Optical and thermal performance of a remote phosphor plate

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ABSTRACT

The objective of this study was to understand how optical and thermal performances are impacted in a remote phosphor LED (light-emitting diode) system when the phosphor plate thickness and phosphor concentration change with a fixed amount of a commonly used YAG:Ce phosphor. In the first part of this two-part study, an optical ray-tracing analysis was carried out to quantify the optical power and the color properties as a function of remote phosphor plate thickness, and a laboratory experiment was conducted to verify the results obtained from the ray-tracing analysis and also to examine the phosphor temperature variation due to thickness change.

Keywords: remote phosphor, LED, white light, thermal management, optical ray tracing

1. INTRODUCTION

Solid-state lighting (SSL) has been gaining popularity due to its high degree of energy efficiency and long life. The light-emitting diode (LED) is one type of SSL technology. Today, the most common method for creating a high-power white LED is the use of a short-wavelength LED chip with a down-conversion phosphor.[1-2] In such packages, the phosphor is either dispersed within a binding medium such as epoxy or silicone and surrounds the LED chip, or the LED chip is coated conformally with a phosphor.[1,3-4] Alternatively, in some white LED packages the phosphor is placed some distance away from the chip, commonly known as remote phosphor LED. Since 1995, several remote phosphor white LED and light engine concepts have been proposed.[5-9] Higher luminous efficacy and longer useful life benefits of the remote phosphor LED were first shown in 2003.[10] In 2005, Narendran et al.[11] demonstrated a remote phosphor concept known as the scattered photon extraction (SPE) package, which allowed the phosphor-converted photons traveling towards the chip to be extracted for improved performance.[11-13] Since 2005, several remote phosphor LED light engines have been commercialized.[14-16] Now there are a few manufacturers who are producing remote phosphor plates for making white LED light engines. The overall performance of a remote phosphor white LED light engine depends on several parameters of the phosphor plate, including its geometry, plate thickness, phosphor concentration, binding material, and other factors. The objective of this study was to investigate how the performances of a phosphor plate, including optical and thermal, are affected when the plate thickness and phosphor concentration are changed. The study used both optical ray-tracing analysis and laboratory experiments.

Past studies have shown that the total radiant power decreased when phosphor concentration or phosphor thickness increased.[17-20] Yamada et al.[21] and Narendran et al.[11] both investigated the forward and backward light emission from a remote phosphor plate at fixed thickness with varying phosphor concentration. These two studies showed the forward and backward phosphor-converted long wavelength, "yellow" radiant power increased as the phosphor concentration increased due to more energy conversion. In the studies of Liu et al.[18] and Nguyen et al.[19], when the phosphor plate thickness increased, the amount of phosphor particles in the plate increased, and the higher phosphor concentration resulted in an increase in phosphor energy conversion.

A thermal study by Dong et al. investigated phosphor temperature as a function of both phosphor concentration and plate thickness using a phosphor plate made of silicone.[22] The result indicated that the phosphor surface temperature rose when the plate thickness increased initially, and then it decreased with further increase of plate thickness.

Based on the literature survey, there is a lack of understanding about how light extraction and surface temperature change with different plate thickness with the same total amount of phosphor. Therefore, the objective of this study was to gain a better understanding of the optical and thermal properties of the remote phosphor plate technology using optical ray-tracing analysis and laboratory experiment.

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2. EXPERIMENT

This study focused on characterizing phosphor plates in which YAG:Ce phosphor is dispersed in epoxy. The plate thickness and the phosphor concentration were changed while the total amount of phosphor was held constant. The corresponding light output in lumens and the phosphor plate surface temperature in degrees Celsius were measured and analyzed. In the case of light output, optical ray-tracing analysis and laboratory experiments were conducted. The remote phosphor package setup used in the optical ray-tracing analysis and the laboratory experiment is shown in Figure 1. In this setup, the light source used was a 6 W (chip-on-board) high-power blue LED with peak wavelength at 455 nm. The phosphor plate diameter was 34 mm. The phosphor plate was loosely placed on top of the aluminum reflector cup. The inner surface of the aluminum reflector cup was specular. The reflector cup had the same diameter as the phosphor plate on the top, 21 mm on the bottom, and 16 mm for the height. The plate thicknesses were 0.8 mm, 2.3mm, and 3.2 mm.

