**Paper**

# Enhancement of Luminous Efficacy by Random Patterning of Phosphor Matrix

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## ABSTRACT

We have demonstrated the ability to increase the luminous flux and luminous efficacy of white light-emitting diodes (LEDs) by randomly patterning the surface of the yellow phosphor matrix. The phosphor was moved away from the LED die by placing it on top of a silicone optic and then roughening the surface of the phosphor/resin mixture. It was found that the roughening increases the luminous flux and efficacy by 10% over the smooth, non-patterned phosphor mixture. The roughened sample's operating voltage, luminous flux, luminous efficacy, CCT, color coordinates, and CRI were 3.2 V, 7.4 lm, 115.6 lm/W, 4244 K, (0.388, 0.448), and 61 at 20 mA, CW, and room temperature operation. A brief presentation on phosphor scattering is introduced to help explain the effect of the roughening.

KEYWORDS: YAG phosphor, luminous efficacy, light emitting diodes

## 1. Introduction

Solid state lighting has gained a large amount of momentum in recent years due to its potential energy saving benefits and reliability. With the cost of crude oil reaching over $70 per barrel in 2006 in the U.S.[1] alternate energy sources are becoming more attractive. The average American household spends approximately 60% of its monthly utility bill on electricity. From this nearly one-quarter is due to lighting[2]. The possibility of using LEDs for solid state lighting came with breakthroughs in GaN LEDs. The achievement of p-type doping in GaN in 1990 by Amano *et al.*[3] and the use of InGaN/GaN double heterostructure in LEDs in 1994 by Nakamura *et al.*[4] led to the GaN system as the bright blue light source for white light in conjunction with the use of phosphors. Using a phosphor as a wavelength converter was first demonstrated by Bando *et al.* in 1996 [5]. This approach for accomplishing white light emission, commonly referred to as the down-conversion technique, has several advantages. First, only one blue LED chip is required as compared to using three LEDs (RGB) for color mixing, which in turn lowers the production cost. Second, they are stable long term unlike other wavelength converters such as dyes[6]. Small size and the absence of mercury make LED lighting more appealing than other illumination sources.

Considerations of the extraction problem in high refractive index materials such as GaN have been shown before[7][8]. Roughening or nanotexturing the surface of an LED[9][10] as well as introducing V-shaped micropits on GaN templates[11] have been shown to increase emission efficiency due to improved light extraction. It has also been previously reported that approximately 60% of the luminous flux of a white LED is reflected back to the die where the photons can be absorbed[12][13]. It is assumed that these reflections can be reduced by randomly patterning the phosphor matrix which would give a higher probability for the photons to escape.

## 2. Experimental Setup

The LEDs used in this experiment were commercially available dies that were 470 x 250 μm². One LED die was placed onto a silver plated TO-56 header (5.6 mm in diameter) and affixed by silver loaded epoxy. It was then wire bonded with 25 μm diameter gold wire. Next, an inverted truncated pyramid optic was placed on top of the die. This optic was composed of a two part silicone resin (GE Silicone RTV615) whose nominal index of refraction is 1.406 with a thermal conductivity of 0.2 $W\ m^{-1}K^{-1}$. Details of this optic are described elsewhere[14]. The purpose of this optic was two-fold. Firstly, the higher index of refraction from the silicone helped to increase the light escape cone by increasing the critical angle. Secondly, this geometry allowed for the scattered photon extraction method to be employed which also increases the light output since not all of the backscattered light from the phosphor layer is reabsorbed in the LED die.

Next a phosphor layer was placed on top of the flat portion of the optic. The phosphor used in this experiment was a commercial $Y_3Al_5O_{12}$ (yttrium aluminium garnet) phosphor (subsequently referred to as YAG phosphor). The phosphor was mixed with a ratio of 81% to 19% phosphor to silicone. Once the phosphor mixture had been prepared, 0.25 g was placed onto the top of the inverted pyramid. A schematic is shown in Figure 1(a). This configuration was then measured in a 500 mm integrating sphere with a spectrometer. This blue LED at 20 mA was 3.2 V, 23.4 mW with a peak wavelength of 448 nm.

