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Extracting phosphor-scattered photons to improve white LED efficiency

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White light-emitting diode (LED) luminous efficacy must improve significantly if LEDs are to become useful for general lighting. Phosphors commonly used in white LEDs backscatter more than half of the down-converted light, of which a significant portion is eventually lost within the package, thus reducing the overall efficacy. This letter describes an experimental study that shows by placing the phosphor away from the die, the backscattered photons can be extracted and the efficacy can be significantly increased. At low currents, the luminous efficacy exceeded 80 lm/W.

Developing high-efficiency white light-emitting diodes (LEDs) for solid-state illumination has been a topic of interest for several years. Of the methods available for creating white light with LEDs, the phosphor-converted (pc) emission method is the most common [1]. The first pc-white LED was introduced during the mid-1990s when cerium doped yttrium aluminum garnet (YAG:Ce) phosphor was combined with a gallium nitride (GaN) based blue LED [1]. In most commercial white LED packages, the phosphor is dispersed within an epoxy resin that surrounds the LED die. Some portion of the blue light (peak wavelength near 460 nm) emitted by the GaN LED is down-converted by the phosphor to produce yellow light (peak wavelength near 545 nm), and the combination produces white light. Presently available commercial white LEDs produce low overall light output and luminous efficacy, which must improve significantly if LEDs are to be useful in general lighting applications. The industry target for luminous efficacy is 150 lm/W by 2012 [2].

Improvements are needed at several stages: internal quantum efficiency, extraction efficiency, and phosphor-conversion efficiency. Some have taken on the challenge of researching materials and growth aspects to improve internal quantum efficiency [3–5]. Others are exploring shaped chips, photonic crystals, and other novel methods to improve photon extraction [6–11]. Still others are investigating new phosphors with greater down-conversion efficiencies and better optical properties [12–17].

Although past literature acknowledges that a significant portion of the light is backscattered by the phosphor and lost within the LED due to absorption, to the best of our knowledge no one to date has attempted to improve performance by extracting these backscattered photons [15, 18]. This letter describes an experimental study that shows by placing the phosphor away from the die, the backscattered photons can be extracted and the overall light output and luminous efficacy can be significantly increased. The method used in this study is referred to as scattered photon extraction (SPE).

To quantify the amount of forward and backward scattered light, several circular glass plates, 5 cm in diameter, were coated with different densities of YAG:Ce phosphor (2 mg/cm^2 to 8 mg/cm^2). These phosphor plates were placed one at a time between two integrating spheres with the phosphor coating facing the right sphere (Fig. 1). A 5 mm blue LED placed inside the right sphere, 2.5 cm away from the glass plate, excited the phosphor material. A spectrometer measured the light output from each sphere through the measurement ports. Light output measured from the left and right spheres indicated the amount of light transmitted through and reflected off the phosphor layer, respectively. The spectrometer data was analyzed to determine the amount of flux in the blue and yellow regions, corresponding to the radiant energy emitted by the LED and the converted energy from the YAG:Ce phosphor.

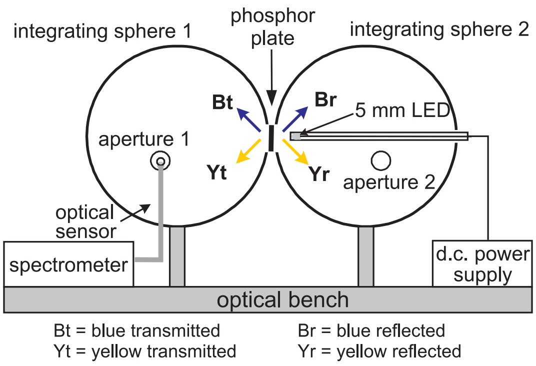

Figure 1 (online colour at: www.pss-rapid.com) Experimental setup used for measuring the light transmitted and reflected from the phosphor.