Optical ray-tracing analysis was carried out using LightTools® commercial software. In the optical ray-tracing simulation, 100,000 rays were traced and the estimated error was 3% to 5%. Input parameters in the simulation included the geometric shapes and dimensions of the phosphor plate and the reflector cup, the surface optical properties of the phosphor plate and the reflector cup, the phosphor optical properties, the light output, the spectral power distribution (SPD) and the near-field ray data file of the exciting LED light source. The geometric shapes and dimensions of the phosphor plate and the reflector cup were matched with the laboratory experiment. The phosphor plate surface optical properties were assumed to be Lambertian scattering on all surfaces. The inner surface of the reflector cup was defined as specular reflective with 95% reflection. Both optical surface properties were set based on best scenario estimation. The phosphor optical properties including the relative phosphor excitation, emission, and absorption spectral distributions were measured in a laboratory experiment. The light output and the SPD of the exciting LED light source were measured in a one-meter integrating-sphere with a spectroradiometer. The near-field ray data file was set based on a typical high-power Lambertian distribution blue LED. The surface temperature of the phosphor plate was measured using an infrared (IR) imaging camera as shown in Figure 1. The LED package was mounted to a metal heat sink to maintain relative constant junction temperature throughout the experiment. The measured pin temperature was controlled within ±2°C variation. No additional housing was introduced into the system. The thermal setup and calibration were the same as a previous study by Perera and Narendran.[23] The emissivity was measured based on recommendations from the IR thermometric community.[24] As discussed by Perera et al.[25], they have shown the benefits of using an IR camera to determine the surface temperature of a remote phosphor plate.

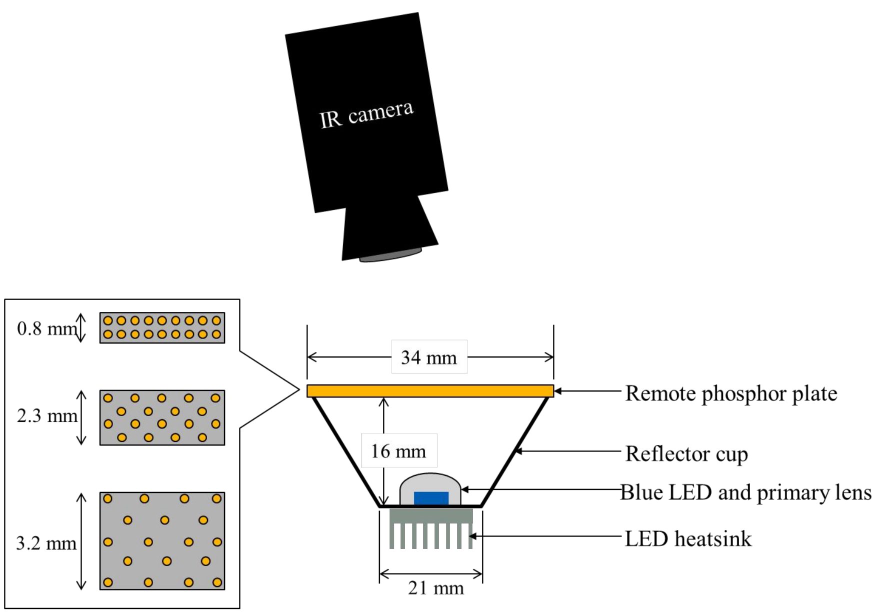

Figure 1. Thermal measurement setup.

3. RESULTS

3.1 Experiment 1

The objective of the first experiment was to simulate and compare the total luminous flux output of a remote phosphor package with phosphor plates of three different thicknesses, 0.8 mm, 2.3 mm, and 3.2 mm. In all cases, the amount of phosphor was kept constant at 50 mg. The selection of 50 mg was to obtain a "white" chromaticity point on the blackbody locus on the 1931 CIE chromaticity diagram. An additional objective was to understand how the temperature of the phosphor plates changes with plate thickness. The results are shown in Figure 2.

