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Thermal investigation of a high brightness LED array package assembly for various placement algorithms

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HIGHLIGHTS

- A thermal management analysis for a LED array package assembly was presented.
- Various LED operating conditions and design algorithms were proposed.
- The temperature distribution and heat flow of the LED array were assessed.
- The optical performance of the LED array was monitored and investigated.
- The proposed design can lower the LED surface temperature and improve its luminous efficacy.

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ABSTRACT

This paper presents a thermal management analysis and experimental validation of natural convective heat transfer of a high brightness LED array package assembly in various placement algorithms. The operating conditions include thermal conductivity of the PCB, heat sink design, and LED placement design in a system module. The temperature distribution and heat flow of the LED array package are assessed by thermal profile measurement using an IR camera and thermocouples. In addition, the heat transfer process of the LED array package assembly in natural convection is also simulated using the computational fluid dynamics (CFD) method. The optical performance of the LED array is monitored and investigated in accordance with the environmental variations. The thermal distribution of a commercial high-brightness LED array product using the developed placement method is compared to that of the original design. The change in radiant flux, LED efficacy, and uniformity of illuminance is compared. The results suggest that the new placement method for a LED array can lower the individual LED surface temperature by more than 10%. As a result, the overall heat dissipating capability of the LED array to the surrounding and hence LED efficacy is improved.

1. Introduction

Over the past few years, high brightness light-emitting diodes (LEDs) have penetrated into a number of lighting applications, including indoor lighting, street lamps, advertising displays, backlights for LCD TV, traffic lights, and decorative lighting. LEDs that use from 500 mW to as much as 10 W in a single package have become standard, and researchers expect that even higher power levels will be used in the future. The luminous efficiency of LEDs has also improved to a certain extent in response to the various applications. At first, gains are made in efficiency so that 20 lm/W has soon been achieved quickly. Efficiency has slowly risen in the last few years to around 100 lm/W, and the trends indicate that 150 lm/W and higher will occur in the next few years. Even though these high-brightness LEDs have a high energy efficiency of around 15–25% from power to light versus 10% in traditional lighting, there is still a significant amount of heat being generated. Heat management is thus an important issue for high-brightness LEDs. Narendran and Gu [1] experimentally demonstrated that the life of LEDs decreased in an exponential manner as the junction temperature increased. Therefore, a low-operating temperature is essential for LEDs. The use of LED lighting in a given region requires a uniform luminous flux, also known as illuminance [2]. Therefore, it is necessary to adopt the form of LED array and increase its brightness and light-emitting area, to improve the uniformity of illumination.

The way LEDs separate themselves or their placement algorithms on the package assembly is a concern. It affects significantly the quality of LED array illumination, such as the

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uniformity and color spectrum shift. Petroski [3] studied the placement spacing problem of LED array packages on Chip on Board (COB) by consideration of the dielectric, copper and solder layer thickness variables. Cheng [4] used analytical approach for optimizing a uniform LED temperature distribution. These investigations focused on equal–spacing of a rectangular die and similar studies were reported [5,6]. Lee [7] proposed a thermal force-directed placement algorithm for multichip modules. In the algorithm, each chip was moved in the direction of the force until the system achieved equilibrium. However, the approach focused on the substrate with no lighting output and did not take the uniform illumination of the LED array grid shapes into account [8]. A comprehensive study of the heat transfer mechanism of LED array-PCB units is lacking in the literature. Also, to design an effective cooling system in a LED array system and obtain an optimum cooling performance, the behavior of natural convection in such a system requires special consideration. For thermal management of high power LEDs, heat sinks [9], thermoelectric coolers [10], metallic bonding methods [11], thermal interface materials [12], and piezoelectric fans [13] are suggested for reducing the LED junction temperature. To ensure that the housing temperatures do not exceed the specified maximum values, the use of heat sinks in LED luminaires is nowadays recognized as a passive device to dramatically reduce the heat in high power LEDs instead of using an active heat sink device, for example, the addition of a fan. The applicable heat transport mechanisms are conduction via the heat sink and convection and thermal radiation to the surroundings. Although an active LED heat sink does provide better cooling, the power needed to run the fan diminishes the energy efficiency of the LED. However, due to the presence of the PCB, its low thermal conductivity may significantly lower the cooling performance for the overall LED-PCB module and eventually affect the optical output efficiency. A heat sink can have many complex shapes but a radial heat sink is more popular than a square plate heat sink. The fin design of a heat sink can have a relatively large influence on the final heat transfer efficiency of LEDs [14]. Comparison of the thermal performance on such designs is thus required.

