Link Foundation Energy Fellowship (2007-2009) Final Report

Yiting Zhu
Ph.D Candidate in Lighting
Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY 12180
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1. Optimizing the Performance of White Light-emitting Diodes for Energy-efficient Lighting

1.1 Introduction

Solid-state lighting (SSL) holds the promise of addressing the rapidly increasing need for energy conservation**.** The industry goal for one SSL technology—the Lighting-emitting Diode (LED)—is to achieve 200 lumens per watt (lm/W) by the year 2020. This number exceeds the efficiency of all current lighting technologies, including incandescent light bulbs (15 lm/W), fluorescent lamps (90 lm/W), and high-intensity-discharge lamps (120 lm/W). Additionally, LED technology provides benefits of a potentially long lifetime of over 100,000 hours and low maintenance cost. In 2003, the U.S. Department of Energy (DOE) forecasted that converting to SSL would decrease lighting energy consumption by 33% in 2025 compared with that in 2005.[1]

Over the past decade, high-brightness monochromatic (colored) LEDs have been replacing traditional incandescent light sources in certain niche applications such as traffic signals and “EXIT” signs. LEDs are able to save up to 80% energy and significantly reduce maintenance costs in these applications. A similar trend is expected in architectural, transportation and general illumination with white LEDs. Even though the efficiency and light output of white LEDs have been improving steadily, they still need to improve by twice as much and offer good color appearance before they achieve the target of 200 lumens per watt with high color quality, as set by the SSL industry.[2]

Phosphor down-conversion is the most popular method of creating white LEDs. This method uses phosphor materials to down convert short-wavelength radiation produced by direct bandgap LEDs. The combination of the short-wavelength radiation ("blue" light) and the phosphor-converted long-wavelength radiation ("yellow" light) is observed as "white" light. The industry goal to improve the performance of phosphor-converted (PC) white LEDs includes: (1) the efficiency, expressed in "lumens per watt" values; (2) the color appearance, described as good color rendering with an enhanced "red" spectral element.

In my doctoral thesis study, I developed a Monte Carlo optical ray-tracing method to characterize the performance of PC white LEDs in a simulation tool. This method will aid in the optical design process of PC white LEDs to achieve high efficiency and satisfying color appearance. Using this ray-tracing method, I further investigated the performance of multiple-layer PC white LEDs, consisting of multiple types of phosphors in a remote-phosphor optical configuration (i.e., the phosphor is placed away from the LED chip), to enhance both efficiency and color appearance.

1.2 Experiment I: Developing a Monte Carlo optical ray-tracing method to optimize PC white LED performance[3]

One of the challenges in conducting a ray-tracing analysis of the PC white LED is not knowing the accurate value for the mean-free-path (MFP) of the phosphor particles in the phosphor-encapsulant medium. MFP denotes the average distance that the photon travels between collisions with phosphor particles.[4] MFP depends on the phosphor particle size and the phosphor density in the phosphor-encapsulant medium. In reality, there are many factors that can affect the accuracy of the MFP value. Any inaccuracies in the estimation of the MFP value will lead to incorrect simulation results. Therefore, it is essential that the phosphor medium used in a ray-tracing analysis be characterized first and the MFP be determined accurately.

In experiment, I created several phosphor-encapsulant samples with various phosphor densities and measured their scattering properties. The phosphor density and the MFP value determine the scattering properties, which are quantified by the light transmission and reflection ratios from the phosphor-encapsulant sample when excited by a "red" light source. The reason to choose a "red" light source is that the "red" spectral power distribution lies outside the phosphor excitation range [Fig. 1], and therefore the "red" photons can only be scattered, rather than absorbed, by the phosphor particles. A higher density phosphor sample tends to reflect more photons than a lower density phosphor sample. Therefore, the MFP values of the different phosphor-encapsulant samples could be determined by matching the experiment results of the light transmission and reflection ratios to the ray-tracing analysis (simulation) results.