Figure 2 illustrates two sample spectra, transmitted and reflected, corresponding to one phosphor density, 7 mg/cm^2. As this figure shows, the spectral power distributions for the transmitted and reflected radiations are different. Figure 3 shows the amounts of transmitted and reflected radiant energies for blue and yellow light, as a function of phosphor density. In white LEDs, the phosphor density is controlled to produce blue and yellow light in the correct proportion such that the resulting white light has a chromaticity typically on or close to the blackbody locus. From the gathered data, it was estimated that about 40% of the luminous flux is transmitted when creating a balanced white light, and the remaining 60% is reflected back to the die. Yamada et al. found similar results [18]. The total radiant energy in a white LED can be written as

$$E_{tot} = (E_{bt} + E_{yt}) + \eta(E_{br} + E_{yr}) , \quad (1)$$

where E_{bt}, E_{yt}, E_{br}, and E_{yr} are transmitted and reflected energies of blue and yellow radiation, and η is the extraction efficiency of the phosphor-backscattered photons. In a commercial white LED, a significant portion of this reflected light is absorbed by the components surrounding the die, resulting in low η values. This is one reason for its low luminous efficacy.

The next step was to design a method to extract most of the light reflected off the phosphor. Figure 4 illustrates an LED package with scattered photon extraction (SPE) implemented. In the SPE package, an optical element allows the phosphor layer to be moved away from the die, leaving a transparent medium between the die and the phosphor. The geometry of the optic plays an important role: it efficiently transfers the light exiting the GaN die to the phosphor layer and allows most of the backscattered light from the phosphor layer to escape the optic.

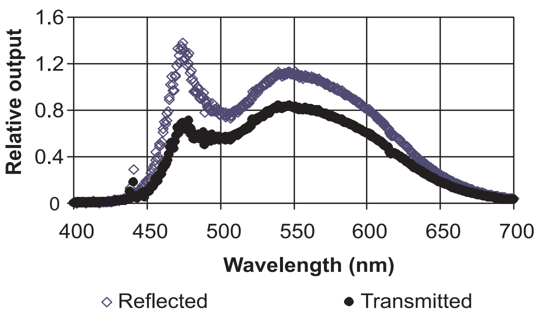

Figure 2 (online colour at: www.pss-rapid.com) Spectral power distributions for the transmitted and reflected radiations of one phosphor-coated plate (7 mg/cm^2).

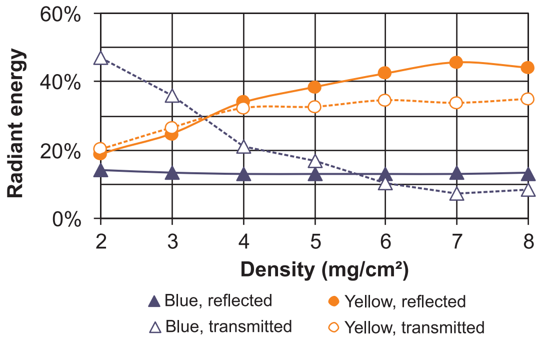

Figure 3 (online colour at: www.pss-rapid.com) Transmitted and reflected radiant energies for blue and yellow light, as a function of phosphor density.

To verify the hypothesis that the SPE package provides higher light output and luminous efficacy than the typical white LED package, six commercial 3 watt blue LEDs and six commercial 3 watt white LEDs were obtained from the same manufacturer. All twelve LEDs had similar peak wavelengths for the blue emission, 451 ± 3.5 nm. A commercial optic that fit the profile requirements of the SPE package optical element was found, and several were acquired for experimentation with the LEDs. Although this optic did not have the optimum geometry to extract all of the backscattered light, it was sufficient to verify the hypothesis. The top flat portion of the optic was coated with a predetermined amount of YAG:Ce phosphor. The required phosphor density was determined in a separate experiment by systematically varying the phosphor density, analyzing the resulting chromaticity, and selecting the density that produced a chromaticity very close to that of the commercial white LEDs used in this study. To compare the performances of the two packaging concepts, SPE and typical, the six commercial white LEDs were fitted with uncoated optics. The light output and the spectrum of these typical packages were measured in an integrating sphere, and the current and the voltage required to power the LEDs were noted. The same measurements were repeated for the SPE packages, which consisted of the six commercial blue LEDs fitted with phosphor-coated optics.

