# Improved Performance White LED

Nadarajah Narendran

Lighting Research Center
Rensselaer Polytechnic Institute
21 Union St., Troy, NY 12180
www.lrc.rpi.edu

Narendran, N. 2005. Improved performance white LED. *Fifth International Conference on Solid State Lighting, Proceedings of SPIE* 5941, 45-50. Bellingham, WA: International Society of Optical Engineers.

*Invited Paper*

# Improved Performance White LED

Nadarajah Narendran
**Lighting Research Center**
Rensselaer Polytechnic Institute, Troy, NY 12180

## ABSTRACT

This paper describes work leading to the development of a new packaging method for white LEDs, called scattered photon extraction (SPE). Previous work by our group showed that the traditional placement of the phosphor close to the die negatively affects the overall luminous efficacy and lumen maintenance of phosphor-converted white LEDs. The new SPE method enables higher luminous efficacy by placing the phosphor at a remote location from the die and by shaping the lens surrounding the die to extract a significant portion of the back-transferred light before it is absorbed by packaging components. Although the remote phosphor concept is not new, SPE is the first method to demonstrate efficient extraction of back-transferred light and show over 60 percent improvement in light output and efficacy compared to similar commercial white LEDs. At low currents, the prototype white LEDs based on the SPE technique showed over 80 lumens per watt. The SPE concept was tried on two types of commercial packages and both showed similar improvements.

**Keywords:** LED, white light LED, photon extraction, phosphor, remote phosphor, SPE, Scattered Photon Extraction, lighting

## 1. BACKGROUND

Displacing traditional light sources with solid-state light sources is the dream of many researchers. Since the first demonstration of white light-emitting diodes (LEDs) in the mid-1990s, researchers have been striving to boost the performance of this technology so that its luminous efficacy far exceeds the commonly used incandescent light bulb and the linear fluorescent lamp. The luminous efficacies of these two traditional light source technologies are nominally around 15 lumens per watt and 85 lumens per watt, respectively. The luminous efficacy of presently available commercial white LED products is in the range of 40 lumens per watt. The target for solid-state light sources is to reach 150 lumens per watt by 2012.[1] For white LEDs to reach this target, improvements are needed in several areas, including the internal quantum efficiency, the light extraction efficiency, and the phosphor efficiency. The white LED luminous efficacy gains made during the past several years can be attributed mostly to improvements in internal quantum efficiency and light extraction efficiency from the chip. Although new phosphor blends have been used to improve color properties, they have not contributed much to the luminous efficacy gains. This may be mainly due to the fact that the commonly used YAG:Ce phosphor in white LEDs is very efficient, and most of the newer phosphor blends have added more energy in the red region of the spectrum, which is likely to lessen the efficacy. Even though the YAG:Ce phosphor is efficient, recently our group showed that the traditional phosphor placement method negatively impacts the overall efficacy of white LEDs.[2] The goal of this paper is to describe the work that led to this finding and to the development of a new phosphor placement method.

## 2. WHITE LED

In the very first commercial white LED, a 5 mm package, the phosphor was dispersed within an epoxy resin that surrounded the blue LED die, as shown in Figure 1. This practice has not changed since, even though LED package shapes have changed. In 2003, we concluded from a laboratory study that the fast degradation of 5 mm-type white LEDs is mainly due to the photodegradation of the epoxy surrounding the die, which depends on both the amount of heat generated at the LED junction and the quantity of short-wavelength radiation.[3]