As seen in the graphs in Figure 2, the simulation and the experiment show similar results. When the phosphor plate thickness increased, the total luminous flux extracted from the remote phosphor LED package did not change significantly in both simulation and experiment cases. However, the corresponding temperature rise was about 4°C (61.8°C to 65.8°C) from the lowest to the highest thickness.

A possible reason for the higher temperature in the case of the thicker phosphor plate is most likely the lower volume fraction of phosphor in the 3.2 mm plate compared to the 0.8 mm plate. In the phosphor plate, heat is generated from the short-wavelength radiation ("blue" light) loss, the phosphor quantum efficiency loss, and the stokes shift loss during phosphor conversion. The heat is eventually dissipated or absorbed in the phosphor-epoxy mixture. Because the thermal conductivity of the epoxy is significantly lower than that of the phosphor, the lower volume fraction of phosphor in the 3.2 mm plate results in a higher surface temperature of the phosphor plate than in the 0.8 mm plate.

When the volume fraction of the phosphor is low, the heat generated by the short-wavelength radiation absorption by the epoxy is high and becomes the dominant factor in raising the phosphor plate temperature. When the phosphor volume fraction increases at 0.8 mm thickness, the heat generated by the absorption of short-wavelength radiation by the epoxy reduces and thus the plate temperature decreases.

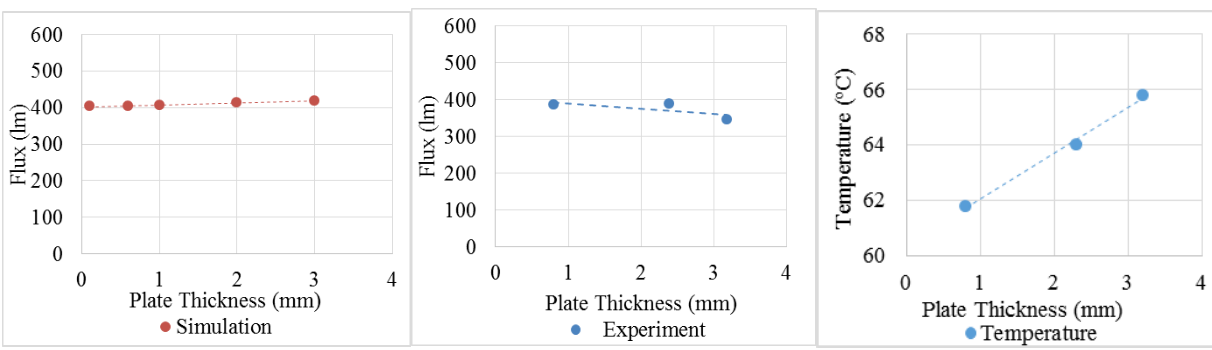

Figure 2. Light output and surface temperature for the 50 mg phosphor as a function of phosphor plate thickness (left: simulation; middle: experiment results; right: measured surface temperatures of the three phosphor plates).

3.2 Experiment 2

In experiment 2, the phosphor plate temperature was analyzed for different amounts of phosphor and phosphor plate thicknesses. In this study, for the same three phosphor plate thicknesses the phosphor amount increased from 50 mg to 100 mg and 200 mg, where 200 mg was found to reach the saturation point where all the short-wavelength energy was absorbed and converted into long-wavelength emission. As in experiment 1, the phosphor plate temperature was measured using an imaging IR camera. The results are shown in Figure 3. As seen in the graphs in Figure 3, when the amount of phosphor increased from 50 mg to 200 mg, the phosphor plate temperature increased. This increase in plate temperature was highest (61.8°C to 75.8°C) when the plate thickness was 0.8 mm and lowest (67.8°C to 69.8°C) when the plate thickness was 3.2 mm. Therefore, at low phosphor concentrations (in other words, small amounts of phosphor), the plate temperature increases with plate thickness increase, and at high phosphor concentrations the plate temperature decreases with plate thickness increase.

