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Refrigerating liquid prototype for LED's thermal management

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HIGHLIGHTS

► New heat management application of refrigerating liquid on a fabricated LED prototype.
► Thermal models setup and comparison between the classical and the new solutions.
► The impact of refrigerating liquid level on LED thermal and luminous performances.
► The relationship between different levels of liquid with LED prototype performances.

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ABSTRACT

The heat management is the critical factor for high performance operation of LED. A new heat management application of refrigerating liquid integrated within a fabricated prototype is proposed and investigated. A series of experiments considering different heights of liquid level were performed to evaluate the heat dissipation performance and optical characteristics of the refrigerating liquid based prototype. The results reveal that the junction temperature decreases as the level of refrigerating liquid increases. The experimental results report that the refrigerating liquid reduces the junction temperature, and can positively influence the luminous radiation performances. An optimization investigation of the proposed solution was carried out to find an optimum thermal performance. The experiments indicated that refrigerating liquid cooling is a powerful way for heat dissipation of high power LEDs, and the fabrication of prototype was feasible and useful.

1. Introduction

In the last years, the energy requirements became more and more important due to the increase of energy demand and reduction of energy sources availability. Hence, the energy efficiency is becoming the main objective in all the industry sectors.

In the lighting area, the power LED represents a technology with high potential, due to their excellent color saturation and long life characteristics. The LEDs guarantee important energy savings with respect to the common light sources. The most common light sources, like incandescent and halogen lamps, are associated with high energy losses and low efficiency. Nowadays, LED plays an important role in many applications. Applications include LCD displays, visual indicators in instruments and computers, interior and exterior automotive lighting including headlights, displays, signals and luminaries.

The heat management (the luminous efficiency and lifetime greatly reduce with increasing junction temperature) is the critical factor for high performance operation of LED. In fact, the lifetime decrease of LEDs with increasing junction temperature is experimentally demonstrated in [1]. Light emission efficiency of LED as a function of thermal conditions is investigated in [2]; the paper discusses how to choose the desired operating temperature, by examining the effect of varying the thermal boundary conditions on the light emission.

Many heat dissipation solutions have been investigated for the thermal management of LED, mainly from package level to system level.

In particular, considering the package level thermal management - which includes thermal material research, package design optimization - the system dynamics for high power LEDs is investigated in [3] and an electric-heat-optical model to predict the junction temperature variations is derived. Chen et. all [4] establishes a compact-thermal model for LED package under different boundary conditions derived based on temperature and heat flow calculated by the detail finite volume model. The finite element method modeling for simulating the LED package with different

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heat slug, PCB, cooling condition and chip size is conducted in [5]. The results are the thermal design rule and correlations for industry new product development.

As to high power LEDs, system level thermal management with external active cooling is necessary and of crucial importance. Currently, fin-heat sink [6] [7], is still the mainstream method in industry due to its highest reliability and lowest cost. Meanwhile, heat pipe [8] is becoming a good option for emerging high power LEDs. Except for that, different advanced cooling technologies are investigated. A microjet array cooling system is proposed in [9–11]. The results demonstrated the advantages of the microjet array as compared to the heat pipe and regular fin-based cooling techniques. Other cooling advanced methods are investigated, like synthetic jets [12] [13], micro-channel cooler [14], electro-hydrodynamic approach [15], thermoelectric cooling [16] and piezoelectric fan [17]. Chen et al. [16] presented a silicon-based thermoelectric (TE) for cooling of high power LED. The test results showed that their TE device could effectively reduce the thermal resistance of the high power LED. Acikalin et al. [17] used piezoelectric fans to cool LEDs. Their results showed that the fans could reduce the heat source temperature by as much as 37.4 °C. An active liquid cooling solution and several configurations of the active liquid cooling system - composed of a pump, cold plates thermally connected to the heat sources (insulated metal substrate board), a liquid reservoir and a heat exchanger - are investigated in [18]. An optimization analysis was carried out to find the optimum thermal performance in the automotive applications. A liquid metal cooling system for heat dissipation of high power LEDs is proposed in [19]. The results demonstrated the cooling advantages of liquid metal as compared to water. Anyway, these strategies often involve complex design process, reliability, cost issues, which are the main obstacles for their commercialization and widespread utilization.