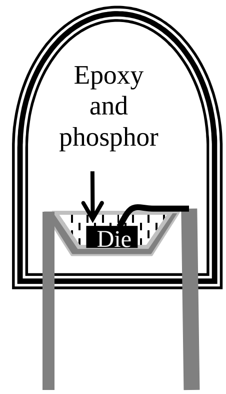


**Figure 1:** Schematic of a 5 mm white LED.

If heat and the amount of short-wavelength radiation were the only reasons for the yellowing of the epoxy, then the obvious conclusion would be that a blue LED would degrade faster than a white LED under similar operating conditions. This is because the white LED would emit a lesser amount of short-wavelength radiation than a similar blue LED, since some portion of the short-wavelength radiation is down-converted to longer-wavelength (yellow) radiation by the YAG:Ce phosphor. On the contrary, the life-test experiments conducted in our laboratory showed that the 5 mm-type phosphor-converted white LED degraded faster than the blue LED.[4] The main difference between a blue and a similar white LED is the phosphor that is dispersed within the epoxy surrounding the die. Since the YAG:Ce phosphor is a stable material, degradation of the phosphor was ruled out. Therefore, a possible explanation is that some portion of the light emitted by the phosphor and the back-transferred, unconverted short-wavelength (blue) light circulates between the phosphor-dispersed epoxy and the reflector of the LED, causing the epoxy to degrade. Furthermore, this region where the light circulates is at a relatively higher temperature because of the hot pn-junction, which could further increase the yellowing of the epoxy. To validate this explanation, an experiment was conducted in 2003 with LEDs that had the phosphor layer both close to the die and further away, as illustrated in Figure 2. The results showed that the LEDs with the phosphor layer away from the die degraded at a slower rate, confirming our hypothesis (see Figure 3).[3]

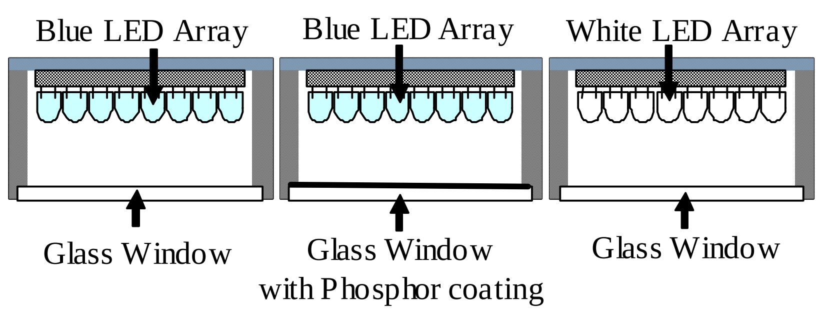


**Figure 2:** Three LED arrays enclosed in an aluminum cylinder.

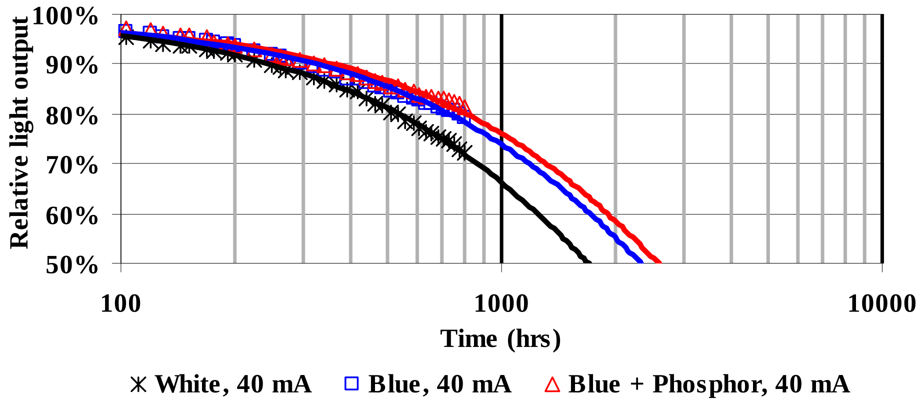


**Figure 3:** Lumen depreciation data for the three LED arrays at 40 mA.

The next question is, if a portion of the light is transferred back towards the die, then how does it affect the overall light output and efficacy of the white LED? Past literature acknowledges that a significant portion of the light is backscattered by the phosphor and is lost within the LED due to absorption.[5,6] In 2003, we performed an optical ray-tracing study to understand how much of the light is trapped within an LED package for a remote-phosphor concept shown in Figure 4.[7] Figure 5 illustrates the results from the ray-tracing analysis.[7] We concluded from this study that beam uniformity (E max/E average) on the phosphor is 19:1, which is rather poor and would cause significant color variation across the surface if a uniform layer of phosphor is placed. The light reflected back into the die was about 12%, and more than 25% of the light was lost between the phosphor, the reflector cup and the die, even though the reflectivity of the reflector was kept very high, 95%. The amount of light trapped within the package increased when the package geometry was reduced. Moving the phosphor to a remote location,

