International Journal of Heat and Mass Transfer 117 (2018) 211–222

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Analysis of a remote phosphor layer heat sink to reduce phosphor operating temperature

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ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form 3 October 2017
Accepted 3 October 2017

Keywords:
LED reliability
Phosphor thermal management
Phosphor heat generation
Infrared thermography
Extended-surface heat conduction
Lumen maintenance

ABSTRACT

The remote phosphor method has provided significant improvement in overall LED lighting system efficiency by reducing the number of photons absorbed at the LED chip. However, increased demand for higher light output from smaller light engines has resulted in high radiant energy and heat densities on the phosphor layer. The problem is exacerbated by the phosphor conversion efficiency decreasing with increased operating temperature in the remote phosphor layer. A higher operating temperature can negatively affect performance in terms of luminous efficacy, color shift, and life. In cases such as this, the system's performance can be improved through suitable thermal management that reduces the phosphor layer temperature. In this study, we present the first investigation to experimentally quantify the operating temperature and optical performance effects of using a dedicated phosphor layer heat sink solution as a thermal management strategy to reduce phosphor layer operating temperature. The effects of heat sink geometry and material parameters on phosphor layer operating temperature and optical performance were investigated. The experimental results showed a decrease in phosphor layer operating temperature with an increase in phosphor layer heat sink interface area, while the total radiant power decreased. Ray-tracing simulations identified the low surface reflectance of the heat sink interface area as the cause of this decrease in radiant power. A finite element model was developed from the experimental results to understand the decrease in phosphor layer operating temperature with increased heat sink interface area. This simulation work was used in identifying the causes affecting observed optical and thermal performance in the short-term experiments. The study also investigated the long-term performance of phosphor layer heat sinks and the findings are reported.

1. Introduction

The evolution of light-emitting diodes (LEDs) over the past several decades has pushed the technology from indicator- and display-type applications to high-power general illumination applications [1]. This was made possible by the invention of the Gallium-Nitride (GaN) LED and by continual improvements in extracting photons and heat from the LED chip [2–5]. One of the most common methods for creating "white" light is to combine the short-wavelength visible radiation from a GaN-based LED with the emission from a wavelength-converting phosphor material [4]. In these phosphor-converted white LED packages, heat is generated at the LED chip and the wavelength-converting phosphor material [6–12].

Unlike traditional lighting technologies, the performance of LED systems is dependent on temperature [6,12]. Therefore, dissipating the heat generated in the LED chip and phosphor material and maintaining a lower operating temperature are critical to LED system performance [1,5]. In the recent past, many methods have been utilized to improve phosphor-converted white LED package efficiency. Remote phosphor is one such method in which the wavelength-converting phosphor material is separated from the LED chip in the LED package. The physical separation of the phosphor layer from the LED reduces the chip's absorption of the down-converted phosphor emission and facilitates increased extraction of these photons [13–15].

Past research studies have stated that LED systems with remote phosphor configurations are prone to having higher phosphor layer operating temperatures [16,17,37,38]. These studies claim that the higher thermal resistance in the heat dissipation path in the remote phosphor configurations causes the phosphor layer operating temperature to be higher compared to the low thermal resistance heat dissipation path created when the phosphor layer is

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.016
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directly coated on the LEDs. This increase in the operating temperature of the phosphor is associated with negatively affecting luminous efficacy, color shift, and life of the LED system [13,18–24]. The heat is generated in the phosphor layer due to conversion efficiency losses, such as quantum conversion losses and Stokes shift losses, and by trapped or absorbed photons in the phosphor layer [4,9–12,33,36]. Past studies have stated that the heat generated in the phosphor layer can be as high as 13% of the electrical power into an LED system, causing the phosphor operating temperature to be in excess of 150 °C [10,17,19].

To decrease the phosphor layer operating temperature, some studies have investigated the use of a thermally conductive binding medium in creating the phosphor layer, while others have studied pulsing the LED drive current to induce a transient cooling effect on the phosphor layer [6,7,9–11,16,25]. In the study described here, we investigated the use of a phosphor layer heat sink for dissipating the heat generated in the phosphor layer. Systematic analyses of the geometry of the phosphor layer heat sink and of the heat sink material properties' impact on operating temperature and light output were conducted for both the short and long term.

2. Methodology

As discussed in the previous section, heat generation in a phosphor-converted LED system is tied to the energy conversion at the LED chip and the phosphor layer. The first of these energy conversions is at the LED chip where electrical energy is converted to short-wavelength visible radiation [6,7]. The next energy conversion is at the phosphor layer where the short-wavelength visible radiation is absorbed and reemitted as broadband, long-wavelength visible radiation [6,7]. The efficiency losses in these conversions generate heat [6–11].