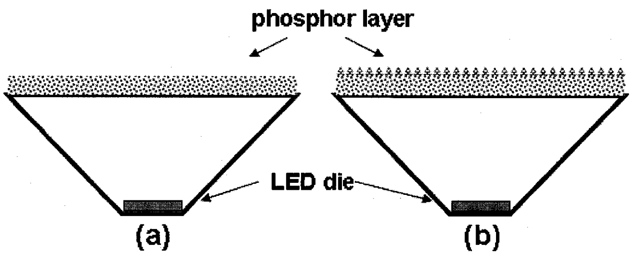


Figure 1 Schematic of a roughened sample (b) and an un-roughened sample (a)

After the smooth phosphor configuration was measured the optic with the phosphor layer was removed from the LED and another inverted pyramid was placed onto the same LED die. The benefit in using the same die was to help eliminate any variations to performance due to differences in drive voltages and radiant flux from die to die. Employing the same die would isolate the reason for any increase in luminous flux and efficacy. The same amount of phosphor mixture by weight was then placed onto the cone optic however a roughened surface was introduced on top of the phosphor mixture as shown by Figure 1(b). The roughened surface was an aluminum oxide 120-grit square piece of sandpaper (120 abrasive particles per inch). The sandpaper gives a uniform and randomly distributed patterning for the phosphor mixture. Once the mixture is cured the sample is removed from the paper and measured in an integrating sphere with a spectrometer. Scanning electron micrograph images were taken of the sandpaper and roughen phosphor layer after curing and are shown in Figure 2. It can be seen that the phosphor layer is smother then the sandpaper.

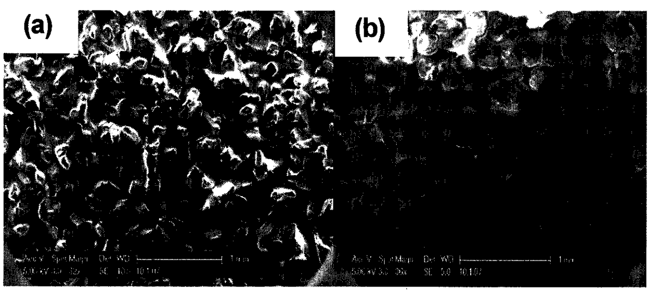


Figure 2 SEM (a) 120-grit sandpaper and (b) phosphor layer roughened
The darker spots in the image are vacant of phosphor material.

## 3. Discussion and Results

The luminous flux and luminous efficacy is given in Figure 3 for the two different configurations. The diode was tested under DC conditions at room temperature.

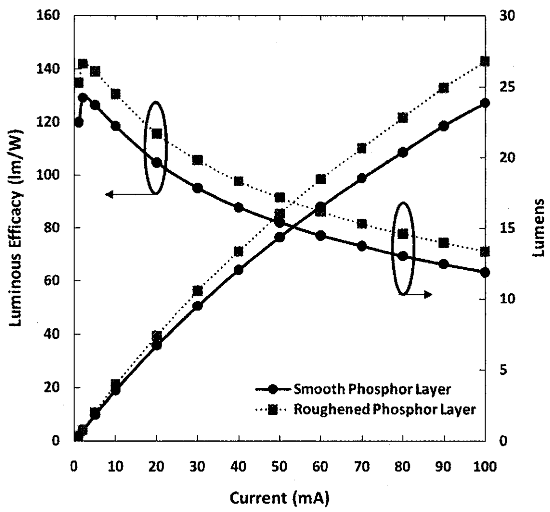


Figure 3 A comparison of luminous flux and efficacy between a smooth phosphor surface and a roughen one

At 20mA DC a typical luminous flux, luminous efficacy, correlated color temperature, color coordinates and color rendering for the smooth sample were 6.7 lm, 104.8 lm/W, 4364 K, (0.379, 0.432), and 62 respectively. The roughen sample was 7.4 lm, 115.6 lm/W, 4244 K, (0.388, 0.448), and 61 respectively. The increase in both luminous flux and luminous efficacy was slightly over 10%.