The efficiency and reliability of solid state lighting devices greatly depend on successful thermal management, according to the patent filed by Yung et al. [15]. This plays a key role in the cost-effectiveness of LED systems [16–18]. The LED packaging must take the high power density at the LED junction and spread it over a larger area. Accordingly, a LED manufacturer must provide the most efficient thermal conduction path possible, while balancing other design factors such as physical dimensions, optical performance and cost. However, no previous work has been found to quantify thermal performance and optical performance, such as color spectrum shift and the luminous efficacy change for different placement conditions of LEDs. In order to overcome the technological gap in the above problems, a thermal investigation of the LED array lighting performance is proposed. "In the concerned LED system, the heat is mainly dissipated by conduction and convention. In comparison, the radiation heat transfer has a very small effect on the net system heat transfer. The heat transfer is essentially via the LED surface area which is fairly small and their temperatures are relatively low (below 80 °C), to keep the LED junction temperatures below the maximum rated temperature of 150 °C. Thus, the radiation heat transfer is not considered in this work. Moreover, the proposed design and material (PCB substrate) are suggested to make an improvement of some commercially available LED array product. This work can provide a local optimum solution for LED thermal management under the same operating environment instead of a completely new redesign work for finding the global optimum solution". The following work demonstrates the efficacy of the proposed approach for the heat dissipation from the LED array package assembly.

2. Experimental method

High-power white LEDs including Philips Lumileds, Wai Chi Opto Technology, EdiPower II and Nichia were used in this study. The total heat generation during the operation of a LED by a DC power source was determined using the power law equation and the control circuit. The LEDs are connected together in series, and a constant current is supplied to each LED using the constant current mode of an Agilent DC power supply. The thermal resistance model calculation using multiple LEDs mounted on the same PCB and heat sink [19] is shown to Fig. 1(a) and (b). The experimental methods used in this study are described as follows:

2.1. Placement conditions of a LED array-PCB assembly

There are five placement study conditions for a LED-PCB assembly in this work.

Condition 1: Effect of PCB materials on the heat dissipation of LED
Condition 2: Effect of LED placement at different locations of PCB substrate
Condition 3: Effect of heat sink designs
Condition 4: Effect of LED array design for a rectangular PCB substrate
Condition 5: Effect of LED array design for a circular PCB substrate

Conditions 1–4 are easy to understand. As for condition 5, the placement configurations (designs) of the LED arrays are different from the first four conditions and much more mathematical calculation is required. The main purpose of the design is to determine an optimum separation for the LED such that the LED lifetime is within the specified range and the LED array is able to maintain the required uniform illuminance. Three placement designs (circular pattern) for a LED array-PCB assembly are shown in Fig. 2(a). Design 1 is a conventional method for a commercial LED-array module on a PCB. In this design, there are 36 LEDs connected in series. The offset distances between R1 and R2, and between R2 and R3 are the same with a constant value of about 22 mm. Design 2 is a modified method for the concerned LED array. This design is distinct from design 1 since only 33 LEDs are used in the LED placement configuration while the offset distances between R1 and R2 (22 mm) and between R2 and R3 (16 mm) are different. Design 3 is another modified design which has a reduced PCB size. It has the same LED placement configuration of 36 LEDs as that of design 1 but different offset distances between R1 and R2 (21 mm) and between R2 and R3 (18 mm). The spectra and the luminous efficacy of the analyzed LED array for different placement designs were acquired by a light integrating sphere and a spectrophotocolorimeter (PMS-80_V1).

2.2. Thermal imaging

Infrared thermography (TH9100, NEC-San-ei Co., Japan) was used in the experimental setup, for the thermal performance of different LED placement designs. In this system, the surface temperatures of the LEDs were determined by infrared radiation (of 8–14 μm wavelength) from the surfaces according to the Stefan–Boltzmann law. A close-up lens was also be fitted to the IR camera (TH91-386, NEC-San-ei Co., Japan). The minimum detection temperature variation is 0.06 °C and the minimum spatial resolution is $95 \times 95\ \mu m^2$. The LEDs were encapsulated in plastic material. The emissivity value was set at 0.95 by referring to the thermal imaging emissivity table.