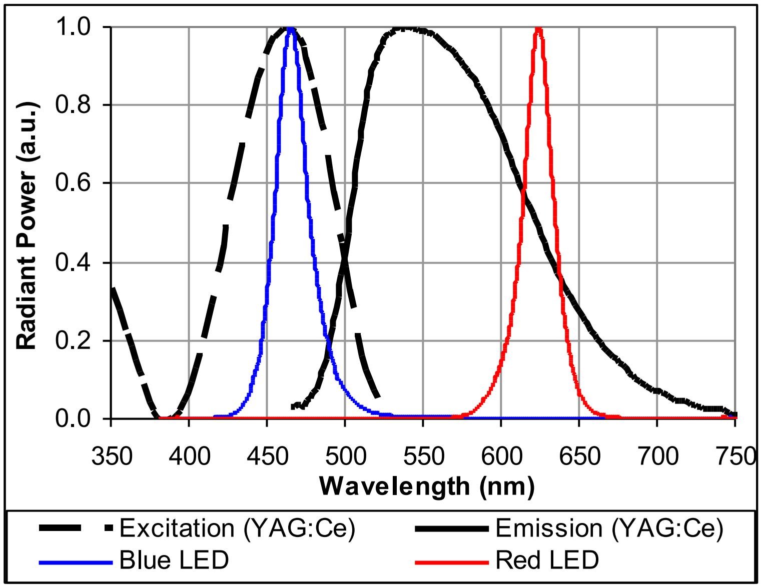

Figure 1. The spectral power distributions (SPDs) of the red and blue LEDs and excitation and emission of YAG:Ce phosphor.

Next, I verified this method by matching the experiment results to the ray-tracing analysis results when the phosphor samples were excited by a "blue" light source, which has an SPD that lies inside the phosphor excitation range [Fig.1]. When "blue" light excites the phosphor, not only does scattering occur, but the "blue" photons are also down-converted to "yellow" photons by the phosphor. Again, good agreement was found between the experiment and ray-tracing results for the "blue" LED experiment [Fig. 2]. Overall, this method provides an excellent match between ray-tracing analysis results and experiment results for light output and chromaticity, and provides a means of accurately determining MFP.

Additional optical ray-tracing analyses of the PC white LED packages with a remote-phosphor configuration and transparent [Fig. 3(a)] or reflective sides [Fig. 3(b)] showed that the transparent side wall package provides higher light output. However, one has to note that for directional lighting applications, additional reflectors are needed to redirect the side wall extracted light. In such cases, the difference between the two configurations may be lower.