The cause of the increase is believed to be due to two reasons. First, as previously discussed, the roughen surface allows for angular randomizations. This increases the probability for the photons to make it into the escape cone and out to free space. A second reason for the increase is due to the scattering nature of the phosphor particle. The absorption and scattering of light by spherical particles is a classical problem in physics where the mathematical formalism is given by the Mie-Debye-Lorenz theory (or Mie theory for short). The key parameters for this theory are the wavelength λ of the incident radiation, the size of the particle which is usually expressed as a dimensionless size parameter α

$$\alpha = \frac{\pi D_p}{\lambda} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where $D_p$ is the diameter of the particle, and the optical property relative to the surrounding medium, the complex index of refraction[15]. For this experiment α>> 1 and Mie theory can be simplified by geometrical optics (if α<< 1 we could simplify to Rayleigh scattering regime). Using the Henyey-Greenstein formula ($P_{HG}$) for approximating the scattering phase function[16] we are able to see the scattering angle θ of a broad size distribution of a particle system by use of the asymmetry parameter g

$$P_{HG} = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}} \quad \cdots\cdots (2)$$

The asymmetry parameter g is defined as the intensity-weighted average of the cosine of the scattering angle. When g = 1 light is scattered totally at θ = 0° (the forward direction), for g = -1 light is scattered completely at θ = 180° (backward direction). Isotropic light scattering is for g = 0. It has been reported elsewhere[17] that for a spherical particle with an index of refraction of 1.85 (n=1.9 for our experiment) embedded in a medium of index 1.41 (ours is 1.406) and a 4 μm diameter that g ~0.8-0.85 and increases slowly as the size is increased (20 μm is the average size of the particles here). Therefore assuming an asymmetry parameter g ~0.85 Figure 4 shows the $P_{HG}$ as a function of the scattering angle.

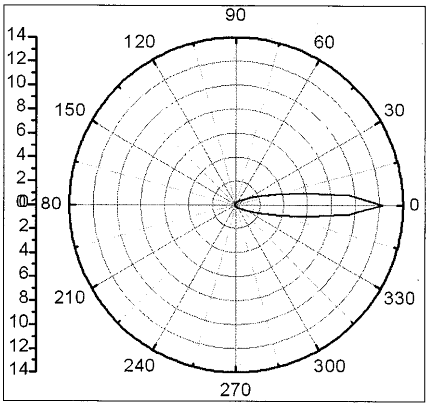


Figure 4 The Henyey-Greenstein phase function for a scattering particle system as a function of scattering angle
Here it is assumed that the asymmetry parameter is 0.85.

As shown in Fig. 4 when light impinges upon a phosphor particle most of the scattered light is in the forward direction. Since this light is not being absorbed by the phosphor the efficiency of the system is lowered. It is believed that when the topmost surface of the phosphor mixture is roughened then the scattered, unabsorbed light has had more chances to come into contact with phosphor particles and thereby be absorbed by them. Although this is a rough estimate of what is happening, the 10% increase assures that the roughening is helping to improve the system's overall performance.

## 4. Concluding Remarks

White illumination by using a wavelength converter such as a phosphor on a blue light emitting diode is one means of achieving efficient and energy saving lighting. We have demonstrated the ability to increase the luminous flux and efficacy of the white LED by 10% by randomly patterning the top layer of the phosphor mixture. By placing a piece of sandpaper onto the uncured phosphor mixture and then curing it, the sandpaper leaves an imprint which randomly patterns the phosphor layer. Due to the mainly forward scattering nature of the phosphor particles this method is understood to help the absorption process of the phosphor by an increase of scattered photon impingement onto the particle. A brief theoretical consideration was given to help confirm this theory.

No optimization was done with the roughening procedure and therefore further opportunities are available to exploit this technique in order to increase the efficiency and light output of these devices.

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