Thermal analysis of LED lighting system with different fin heat sinks*

Hou Fengze(侯峰泽)[1], Yang Daoguo(杨道国)[1,†], and Zhang Guoqi(张国旗)[1,2]

[1]School of Mechanical & Electrical Engineering, Guilin University of Electronic Technology, Guilin 541004, China
[2]Philips Lighting, Eindhoven, the Netherlands

Abstract: This paper designs a 3 × 3 light emitting diode (LED) array with a total power of 9 W, presents a thermal analysis of plate fin, in-line and staggered pin fin heat sinks for a high power LED lighting system, and develops a 3D one-fourth finite element (FE) model to predict the system temperature distribution. Three kinds of heat sinks are compared under the same conditions. It is found that LED chip junction temperature is 48.978 ℃ when the fins of heat sink are aligned alternately.

Key words: LED; thermal design; LED array; heat sink
DOI: 10.1088/1674-4926/32/1/014006 **EEACC:** 2520

1. Introduction

Energy crisis, global warming, energy saving and emission reduction have become some of the most concerned topics in the world. As a new generation green solid-state light source, LED has been widely regarded due to its distinctive advantages such as high luminous efficiency, energy saving, long lifetime, and being environment-friendly. It is being developed for solid-state lighting (SSL) for general illumination in commercial and household applications while offering up to 75% savings in electric power consumption over conventional lighting systems[1]. At present, some countries have already carried out LED semiconductor lighting R&D, production, and application such as the "solid-state lighting program" of USA, the "rainbow scheme" of Europe, the "21st century lighting plan" of Japan, and the "GaN semiconductor lighting plan" of South Korea. At the same time, China has launched the "semiconductor lighting major project". Hundreds of semiconductor lighting research institutes, universities, and enterprises have begun to conduct R&D, production and application.

However, there are only 15%–20% of the power transformation of LED to illumination, whereas 80%–85% dissipate heat[2]. Besides, LED is a cold light source. From the chip to the heat sink, most of the heats are transferred by conduction, and are dissipated to the ambient by convection. When LED works continuously, it will generate a lot of heat. If heat is not carried off and dissipated in time, the operational lifetime and reliability of the high power LED may be significantly reduced[3]. Therefore, effective thermal management and optimization design are very important.

When designing an LED lighting system, in order to control chip junction temperature better, good thermal design mainly considers two factors: internal packaging and external heat sink structure. It can improve the capability of heat conduction from the chip to the heat sink by optimizing the internal packaging structure of LED device. Meanwhile, it can improve the capability of heat dissipation from the heat sink to the ambient by optimizing the heat sink structure.

In order to satisfy the requirement of daily lighting, luminous flux of LED lighting system must reach more than 1000 lumen levels at acceptable cost while maintaining reliability[4]. The paper designs a 3 × 3 high power LED array with the total power of 9 W, which satisfies the requirement of daily lighting. However, thermal characterization of LEDs in an array is very different from that of a single LED.

The junction temperature of LED array will be significantly influenced by ambient temperature and side effect from multiple chips[5]. Because LED device is small, and its internal structure is very complicated, so it is difficult to accurately measure the internal temperature distribution by experimental method. However, it can predict internal temperature distribution by finite element analysis.

This paper presents the thermal analysis of plate fin, in-line and staggered pin fin heat sinks for a high power LED lighting system, and 3D one-fourth FE model is developed to predict the system temperature distribution. Thermal behaviors of them are compared under the same condition, and the optimal fin heat sink is obtained.

