphor quantum loss. Second is stokes loss, where reduced photon energy is caused by down-conversion of the re-emitted photons pumped by the blue photons, and is a function of the spectrum of the white light. The third example is geometry loss, which includes all possible absorptions in surfaces or materials other than the phosphors, and depends on the packaging construction.

To calculate the PkE in a real pcW-LED, we need to measure the power of the white light outside the device and the blue light from the blue die to the packaging volume. Generally, the blue die is covered by a layer comprising phosphor and the encapsulation material (such as silicone). The blue light in the packaging is different from that emitted from a bare blue die to the air, and the light extraction of the blue die changes. In fact, it is almost impossible to directly measure the power of the blue light inside the packaging volume. To solve the problem, we propose a recovering multiplier (128.8% for common thin gallium nitride dies) reached by a two-step procedure. The first step is to measure the power of the bare blue die after die- and wire bonding on the board. The second is to evaluate the Fresnel loss (caused by discontinuity in refractive index) and the light extraction enhancement of the encapsulation lens on the blue die, using accurate simulation with precise optical modeling.

Finally, we can evaluate the power of the blue light in the packaging from the power of the bare blue die × the recovering multiplier.

Continued on next page
We analyzed the PkE for seven different pcW-LEDs to estimate the possible PkE limit (see Figure 1). Assuming a state-of-the-art EQE, we studied the potentially attainable luminous efficacy of a pcW-LED with appropriate CCT. Our study is based on a precise phosphor simulation model (see Figure 2), which includes the effects of light scattering, light absorption, down-conversion of the phosphor, and spectrum-shaping technology. We controlled the CCT of all the samples and the corresponding simulations at 6500 ± 500 K and 6500 ± 100 K, respectively. Figure 3 shows a comparison of the measurements and simulations of the PkLs for the seven pcW-LEDs, demonstrating that geometry loss plays an important part. We found a relatively high PkE in packaging types I, IV, and VII, and the highest PkE reached 63% for the smaller phosphor particle size (6 μm). Larger particles of 15 μm caused reduced backward scattering, dramatically lowering the PkL in the packaging of type VII. Our simulation shows that the PkL could be 25% or lower, and the corresponding PkE could reach the maximum if we apply a standard-size phosphor. The ideal PkE is 85% when the Stokes loss is the only power reduction in the PkL. However, in reality, we have to count the phosphor quantum loss, so the PkE drops to 81%. If geometry loss is also counted, the PkE could reach 73% in type IV with the smaller phosphor particle size, and 77% in type VII with larger ones. Actual measurement reveals similar properties.

In summary, we have studied the efficiency for various types of pcW-LED packaging, examining all the related energy losses, and have noted that particle size plays an important part in geometry loss. Without considering the thermal effect, the highest measured PkE is 67%, and our simulation shows we could potentially achieve 75%.

Our future work will focus on testing a new phosphor coating structure to enable pcW-LEDs to perform with high efficiency, a high color rendering index, and enhanced spatial-color and temporal-color uniformity. We can apply this technology to both general and specialist lighting, notably for agricultural purposes.

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Ching-Cherng Sun is leader of the LED solid-state lighting research group, and serves as director of the Optical Sciences Center. He is currently a Fellow of SPIE and OSA. His research in LED lighting includes light extraction analysis, optical modeling for light source and phosphor, LED packaging, and anti-glare technology.

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Figure 2. Phosphor modeling for precise simulation of the blue and down-conversion lights.

Figure 3. Simulation and corresponding measurement of the packaging loss for seven pcW-LEDs. R: Surface reflectance. α: The absorption coefficient of the active layer. 6 μm, 15 μm: Size of the phosphor particles.
References