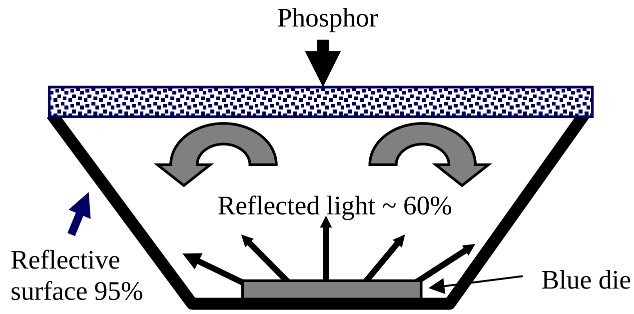


**Figure 4:** Remote phosphor concept. The phosphor layer is placed away from the die.[7]

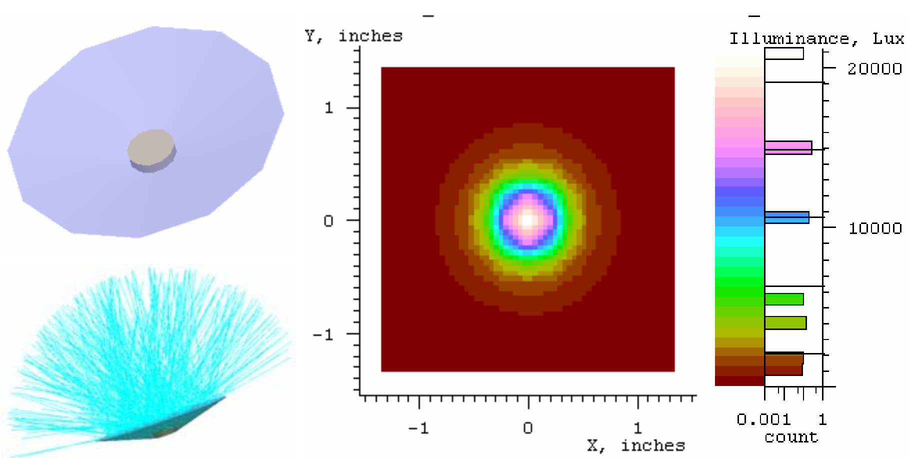


**Figure 5:** Ray-tracing analysis results showing the light level on the phosphor.[7]

as shown in Figure 4, with a reflector arrangement did not show much improvement in terms of extracted light out of the package over the traditional package, where the phosphor was placed close to the die. Furthermore, if more than 60% of the light is back-transferred by the phosphor layer, placing a reflector at the back end to reflect this light through the phosphor would instead recirculate the light between the phosphor and the reflector cup. The quantity of recirculated light will depend on the reflectivity of the reflector cup. The result of recirculation is lost light and degraded epoxy.