2. Modeling and simulation

2.1. Parametric modeling

LED lighting system modeling is created by ANSYS parametric design language (APDL). This system mainly consists of high power LED array, solder, metal core printed circuit board (MCPCB), thermal interface material (TIM), and heat sink, etc. The material parameters of the lighting system are shown in Table 1. The LED array is composed of 9 high power LEDs and mounted on 38 × 38 mm MCPCB with a 12.5 mm pitch. In order to improve the capability of heat dissipation, heat sink is installed under the MCPCB by TIM. In general, a high power LED is mainly consists of epoxy lens, silicone encapsulant, chip, bond wire, slug, reflector and substrate, etc. Because epoxy lens, silicone encapsulant, and reflector have low thermal conductivity, so heat is generated and dissipated

---

* Project supported by the National Natural Science Foundation of China (No. 60666002).
† Corresponding author. Email: daoguo.yang@gmail.com
Received 20 September 2010

Table 1. Material parameters of the lighting system.

Material	Thermal conductivity [W/(m·K)]
Lens	0.2
Chip (SiC)	350
Slug (Cu)	398
Substrate (Ceramic)	36
Solder (SnAgCu)	73
MCPCB	150
TIM	1.1
Heat sink (Al)	216

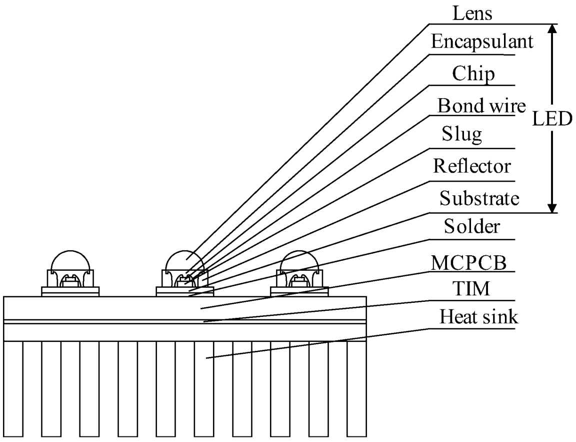

Fig. 1. Schematic structure of the lighting system.

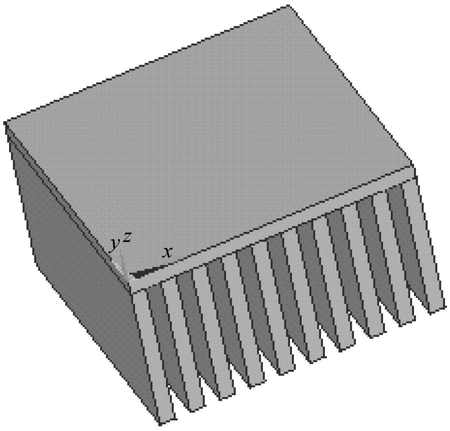

Fig. 2. Plant fin heat sink.

from the chip. It transfers through slug and ceramic substrate into solder layer, passes through MCPCB and TIM till heat sink is carried out. Finally heat is dissipated to the ambient by convection. The schematic structure of the lighting system is shown in Fig. 1.

The paper designs three kinds of fin heat sink. In the plate fin heat sink, the size of the pins and the base, and the pitch is: fin 2 × 20 × 20 mm, base 38 × 38 × 2 mm, and pitch 4 mm. The plate fin heat sink is shown in Fig. 2. The only difference between pin fin heat sink is the topology of pin fin placement: in-line and staggered. The size of the pins and the base, and the pitch is identical: pin 2 × 2 × 2 mm, base 38 × 38 × 2 mm, and pitch 4 mm. In the staggered heat sink, the pin rows are aligned alternately. The inline and staggered pin fin heat sinks are shown in Figs. 3 and 4, respectively.

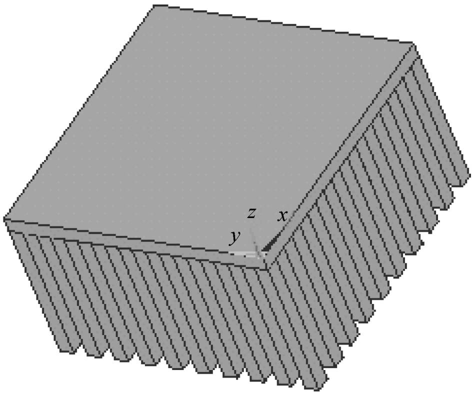

Fig. 3. In-line pin fin heat sink.

