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Zhu, Y., and N. Narendran. 2009. Investigation of white LED performance with multi-layer phosphors. *Compound Semiconductor Photonics: Materials, Devices and Integration, Proceedings of the International Conference on Materials for Advanced Technologies, Symposium O,* Singapore, June 28–July 3, 2009, pp. 1–3.

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Abstract

The most common phosphor in white LEDs is YAG:Ce; however, low radiant energy produced by this phosphor in the long wavelength (red) portion of the spectrum results in low color rendering (CRI) values, making the white LEDs less acceptable for general illumination. Mixing a suitable red phosphor with YAG:Ce improves CRI. Past studies have shown that when more than one phosphor is used in a conventional white LED package, mixing two types of phosphors into a single mixture results in lower light output compared to stacking the individual phosphors in layers of specific order. In this manuscript, we present results where two types of phosphor were used in a remote phosphor configuration with scattered photon extraction (SPE). Results show that when using two types of phosphors in an SPE white LED package, several factors will influence its performance.

1. Introduction

Solid-state lighting holds the promise of addressing the rapidly increasing need for energy conservation. Phosphor-converted (PC), indium gallium nitride (InGaN) based white LEDs have advanced to compete with some traditional light sources in certain applications. However, challenges remain to reach the 200 lumens per watt industry target. Past studies have addressed preparation methods and geometric tailoring of phosphor particles to improve quantum efficiency, and placement of phosphor to improve light output and luminous efficacy.[1-4] The SPE (scattered photon extraction) method, in which the optics between the chip and the remote phosphor layer are tailored to extract the backscattered light, experimentally showed as much as 60% improvement in light output and luminous efficacy.[4] While light output and luminous efficacy improvements are needed, improvements are also needed in color properties, rendering, and white light appearance. Mixing a yellow or green phosphor, like YAG:Ce, with a narrower band red phosphor, like $SrS:Eu^{2+}$, is one way to improve color.[5] A few studies show that mixing multiple phosphors into a single mixture results in lower light output compared to stacking them in layers.[6,7] However, in all these studies, the multiple layers were placed adjacent to the die. No studies have systematically analyzed multiple phosphors in remote phosphor configurations. The objective of this study was to understand how multiple phosphors in a mixture or stacked layers affect the final performance of the SPE white LED package, in terms of light output and color properties.

2. Experiment

Two types of phosphor were applied to an SPE-based white LED package and analyzed for light output and color properties. In the first part of the study, YAG:Ce was characterized as a single layer and as two stacked layers. In the second part, YAG:Ce and a red phosphor (λ_p~615nm), were characterized as a single layer mixture and as two stacked layers in alternate orders. Experimental results were compared with optical ray-tracing and theoretical analysis. Light output and spectral power distributions were measured in an integrating sphere with a spectrometer. Optical ray-tracing was carried out in LightTools following a method used previously.[8] A theoretical analysis of the light interaction with the phosphor layers was conducted following the method used in [9].

3. Experiment Results and Discussion

First, we characterized multiple layers consisting of the same phosphor, YAG:Ce. A single layer of YAG:Ce was characterized at densities of 4 and 8 mg/cm^2, and two layers were characterized with each layer at 2 and 4 mg/cm^2. Results show the performance of a single layer is nearly equal to that of two layers when the amount of phosphor is the same. Results from the theoretical calculations, experiment, and optical ray-tracing agreed well. Second, we characterized multiple layers of two phosphors, YAG:Ce and a red phosphor, at 4 mg/cm^2 each. Initially, YAG:Ce was the first layer and red as the second layer; then the order was switched. Then the two phosphors were mixed into one layer. Once again, the results from the experiments, optical ray-tracing, and theoretical calculations showed good agreement. Fig. 1 illustrates the chromaticity values (u', v') of the three phosphor configurations on the CIE 1976 UCS diagram. The chromaticity values of the three configurations are different. Table 1 shows the light output results. The first layer being yellow and the second layer being red with each at 4 mg/cm^2 densities (Y4-R4) yielded 50% more light in photometric units (lm) than the single layer mixture of yellow and red phosphors.

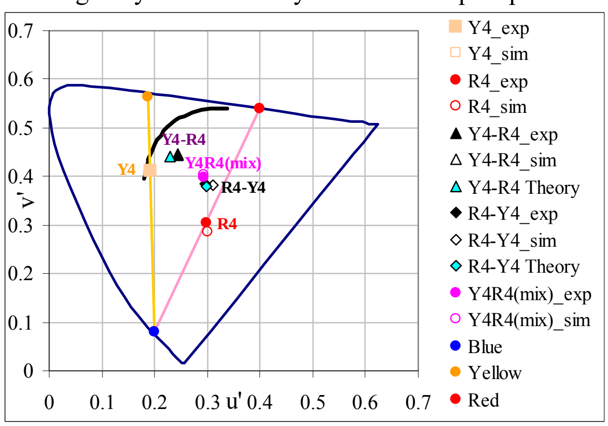

Fig. 1. The CIE 1976 UCS diagram of the multiple phosphor configurations

Phosphor Concentration	Experiment		Simulation		Theory	
	P(W)	Φ(lm)	P(W)	Φ(lm)	P(W)	Φ(lm)
Y4-R4	0.102	27.8	0.099	26.6	0.108	29.6
R4-Y4	0.089	17.5	0.082	15.7	0.092	17.4
R4-Y4 mixture	0.088	18.4	0.088	18.6		

Table 1. Light output of three phosphor configurations: (1) Y4-R4; (2) R4-Y4; (3) Y4R4 mixture

The much lower quantum efficiency of the red phosphor (59% vs. 91% for YAG:Ce) could possibly explain the lower light output of the R4-Y4 phosphor layer than the Y4-R4. In a follow-up step, we studied how the quantum efficiency of each phosphor affects the results by analyzing the configuration performances assuming equal quantum efficiencies. The results showed that the light output in radiometric units (W) is very close for the three configurations, while the light output in photometric units (lm) is different. This difference is because the spectral power distributions are different for the two phosphors, and when weighted by the eye sensitivity function, the lumen values are different.

Since the goal is to achieve white light with chromaticity values on or very close to the blackbody locus, an optical ray-tracing analysis was carried out with the two-phosphor SPE white LED package. Comparing Y14-R2.5 with R2.5-Y14, the results showed Y14-R2.5 was on the blackbody locus and had 80% more lumens than R2.5-Y14, which had chromaticity values far below the blackbody locus.

4. Conclusions

When using a single phosphor in an SPE white LED package, a single layer or multiple layers provide similar performance in terms of light output and color properties. When using two types of phosphor, several factors will influence its performance: mixture or stacked layers; specific order of the layers; densities of the phosphor medium; quantum efficiency of the different phosphors; luminescent spectral power density; phosphor absorption and emission spectra; refractive indices of the layers. In the SPE white LED package, the first layer is the dominant layer because the highest excitation energy is incident on the first layer, and nearly half of the converted photons generated inside the first layer can be extracted without any scattering or absorption loss. In conventional PC white LED packages, this portion of light is usually absorbed and lost inside the die, and therefore, its performance will be different from the SPE packages.

Acknowledgments

The authors thank The Link Energy Foundation, Energy Fellowship Program (2007-2009) for supporting this work.

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