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Investigation of the Optical Properties of YAG:Ce Phosphor

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ABSTRACT

Recently, many studies have used optical ray-tracing analysis to investigate novel concepts of phosphor-converted white LEDs. Even though optical ray-tracing is a convenient tool, the accuracy of the results depends very much on the optical properties of the various components within the package used in the analysis. Presently, light transmission, reflection, and absorption properties of white LED phosphors are not very well quantified. Therefore, a laboratory study was conducted to quantify at different wavelengths of light the optical properties of a medium that has YAG:Ce phosphor mixed into epoxy. When short-wavelength radiation (blue light) strikes the epoxy-phosphor medium, some portion of the blue light is converted to longer wavelength radiation (yellow light). At a phosphor density suitable for creating a balanced white light, the amount of back-transferred and forward-transferred light, including blue and yellow light, are 53% and 47%, respectively. At a similar phosphor density, when green and red radiant energies strike the epoxy-phosphor medium, most of the energy is not converted by the YAG:Ce phosphor because it is beyond the phosphor's excitation region. In this case, nearly equal amounts of green and red radiant energy are transferred in the backward and forward directions. To demonstrate the usefulness of the results obtained in this study, an optical ray-tracing analysis of a remote phosphor white LED package was conducted. This analysis showed that the surface finish of the reflector cup of a reflective type remote phosphor white LED package does not affect extraction efficiency. However, the extraction depends very much on the effective reflectivity of the inside surfaces of the reflector cup.

Keywords: light-emitting diode (LED), YAG:Ce, phosphor, transmission, reflection, absorption

1. INTRODUCTION

Phosphor down conversion is one of the common methods available for creating white light-emitting diodes (LEDs).¹⁻³ In most commercial white LEDs, the phosphor is mixed in an epoxy encapsulant and placed around the emitter chip.^{2,3} Since the late 1990s, several remote phosphor concepts have been proposed for white LEDs.⁴⁻⁶ In these concepts, the phosphor is moved away from the chip, as illustrated in the example in Fig. 1. However, the benefits of remote phosphor were not quantified until recently.

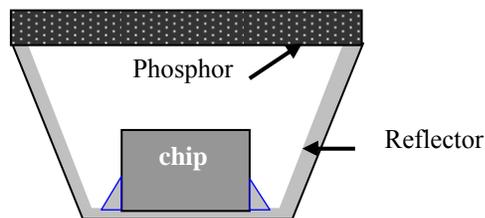


Fig. 1. Remote phosphor white LED package concept: The phosphor layer is placed further away from the chip.

In 2003, our research group conducted a phosphor placement study where the phosphor layer was moved away from the chip.⁷ In that study, an optical ray-tracing analysis was conducted to understand how much of the light is trapped within the LED package.⁷ Following that, in 2004 we demonstrated improved light extraction from a white LED package by moving the phosphor away from the chip and creating a custom optical element between the chip and the phosphor layer, as shown in Fig. 2.⁸ This method was called Scattered Photon Extraction (SPETM), and the experimental results showed over 60% improvement in light output and luminous efficacy.⁹ Furthermore, in 2004 our group showed that with remote phosphor placement, the life of white LEDs can be improved.¹⁰

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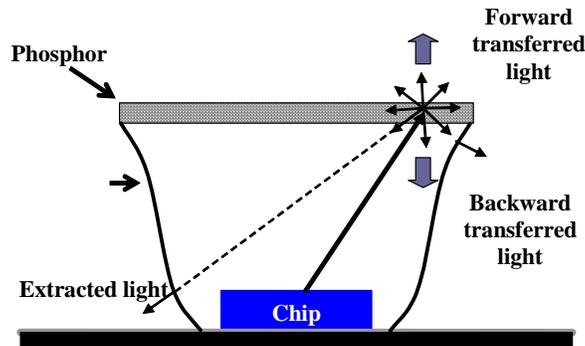