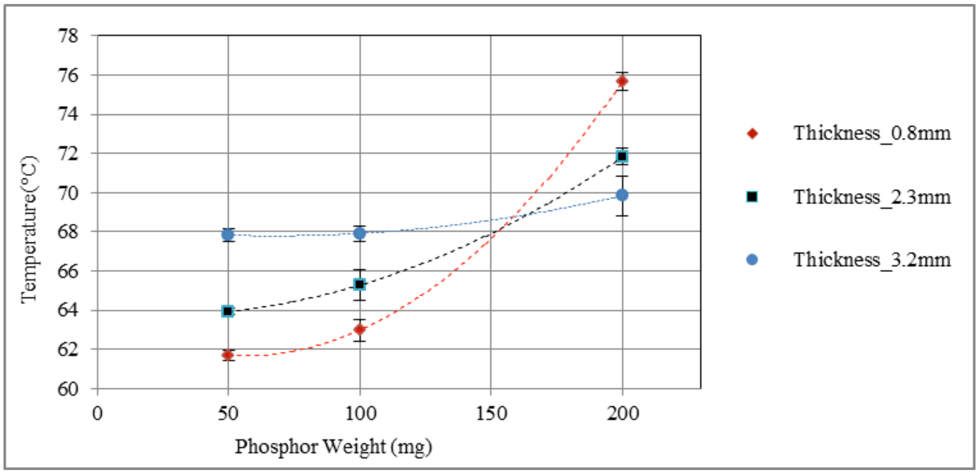

Figure 3. Phosphor plate temperature as a function of phosphor plate thickness and phosphor concentration.

The observed results in Figure 3 can be explained as follows. Epoxy has very low thermal conductivity compared to YAG:Ce phosphor particles. At higher phosphor concentrations, the effective thermal resistance from the heat source to the ambient is low because of the shorter distances between the phosphor particles. Therefore, the heat generated within the plate is transferred to the top surface of the plate more that in the case of low phosphor concentrations that have higher thermal resistance. Furthermore, at low phosphor concentrations the amount of heat generated by the short-wavelength radiation absorption by the epoxy is high, as explained earlier. These two competing phenomena cause plate temperature to increase with plate thickness increase at low phosphor concentrations, and the plate temperature to decrease with plate thickness increase at high phosphor concentrations.

Figure 4 shows how the phosphor plate temperature changes as a function of plate thickness for different amounts of phosphor (50, 100, and 200 mg). It can be inferred from Figure 4 that if the phosphor plate thickness is around 4 mm, the plate temperature will be the same at any phosphor concentrations.

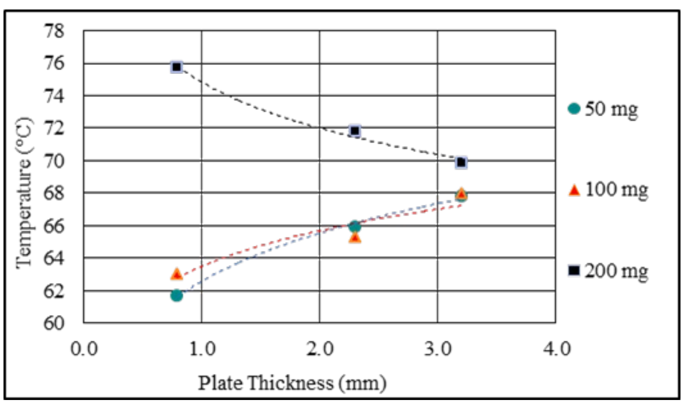

Figure 4. Phosphor plate temperatures as a function of thickness for different phosphor concentrations.

4. DISCUSSION

When making phosphor plates for use in remote phosphor LED light engine applications, it is important to consider both the overall system efficacy and the useful life that depend on the phosphor plate temperature. From this study, it is evident that phosphor concentration and plate thickness affect optical and thermal performances. In practice, it may be necessary to adjust the phosphor concentration to obtain a desired chromaticity value. To maintain a certain phosphor plate temperature and thus useful operating life, independent of phosphor concentration; one can conduct a similar analysis and identify a suitable plate thickness.

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