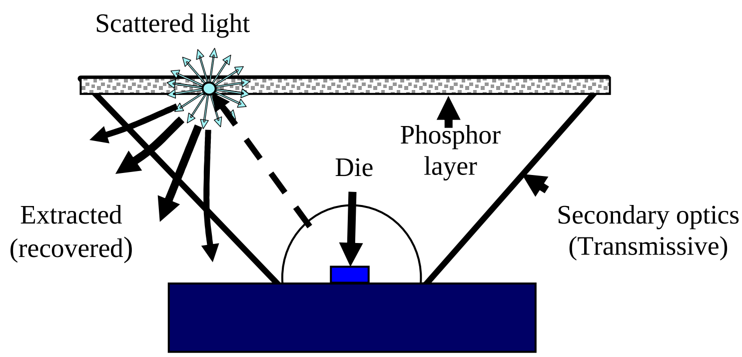


**Figure 6:** White LED using SPE concept.[2]

This led us to the conclusion that to maximize the light output from a white LED, the phosphor layer has to be moved away from the die. Additionally, the back-transferred light from the phosphor layer has to be extracted from the back before it is absorbed and lost, thus reducing recirculation. Based on these conclusions, the scattered photon extraction method (SPE) was developed. Unlike in traditional white LED packages, in the SPE package the phosphor layer is placed at a remote location, and the lens surrounding the die is reshaped to extract a significant portion of the back-transferred light before it is absorbed and lost within the package (Figure 6).[2] The remote phosphor concept is not new. Chen in 1999, Duggal in 2001, Reeh in 2003, Duclos in 2003, Taguchi in 2004, Ouderkirk in 2004, and Noguchi in 2004 all have demonstrated white LED packages that use the remote phosphor concept.[8-14] In most of these concepts, the phosphor layer is placed further away from the die, as shown in Fig. 4. However, SPE is the first method to demonstrate efficient extraction of back-transferred light to show over 60 percent improvement in light output and efficacy compared to similar commercial white LEDs, which have the phosphor closely surrounding the die. [2]

The key aspect of the SPE method relies on the fact that a significant portion of the phosphor converted light is transferred back towards the die. An experiment was conducted to quantify the amount of forward and backward scattered light. The details of this study are explained in another paper.[2] Results of this study showed that about 40% of the light is transmitted while 60% is reflected backwards when creating a balanced white light with chromaticity values on the blackbody locus.[2] Once this was known, the next challenge was creating an optical element (secondary optics) that efficiently transferred the short-wavelength (blue) radiation from the die to the phosphor layer and then extracted the back-transferred light before these photons were absorbed by components such as the die, the reflector, and the epoxy. Through ray-tracing analysis, an optimum lens (secondary optics) was designed. The top surface of the optical element was coated with an appropriate amount of phosphor. At the correct phosphor density, the final white light had chromaticity values on the blackbody locus. This optical element was attached to a commercial high-power blue LED to form the SPE white LED package. The amount of light exiting the top side and the rear of the secondary optics was measured. As expected, the ratio of the light in the forward to reverse directions was 40:60, indicating that the secondary optics is efficiently extracting the backscattered photons. Figure 7 illustrates the luminous efficacy of a traditional white LED and the luminous efficacy of a prototype SPE white LED created from a similar blue LED and how they change as a function of drive current. At low currents, the prototype white LEDs based on the SPE technique showed over 80 lumens per watt.[2] The SPE concept was tried on a second commercial LED package, and that, too, showed similar improvements.

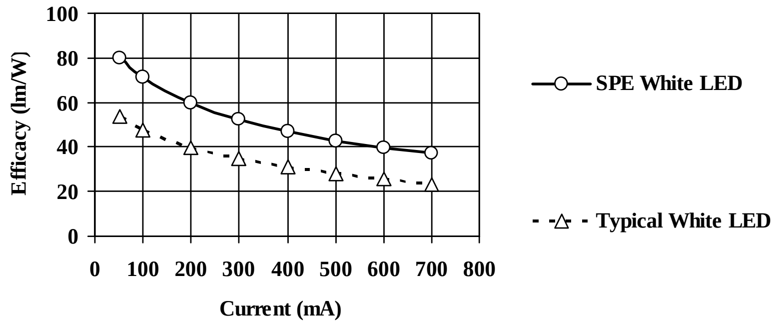


**Figure 7:** Comparison of traditional white LED efficacy with SPE white LED efficacy as a function of current.

## 3. SUMMARY

The white LED luminous efficacy gains made during the past several years can be attributed mostly to improvements in internal quantum efficiency and light extraction efficiency from the chip. However, phosphor improvements have not contributed much to these luminous efficacy gains. This may be mainly due to the fact that the commonly used YAG:Ce phosphor in white LEDs is very efficient to begin with. Even though the YAG:Ce phosphor is efficient, recently our group showed that the traditional phosphor placement method in white LEDs negatively impacts the overall efficacy. This paper describes the work that led to this finding and to the development of the scattered photon extraction package (SPE). SPE has enabled higher luminous efficacy with phosphor-converted white LEDs. Unlike in traditional white LED packages, in the SPE package the phosphor layer is placed at a remote location and the lens surrounding the die is shaped to extract a significant portion of the back-transferred light before it is absorbed and lost within the package. Although the remote phosphor concept is not new, SPE is the first method to demonstrate efficient extraction of back-transferred light and show over 60 percent improvement in light output and efficacy compared to similar commercial white LEDs, which have the phosphor close to the die. At low currents, the prototype white LEDs based on the SPE technique showed over 80 lumens per watt. The SPE concept was tried on two types of commercial packages and both showed similar improvements. The SPE-based white LEDs can be extremely useful in accelerating the development of solid-state light sources for general lighting applications.