Fig. 2. Scattered Photon Extraction (SPE™) white LED.^{8,9}

Optical ray-tracing is a very common tool amongst researchers and manufacturers of LEDs because it allows for analyzing novel LED packaging concepts rapidly and inexpensively. Several past studies have used optical ray-tracing analysis to investigate white LEDs and light propagation through phosphor media.¹¹⁻¹⁶ Although it is a convenient tool to analyze white LED packages, the accuracy of the results depends very much on the optical properties and the values used for light transmission, reflection, and absorption for the different components within the LED package. Presently, light transmission, reflection, and loss properties of commonly used phosphors are not very well quantified. Therefore, researchers assume certain properties and values for these parameters when conducting ray-tracing analyses. Some of these assumptions from past ray-tracing studies include^{8, 11-16}:

- Isotropic light emission from phosphor particles
- Isotropic or random light scattering by phosphor particles
- The light-scattering coefficient is independent of wavelength
- Phosphor medium is transparent at 550 nm

Yamada et al. in 2003 and Narendran et al. in 2005 quantified forward and backward transmitted light from a layer of YAG:Ce phosphor for an excitation radiation near 470 nm (blue) and down-converted broadband yellow light.^{9,11} Narendran et al. showed that more than 60% of the light propagates backwards toward the excitation source, and most of it is lost within an LED package.⁹

In a phosphor-converted white LED package, the backward yellow light will return to the phosphor layer after being reflected from the different components within the LED package. In this case, it is not known what will happen to the yellow light when it strikes the phosphor medium. To the best of our knowledge, there are no past studies that have quantified the transmission and reflection properties of light outside the excitation wavelength region of YAG:Ce phosphor. Therefore, an experimental study was conducted to quantify these properties within a YAG:Ce phosphor mixed in an epoxy medium at wavelengths within the emission region of the phosphor. These results could be very useful for obtaining more accurate results when conducting optical ray-tracing analyses of white LED concepts.

As a starting point, this study considered three narrowband light beams with peak wavelengths of 470 nm (blue), 520 nm (green), and 625 nm (red), propagating through an epoxy medium mixed with YAG:Ce phosphor. As illustrated in Fig. 3, the 470 nm (blue) radiation is within the excitation wavelength region of the YAG:Ce phosphor, while 520 nm (green) and 625 nm (red) are mostly beyond the excitation region. For the 520 nm beam, a very small portion of the radiant energy lies within the excitation region.

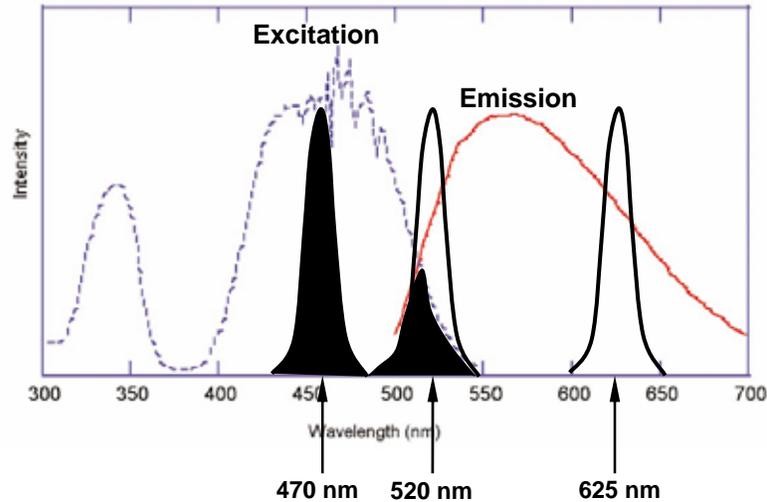


Fig. 3. Excitation and emission spectra of YAG:Ce phosphor, and the spectra of the three light sources (470, 520, 625 nm) used in this study.¹⁷

The phosphor density considered here was 8 mg/cm^2 , since our past study showed that at this density the white light produced by the white LED package is balanced, with its chromaticity coordinates very close to the blackbody locus.