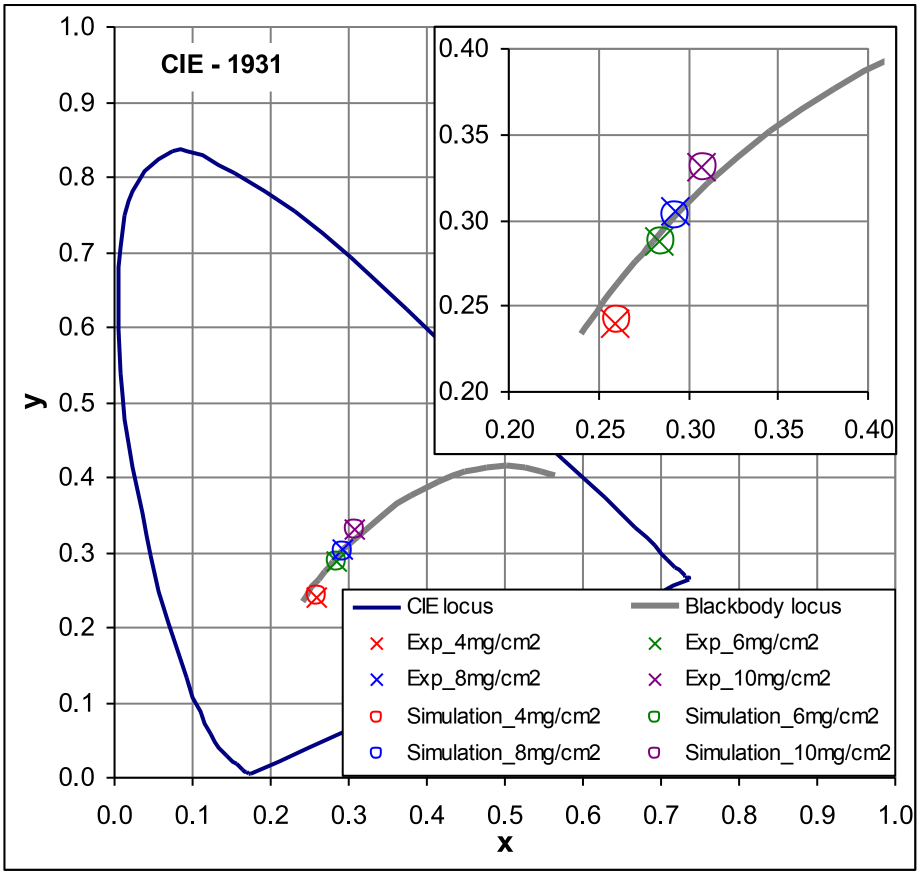

Figure 2. Comparisons of experiment and simulation results of chromaticity values when the phosphor samples are excited by a “blue” light source.

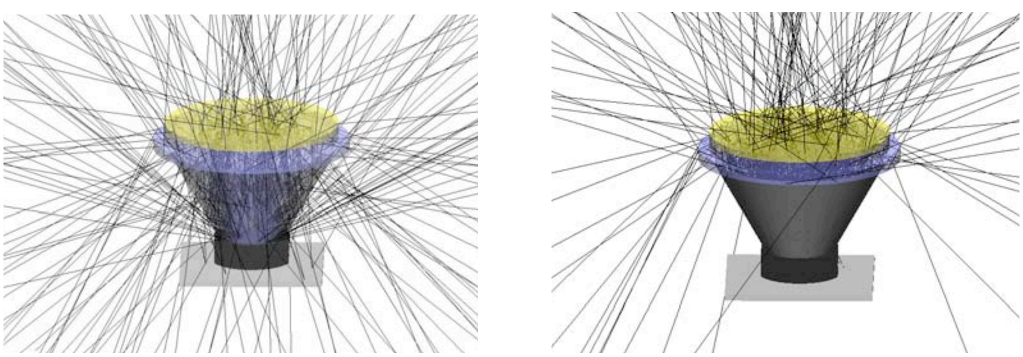

Figure 3: (a) remote-phosphor package with transparent side surfaces; (b) remote-phosphor package with reflective side surfaces.

1.3 Experiment II: Investigation of white LED performance with multi-layer phosphors[5]

To improve the color appearance of PC white LEDs, additional phosphors can be introduced in combination with the traditional YAG:Ce phosphor. A few studies have shown 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 phosphor 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 a PC white LED with a remote-phosphor configuration, in terms of light output and color properties.

Two types of phosphor were applied to a remote-phosphor PC white LED package and analyzed for light output and color properties. A yellow and a red phosphor 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 spectro-radiometer. Optical ray-tracing was carried out using the method introduced above. A theoretical analysis of the light interaction with the phosphor layers was conducted following the method used in [8].

The experiment showed that when using two types of phosphor, several factors will influence LED performance: mixture or stacked layers; specific order of the layers; phosphor densities in the phosphor-encapsulant medium; quantum efficiency of the different phosphors; luminescent spectral power density; phosphor absorption and emission spectra; refractive indices of the layers. In the remote-phosphor 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 remote-phosphor packages.