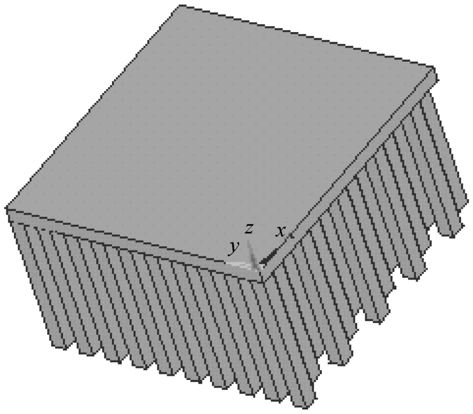

Fig. 4. Staggered pin fin heat sink.

2.2. Simulation

The heat conduction equation with heat generation, shown in Eq. (1), is used to obtain the temperature distribution when the LED works:

$$\frac{\rho C}{K}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}, \tag{1}$$

where ρ is the density, C the specific heat, K the thermal conductivity, t the time, T the temperature, and x, y and z the spatial coordinates[6].

The symmetry of the boundary condition and the geometry of the whole model allow only one-fourth of the FE model to be analyzed. For the boundary condition, it is assumed that the ambient temperature is 25 ℃. Meanwhile, the convective heat transfer coefficient is assumed to be 10 W/(m^2·K). The size of the LED chip is 0.9 × 0.9 × 0.2 mm, because about 80% of the supply power is converted to heat dissipation, whereas only 20% of the supply power transformation to illumination, so heat generation applied to the chip is:

$$q=\frac{P_\mathrm{D}}{V}=\frac{1\times 80\%\times 10^9}{0.9\times 0.9\times 0.2}=4.94\times 10^9\ \mathrm{W/m^3}, \tag{2}$$

where q is the heat generation, P_D the power dissipated by the LED, and V the volumes of the LED chip.

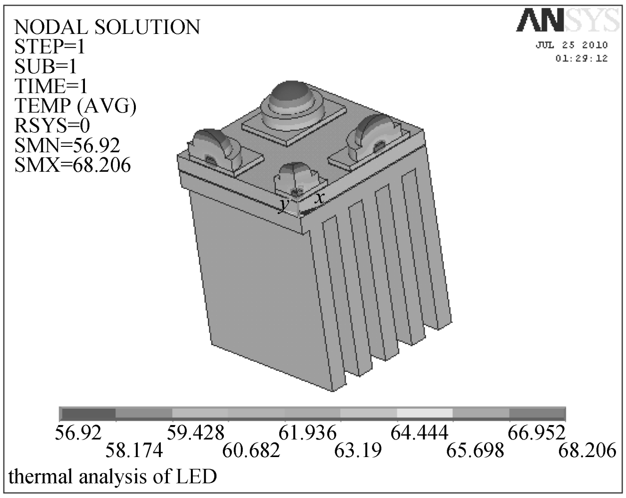

Fig. 5. Temperature distribution of plate fin heat sink.

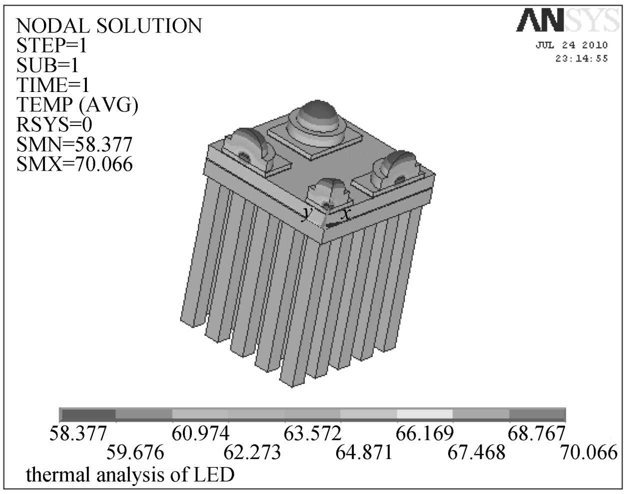

Fig. 6. Temperature distribution of in-line pin fin heat sink.