2. EXPERIMENT

2.1 Experimental setup

The experimental setup is shown in Fig. 4. Two 20 cm diameter integrating spheres (1 and 2) were set up on an optical bench (3). The two integrating spheres were connected by a slide holder port-plug (4) with a 15 mm diameter aperture. A phosphor slide (5), similar to the one shown in Fig. 5, with a 15 mm diameter phosphor-epoxy mixture (8 mg/cm^2 phosphor density) coating area was inserted into the port-plug slot. Integrating sphere #1 (1) was used to measure the amount of transmitted radiant power, while integrating sphere #2 (2) was used to measure the amount of reflected radiant power. A 0.85 mm diameter fiber optic (6) probe was inserted into integrating sphere #2 (2), and the fiber probe was wrapped with a high reflectance white Teflon tape to reduce absorption. The output end of the fiber probe was placed 1.2 cm away from the phosphor slide in integrating sphere #2 (2), and the other end was inserted into an aluminum block (7) with three 4 mm diameter holes. On the other side of the aluminum block (7) were three 22.4 mm diameter holes used to house three LEDs (8). For practical reasons, three blue, three green, and three red 1 W high-power LEDs were used to increase the light output within the two spheres and to reduce the measurement errors from the spectrometer (12). The LEDs had peak wavelengths at 470 nm, 520 nm, and 625 nm and full-width half-maximums of 25 nm, 35 nm, and 20 nm, respectively. Three LEDs of the same color were connected in parallel to a dc power supply (9). A spectrometer (12) was used to measure the spectral power distribution (SPD) of both the reflected and transmitted radiant powers by inserting an optical sensor into the port-plug apertures (10) and (11) of both integrating spheres. Finally, a standard halogen lamp was used to calibrate the spheres and account for the self-absorption of the fiber optics in integrating sphere #2 for the reflected radiant power measurement.

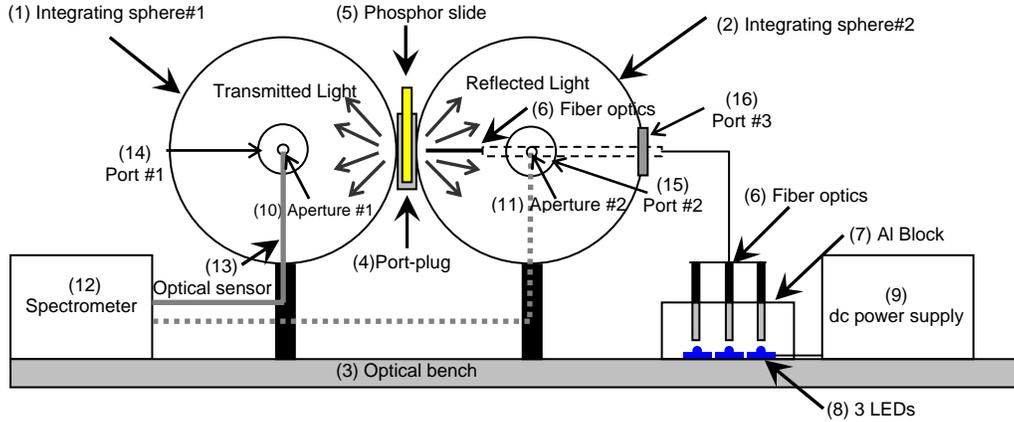


Fig. 4. Schematic showing the main components of the experimental setup.

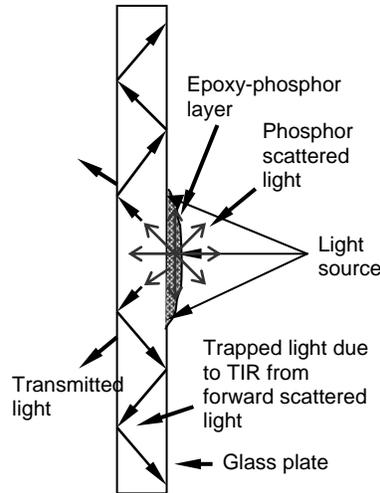


Fig. 5. Schematic showing a sample phosphor slide.