## ACKNOWLEDGMENTS

I wish to thank my colleagues at the Lighting Research Center (LRC), including Yimin Gu, Jean Paul Freyssinier, and Yiting Zhu, for their support in conducting some of the studies explained in this manuscript; and Jennifer Taylor for her help in preparing this manuscript. I would like to thank the U.S. Department of Energy and the University of California at Santa Barbara for their support in the form of a grant (Cooperative Agreement No. DE-FC26-01NT41203). I also wish to thank the LRC for its valuable assistance and cooperation in making it possible for me to attend the SPIE conference and share this valuable information.

## REFERENCES

1. Optoelectronics Industry Development Association (OIDA). *Light emitting diodes (LEDs) for general illumination : An OIDA technology roadmap update 2002.* Optoelectronics Industry Development Assn., Washington DC, 2002. http://lighting.sandia.gov/lightingdocs/OIDA_SSL_LED_Roadmap_Full.pdf.

2. Narendran, N., Y. Gu, J.P. Freyssinier-Nova, and Y. Zhu. “Extracting phosphor-scattered photons to improve white LED efficiency.” phys. stat. solidi (a) **202 (6)**, R60-R62, 2005.
3. Narendran, N., Y. Gu, J.P. Freyssinier, H. Yu, and L. Deng. “Solid-state lighting: Failure analysis of white LEDs.” J. Crystal Growth **268 (3-4)**, 449-456, 2004.
4. Narendran, N., and L. Deng. “Performance characteristics of light-emitting diodes.” In *IESNA Annual Conference Technical Papers*, 157-164, Illuminating Engineering Society of North America, New York, 2002.
5. Taskar, N., R. Bhargava, J. Barone, V. Chhabra, V. Chabra, D. Dorman, A. Ekimov, S. Herko, and B. Kulkarni. “Quantum-confined-atom-based nanophosphors for solid state lighting.” In *Third International Conference on Solid State Lighting, Proceedings of SPIE,* Ian T. Ferguson, Nadarajah Narendran, Steven P. DenBaars, John C. Carrano, eds., **5187**, 133-141, International Society for Optical Engineering, Bellingham, WA, 2004.
6. Yamada, K., Y. Imai, and K. Ishii. “Optical simulation of light source devices composed of blue LEDs and YAG phosphor.” J. Light & Vis. Env. **27(2)**, 70-74, 2003.
7. Lighting Research Center at Rensselaer Polytechnic Institute. *Second year final report: High efficiency nitride-based solid state lighting.* (PowerPoint presentation.) Presentation to U.S. Department of Energy for sponsored project “High efficiency nitride-based solid state lighting” Cooperative Agreement No. DE-FC26-01NT41203, November 17, 2003.
8. Chen, H. 1999. LED structure with ultraviolet-light emission chip and multilayered resins to generate various colored lights. US Patent 5,962,971, Oct. 5, 1999.
9. Duggal, A., et al. Phosphors for white light generation from UV emitting diodes. US Patent 6,294,800 B1, Sept. 25, 2001.
10. Reeh, U., et al., Light-radiating semiconductor component with a luminescence conversion element, US Patent 6,576,930 B2, Jun 10, 2003.
11. Duclos, S., et al. 2003. Phosphor coating with self-adjusting distance from LED chip. US Patent 6,635,363 B1, Oct. 21, 2003.
12. Taguchi, T., Y. Uchida, and K. Kobashi. “Efficient white LED lighting and its application to medical fields.” phys. stat. solidi (a) **201 (12),** 2730-2735, 2004.
13. Ouderkirk, A., et al. 2004. Methods of making phosphor based light sources having an interference reflector. US Patent Application 2004/0116033 A1, Jun. 17, 2004.
14. Noguchi, K., et al. 2004. White light emitting device. US Patent Application US 2004/0070338 A1, Apr. 15, 2004.