Phosphor layers attached to conductive structures have the potential to reduce phosphor layer operating temperature [26–28]. This reduction in operating temperature results from effectively dissipating the heat generated in the phosphor layer to the ambient. The schematic diagram in Fig. 1 illustrates the heat dissipation mechanisms available for a phosphor layer heat sink structure. The heat transfer mechanisms available include: conduction, which is heat transfer along the phosphor layer following temperature gradients; convection, which is heat transfer from the phosphor layer and the heat sink to the ambient; and radiation, which is radiative heat transfer from the phosphor layer and the heat sink to the surrounding. Fig. 1 shows the phosphor layer attached to a low conductive heat sink (left), which uses a low thermal conductivity material such as polymer plastics or rubber, and a high conductive heat sink (right), which uses a high thermal conductivity material such as aluminum or copper.

The high conductive heat sink extracts the heat generated in the phosphor layer adjacent to the heat sink, creating a flow of heat. Heat generated in the phosphor layer is transferred towards the heat sink. In comparison, the low conductive heat sink is capable of extracting only a limited amount of heat from the phosphor layer adjacent to the heat sink. Therefore, the generated heat can be dissipated only via convection and radiation to the ambient or the surrounding. The restricted heat transfer in the low conductive heat sink causes the phosphor layer operating temperature to be higher compared to the phosphor layer operating temperature in the high conductive heat sink.

3. Experiment

To assess the ability of a phosphor layer conductive structure to dissipate heat, several phosphor layer heat sinks were constructed. The geometrical configurations of these phosphor and binder material heat sinks are illustrated in Fig. 2. The shaded circular areas represent the phosphor and binder material mixture in the unshaded square heat sinks (Fig. 2). The heat sink plate was fabricated from a 1.5 mm thick aluminum plate. The required perforation design was then machined as illustrated in Fig. 2 to obtain three distinct heat sink geometrical configurations. The thickness of the phosphor layer was maintained at 1.5 ± 0.1 mm. A $CaSiAlN_3$:Eu^{2+} Nitride phosphor (INTEMATIX R650) was mixed with a two-part optical grade epoxy (EPOXIES 20-3238) to create the phosphor layer described above. The two-part liquid epoxy and phosphor was pre-mixed and deposited into the cylindrical cavities machined in the heat sink plate. A PTFE mold was used as a backing substrate and a top cover to contain the liquid mixture of epoxy and phosphor, as well as to maintain a flat surface in the heat sink cavities until thermally cured. The created phosphor layer in all heat sink configurations was controlled to have a 10% mixing ratio of phosphor by weight.

Fig. 3 illustrates a schematic diagram of heat sink configurations #1 and #2. The total emitting area of the phosphor layer was held constant for all configurations (i.e. $A = \sum A_i$ for all i = 1 through 7 in Fig. 3). The same total emitting area was maintained for heat sink configuration #3.

Fig. 3 also illustrates the cylindrical surface between the phosphor layer and the heat sinks through which the heat generated in the phosphor layer is conducted. This surface is indicated in the figure by the hatched area and from here onward will be referred to as the heat transfer interface. As the number of cylindrical segments increased in the heat sink while maintaining the

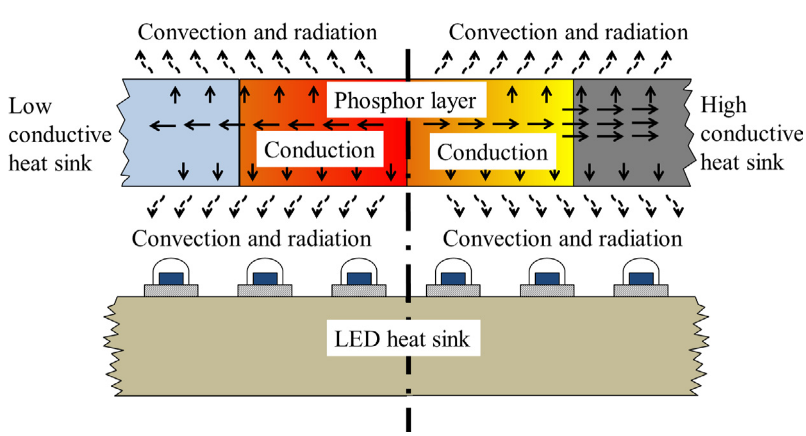

Fig. 1. Schematic diagram of the heat transfer in the remote phosphor layer of an LED system with low conductive (left) and high conductive (right) heat sink configurations.