2.2 Experimental measurements

First, the optical sensor of the spectrometer was calibrated. Then the LEDs were turned on and stabilized for 15 minutes before measurements were taken. The phosphor slide was inserted into the slide holder between the two integrating spheres. The spectral power distributions (SPDs) of the transmitted and reflected radiant powers were measured by using a spectrometer attached to the sensor port of each integrating sphere.

For the blue light, SPDs were measured for both reflected and transmitted radiant powers. For any spectrum, the total radiant power was calculated by:

$$P = \int P_{\lambda} d\lambda \quad (1)$$

where P_{λ} is the radiant power in a small wavelength interval, $d\lambda$.

By defining the wavelength region from 420 nm to 499 nm as unconverted blue radiant power, and the wavelength region from 500 nm to 700 nm as converted yellow radiant power, transmitted yellow radiant power, reflected yellow radiant power, transmitted blue radiant power, and reflected blue radiant power were obtained from calculations after the SPD measurements.

For the green light, the measurement included reflected radiant power (green) and transmitted radiant power (green). Green radiant power (for both reflected and transmitted) was defined from 450 nm to 650 nm to avoid the noisy signal beyond this spectral range. It should be noted that since the green light is partially within the excitation wavelength region, a very small portion of the green light within the excitation wavelength will be absorbed by YAG:Ce phosphor and converted to yellow light. Since it is small, the contribution is neglected in the analysis.

For the red light, the measurement included reflected radiant power (red) and transmitted radiant power (red). The spectrum for the red light is beyond the phosphor excitation wavelength region and cannot be converted by the phosphor. The wavelength region for red radiant power (for both reflected and transmitted) was defined from 500 nm to 700 nm to avoid the noisy signal beyond this range.

The sum of the reflected and transmitted radiant powers for a clear slide with only epoxy (i.e., 0 mg/cm² phosphor density) was taken as the reference total radiant power. All yellow, blue, green, and red reflected or transmitted radiant powers were divided by the “reference total radiant power” to obtain the relative values of yellow, blue, green, and red reflected or transmitted radiant powers. These ratios were calculated to make the reflected and transmitted radiant powers comparable for all cases.

3. RESULTS

Light loss is calculated from the reflected and transmitted radiant powers:

$$\text{Light loss} = 1 - (\text{Transmitted} + \text{Reflected}) \quad (2)$$

Here, light loss includes energy conversion loss due to down conversion by the phosphor and light loss within the optical setup used in this study. The results for light reflection, transmittance, and light loss are given in Table 1. These values are for a phosphor density of 8 mg/cm².

Table 1. Light reflection, transmission, and light loss for blue, green, and red light at 8 mg/cm² phosphor density

	Reflected	Transmitted	Lost	Total
Blue (unconverted)	5%	6%	36%	100%
Yellow (converted)	29%	24%		
Green	40%	42%	18%	100%
Red	43%	44%	13%	100%

The light loss within the optical setup is mostly due to the trapped light inside the glass slide shown in Fig. 5. With increasing light scattering by the phosphor, light rays at higher incident angles that are coupled into the glass slide would undergo total internal reflection and thus be trapped. The down conversion loss is mostly for the blue light. Green has very little down conversion loss, almost negligible. In the case of red light, there is no down conversion loss. Therefore, light loss for red is the lost light due to trapping within the glass slide. Therefore, by subtracting the percentage of light loss due to trapping, the down conversion loss can be estimated for the blue light. The assumption here is that the amount of trapped light is similar for red, green, and blue light. Therefore, the 23% (36% – 13%) conversion loss from blue light for YAG:Ce phosphor is in agreement with values generally reported in literature.¹⁸

3.1 Optical ray tracing analysis

To study the usefulness of the results, a ray-tracing analysis of a phosphor-converted white LED was conducted. The LED configuration selected for study is shown in Fig. 6, and is similar to the configuration studied by Kim et al.¹³ The figure shows a remote phosphor LED, where the phosphor is placed at the top of the reflector cup. The inside surface of

the reflector has a 95% reflectance, and the short-wavelength chip has a 50% reflectance. The chip dimensions are 0.22 mm by 0.22 mm and 0.10 mm height. The reflector sides are at an angle of 45 degrees. The optical ray-tracing analysis was conducted with the assumption that the phosphor medium is the light emitter and it emits 550 nm light. The ray-tracing analysis was conducted for two additional assumptions:

1. The phosphor emits light isotropically, thus an equal amount of light up and down; the epoxy and the phosphor medium have indices of refraction 1.6 and 1.8, respectively; and the epoxy and the phosphor medium are transparent at 550 nm, similar to some of the assumptions made in the past studies.¹⁴
2. The amount of yellow light emitted by the phosphor medium downwards toward the chip is 55% and upwards is 45%. These values are obtained from the transmitted and reflected data for converted yellow light described in Table 1. Then for yellow light returning back to the phosphor layer after being reflected from the side walls and the chip, nearly equal amounts of light are transmitted through and reflected back. This ratio is obtained from the reflected and transmitted data in Table 1, for red and green light.

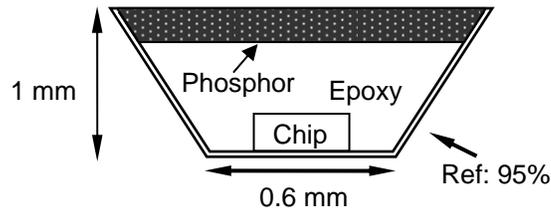


Fig. 6. White LED with the phosphor layer close to the chip (left); white LED with phosphor away from the chip (right)^{13,14}

The results from the optical ray-tracing analysis are shown in Table 2. With the first assumption, the efficiencies of the final output radiant energy were 62% and 79% for specular and diffuse reflectors, respectively. These results are similar to what Kim et al. found in their ray-tracing analysis; they concluded that the diffuse surface for the reflector is more efficient than the specular reflector.¹³ However, when the light transmission and reflection properties were changed per the second assumption, the results for the efficiencies of the final output radiant energy were the same for both types of reflector surfaces, 73%. It should be noted here that if the reflectance value of the inside surface of the reflector cup is reduced, then the light extraction efficiency will also be reduced. As an example, if the reflectance is reduced from 95% to 85%, the extraction efficiency will reduce to 60% from 73%, but the extraction efficiency for the two surface types will be the same. This might explain why Kim et al. observed similar extraction efficiency values for the specular and diffuse surfaces in their experiment.¹³ In this example, the extraction efficiency of back-scattered light depends very much on the effective reflectivity of the inside surface. With increased distance between the phosphor and the chip, the surface area covered by the sides of the reflector is much larger than the chip surface area; thus, the effective reflectivity is dominated by the reflectance of the reflector surface. With a scattering medium like the YAG:Ce phosphor in the package, the surface finish of the reflector cup should not affect extraction efficiency.

Table 2. Ray-tracing analysis results.

Assumption	Light extraction (Remote phosphor [reflective cup])
Phosphor medium is transparent at 550 nm, per past literature	62% (specular)
	79% (diffuse)
Phosphor as a scattering medium, per findings from this study	73% (specular)
	73% (diffuse)

4. SUMMARY

This study demonstrated that YAG:Ce phosphor mixed in epoxy behaves like a scattering medium. At a phosphor density suitable for creating a balanced white light, when short-wavelength radiation (blue light) strikes the epoxy-phosphor medium, some portion of the blue light is converted to longer wavelength radiation (yellow light). The amount of back-transferred and forward-transferred light, including blue and yellow light, are 53% and 47%, respectively. At a similar phosphor density, when green and red radiant energies strike the epoxy-phosphor medium, most of the energy is not converted by the phosphor because it is beyond the excitation region of the YAG:Ce phosphor. In this case, nearly equal amounts of green and red radiant energy are transferred in the backward and forward directions. To demonstrate the usefulness of the results obtained in this study, an optical ray-tracing analysis of a remote phosphor white LED package was conducted. Results from the optical ray tracing showed that with a scattering medium like the YAG:Ce phosphor in the package, the surface finish (diffuse and specular) of the reflector cup of a reflective-type remote phosphor white LED package should not affect extraction efficiency. However, the extraction depends very much on the effective reflectivity of the inside surfaces of the reflector cup.

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