The present paper deals with the thermal management of LEDs. In particular, a new heat management application of refrigerating liquid integrated within a fabricated prototype is proposed and investigated. The proposed solution is first analyzed setting up thermal models and comparing the classical and the new solutions, and successively it is experimentally analyzed both from the thermal performance and light emission efficiency point of view.

2. Junction temperature and power LEDs

The main issue concerning the power LEDs is the heat generated by the junction during LED operation. The increase of junction temperature affects the operating characteristics of the power LED such as [20], [21]:

- Reduction of the luminous flux and of the light efficiency;
- Decrease of the forward voltage;
- Increase of the fundamental wavelength of emitted light;
- Reduction of useful life of the component, thus accelerating its degradation.

In a laboratory test, the amber color is imposed to a power LED supplied with constant current. The increase of junction temperature with 10 °C determines a 5% decrease of the light flux, a reduction of the direct voltage of 20 mV and a translation motion of the fundamental wavelength of 2 nm toward high wavelengths [18]. Considering the reported variations, for the light industry very susceptible to chromatic characteristics of the light and energy efficiency, the correct management of temperature is fundamental. The power LEDs with white light are more susceptible to the junction temperature variation. For example, filtering the radiation of the blue light with specific phosphor layers, the white light is obtained. In case of temperature variation, the fundamental wavelength of this LED could exceed the efficiency range of phosphors. Thus, a large part of light radiation cannot be converted and the color temperature is importantly increasing.

The junction temperature of a LED is affected by the drive current, the LED forward voltage, the method of driving the LED, the thermal path (thermal resistance) from the LED junction to ambient, the power output of LEDs per dissipating surface area, the orientation of LED fixture, the spatial LED configuration, and the ambient temperature. The power dissipation determines how much heat is generated, while thermal resistances and ambient conditions dictate how much heat is efficiently removed. All of the light and heat produced by LED is generated at the *p-n* junction of the device. Since the junction is very small, the heat generation rate per unit area is very large.

The typical configuration of a power LED is shown in Fig. 1. In most cases, power LEDs are mounted on metal-core printed circuit boards (MCPCB). The thin layer of dielectric material (anotherm, for example, uses 0.035 mm of aluminum oxide) is chemically grown on the aluminum core. This guarantees the electrical insulation without influencing the heat transfer. In addition, it allows fixing the plate directly on the heat sink. As alternative, boards PCB or in graphite are used, where heat dissipation channels are built-in correspondence with the component. Hence, every emitter has a circuit that is used as electrical connection and as well as heat exchange interface. The junction is integrated in a protective layer in silica, which in many products is used as the main optics. This one is in directly contact with a small size metal support that quickly and efficacy dissipates the junction heat. In the end, in almost all the light applications, the power LEDs are fixed on a supplementary heat exchanger for a correct thermal management in time.

3. Thermal management

3.1. Unidirectional thermal model for power LEDs

Thermal management is one of the major issues to be improved for implementing LEDs into lighting fixtures because heat affects the performance and reliability of those fixtures and LEDs. The thermal resistance of a LED is an important parameter for analyzing the device performance, indicating the obstruction of the heat flow from the *p-n* junction to the ambient during operation. Therefore, measuring junction temperature is one way to evaluate the performance of a LED.

The one-dimensional heat transfer lumped model of a LED is shown in Fig. 2. The temperatures of each part are defined as single value and disregarding temperature gradient. The different components in the heat conduction path can be modeled as

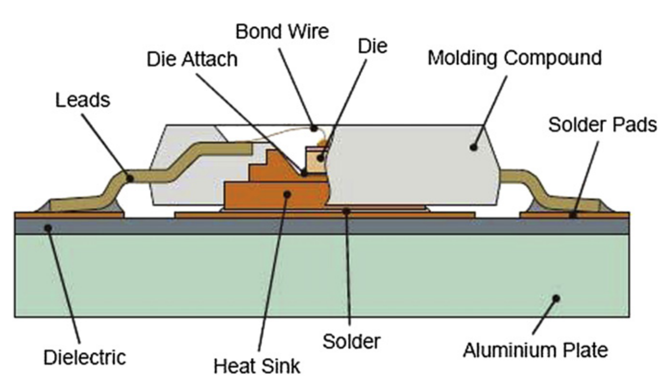

Fig. 1. Typical configuration of a power LED.