The whole model is meshed using the free mesh method. Temperature distribution of plate fin, in-line and staggered pin fin heat sinks are shown in Figs. 5–7, respectively. The maximum temperature of the array system occurs in LED chip junction. From Figs. 5–7, it is found that LED chip junction temperature is 68.204, 70.66, and 48.978 ℃, respectively, which all meet the requirement that the chip junction temperature must be below 120 ℃ when it works normally. It is critical to maintain a junction temperature below 120 ℃ during operation in order to obtain better performance with a longer life of high power LED. Perfect packaging for high power LED should be able to not only handle high electric power input, but also succeed in efficient thermal dissipation[7]. When pin fins of heat sink are aligned alternately, LED chip junction temperature is lowest, and the capability of heat dissipation is best.

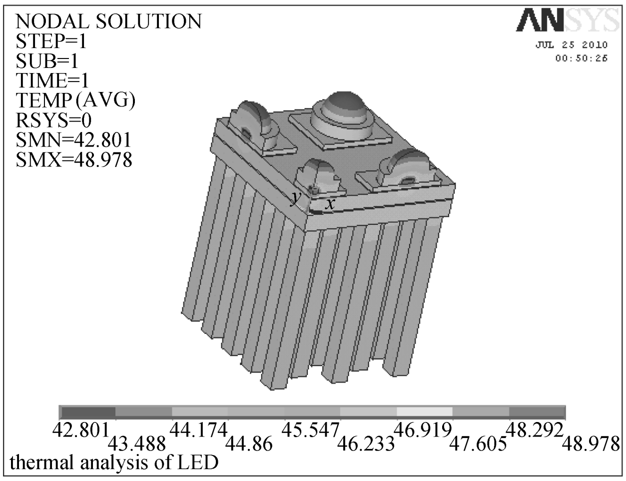

Fig. 7. Temperature distribution of staggered pin fin heat sink.

3. Conclusion

The paper designs a 3 × 3 LED array with the total power of 9 W, and presents the thermal analysis of plate fin, staggered and in-line pin fin heat sinks for a high power LED lighting system. A 3D one-fourth finite element model is developed to predict the system temperature distribution. Three kinds of heat sinks are compared under the same condition. It is found that LED chip junction temperature is 48.978 ℃ when the fins of heat sink are aligned alternately.

References

[1] Vetrovec J, Litt A. High-performance heat sink for solid-state lighting. Proc SPIE, Vol. 7231, 2009

[2] Weng C J. Advanced thermal enhancement and management of LED packages. International Communications in Heat and Mass Transfer, 2009: 245

[3] Gao S, Hong J. Design optimization on the heat transfer and mechanical reliability of high brightness light emitting diodes (HBLED) package. Electronic Components and Technology Conference, 2008: 798

[4] Yu Xingang, Liang Xingang. Temperatures and thermal stresses in high-power light emitting diodes. Journal of Tsinghua University (Sci & Tech), 2007, 47(8): 30

[5] Kim L, Choi J H, Jang S H. Thermal analysis of LED array system with heat pipe. Thermochimica Acta, 2007: 21

[6] Luo X B, Yang J H, Liu S. Effect of temperature and moisture on LED reliability and its mechanism analysis. Semicond Optoelectron, 2009, 30(3): 368

[7] Tan L X, Li J, Wang K, et al. Effects of defects on the thermal and optical performance of high-brightness light-emitting diodes. IEEE Trans Electron Packag Manuf, 2009, 32(4): 233