1.4 Conclusion

A Monte Carlo optical ray-tracing method has been developed to optimize the performance of PC white LEDs. This method can be widely used in the SSL industry to accelerate the optical design process of PC white LEDs. By using this optical ray-tracing method, together with experimental and theoretical methods, PC white LEDs with multi-layer phosphors (in a remote-phosphor configuration) have been systematically investigated. It was found that the characteristics of white LEDs with multi-layer phosphors are different between remote-phosphor configuration and conventional configuration (i.e., phosphor placed close to the LED chip). By utilizing the remote-phosphor configuration and careful selection and design of the multiple phosphor layers, high light output and good color quality white LED packages can be expected, enabling the achievement of the industry goal of 200 lumens per watt with good color quality.

1.5 References

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[4]Kittel, C. 2005. Introduction to Solid State Physics. John Wiley & Sons, Inc.

[5]Zhu, Y., Narendran, N. 2009. Investigation of White LED Performance with Multi-Layer Phosphors. *Proc. of ICMAT 2009 Conference*, ICMATA00715-01274.

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[8]Fran, Y. and Tseng, T. 1999. Involvement of Scattered UV Light in the Generation of Photoluminescence in Powdered Phosphor Screens. *J. Phys. D: Appl. Phys.,* Vol.32, pp.513-517.

2. List of All Archival Journal Papers or Scholarly Reports

Advisor: Dr. Nadarajah Narendran
Sept. 28, 2009

1. Zhu, Y., Narendran, N., 2009. Investigation of Remote-phosphor White Light-emitting Diodes with Multi-layer Phosphors. Will be submitted to Appl. Phys. Lett..
2. Zhu, Y., Narendran, N., 2009 (in press). Investigation of White LED Performance with Multi-layer Phosphors, *Proc. of ICMAT 2009 Conference,* ICMATA00715-01274.
3. Zhu, Y., Narendran, N., 2008. Optimizing the Performance of Remote Phosphor LEDs, *J. Light & Vis. Env.*, Vol.32, No.2, pp115-119.
4. Zhu, Y., Narendran, N., 2007. Optimizing the Performance of Remote Phosphor LED, *Proceeding of First International Conference on White LEDs and Solid State Lighting*, Tokyo, Japan, November 26-30, 2007, P411–P414..

3. How Discretionary Funds Were Spent?

The $5,000 research fund has been spent on a computer for faster speed Monte Carlo optical ray-tracing simulations; on a vacuum oven for curing phosphor-encapsulant samples; and on phosphors, epoxies, optics and microscopic glass slides for preparing phosphor samples.

The $2000 fund for supporting the attendance at technical meetings has been spent on: (1) attendance at the 1st International Conference on White LEDs and Solid State Lighting in Tokyo, Japan in Nov. 2007; (2) attendance at the SPIE-Ninth International Conference on Solid State Lighting in San Diego in Aug. 2009.

4. How Did the Fellowship Make a Difference?

The award of the Link Foundation Energy Fellowship has enabled me to be on track of finishing my doctoral degree in Lighting, and has helped me to concentrate on and develop new interests in the solid-state lighting research. The Energy Fellowship has supported me in discovering and solving the described research topics with the motivation of helping the lighting industry to develop energy-efficient solid-state lighting technology with good color properties. With this Energy Fellowship, I was able to develop a simulation method for phosphor-converted white light-emitting diodes (LEDs); to systematically characterize a color property improved phosphor-converted white LED by using multiple-layer phosphors; and to expand my research interests to the material science of the phosphor—the synthesis and characterizations of phosphor materials for LEDs. During the past two years, the Energy Fellowship has supported my attendance at two international SSL conferences and given me the opportunities to present my work there. My poster presentation about MFP determination through Monte Carlo optical ray-tracing was given the “Best Paper” award at the first international conference on white LEDs and Solid-state Lighting in Tokyo, Japan, in November 2007. My attendance at these two international conferences expanded my vision and understanding of solid-state lighting technologies and applications. Although this fellowship award has been only a short period of two years, the experience and knowledge that I have accumulated during the past two years has taken me to a new level of research capabilities and vision. In the future, I am committed to continuing research and leadership on solid-state lighting technologies for energy-efficient lighting.