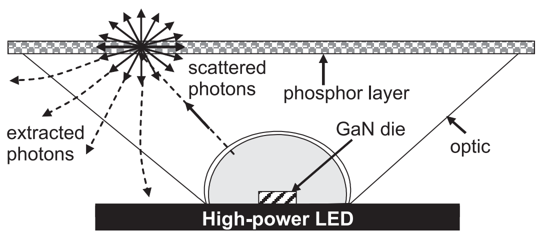

Figure 4 Schematic of the SPE white LED package. (Not drawn to scale.)

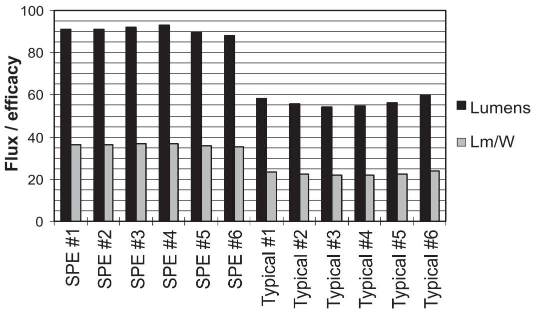

Figure 5 Luminous flux and efficacy of twelve white LED packages, SPE and typical.

Figure 5 shows the results for all twelve white LED packages, SPE and typical, at equal power. The average luminous flux and the corresponding average efficacy for the SPE LED packages are 90.7 lm and 36.3 lm/W, respectively. In comparison, the average luminous flux and the corresponding average efficacy for the typical white LED packages are 56.5 lm and 22.6 lm/W, respectively. Therefore, the SPE LED packages on average have 61% more light output and 61% higher luminous efficacy. The variations of luminous flux and corresponding efficacy between similar packages were small, with a standard deviation of less than 4%. The SPE packages consistently had higher luminous flux and efficacy compared with the typical white LED packages, thus verifying the hypothesis. Although not presented here, we investigated various other commercial products and found the SPE packages consistently showed improved performance, of the order of 30% to 60%.

To study the impact of current on light output and efficacy, two LED packages from the above twelve were selected, one typical and one SPE. These two LEDs were subjected to the same light output measurement procedure, but their input current was decreased from 700 mA to 50 mA in several steps. Figure 6 illustrates the light output and efficacy of these two LED packages as a function of current. At very low currents, the SPE package exceeds 80 lm/W, compared to 54 lm/W for the typical package.

One issue needing investigation is the spatial color variation. The SPE optics need further refinement to achieve a spatially uniform white light. Additionally, moving the phosphor layer away from the die could increase the size of the source luminous area. Although not an issue for general lighting, this could impact directional lighting applications where small, efficient optics are needed.

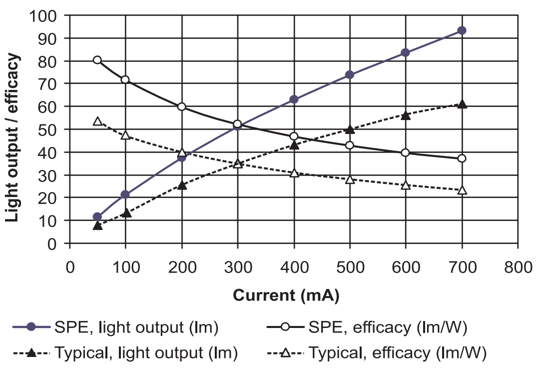

Figure 6 Light output and efficacy as function of current for the SPE and typical white LED.

In summary, it has been demonstrated that by extracting the backscattered light, the overall light output and luminous efficacy of a white LED can increase significantly. At low currents, the SPE LED package showed over 80 lm/W. Moving the phosphor layer away has an additional benefit of improving source life [19]. Because the SPE method increases the overall efficacy, it brings hope to white LEDs exceeding 100 lm/W in the near future.

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