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Heat dissipation design and analysis of high power LED array using the finite element method

Hui Huang Cheng [a], De-Shau Huang [b], Ming-Tzer Lin [a,*]

[a] *Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung 402, Taiwan, ROC*
[b] *Graduate School of Vehicle & Mechatronic Industry, Nan-Kai University of Technology, Nantou 542, Taiwan, ROC*

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ABSTRACT

High-power Light Emitting Diode (LED) technology has developed rapidly in recent years from illumination to display applications. However, the rate of heat generation increases with the LED illumination intensity. The LED chip temperature has an inverse proportion with the LED lifetime. High-power LED arrays with good thermal management can have improved lifetime. Therefore, for better optical quality and longer LED lifetime it is important to solve the LED thermal problems of all components. In particular, Metal Core Printed Circuit Board (MCPCB) substrate heat sink design and thermal interface materials are key issues for thermal management. This paper presents an integrated multi-fin heat sink design with a fan on MCPCB substrate for a high-power LED array using the finite element method (FEM). The multi-fin heat sink design and simulation results provide useful information for LED heat dissipation and chip temperature estimation.

1. Introduction

Due to the recent low carbon dioxide emission requirement and energy saving movement, high-power Light Emitting Diode (LED) technology has developed rapidly in the last 10 years. Recently, the Light Emitting Diode (LED) has become widely used in modern flat-panel displays. The new LED backlighting technology creates more vibrant colors and sharper images for users, especially in high-power LED backlighting. The LED power increases with illumination intensity, which affects both the optical quality and LED lifetime. About 20% of the energy is used for light emitting, with the rest is dissipated in the form of heat. If the heat cannot be dissipated quickly from the PN chip, the LED illumination intensity and lifetime will be reduced. In general applications the LED illumination system must maintain 1200–1500 lumen levels while maintaining reliability [6]. It is essential to solve the heat dissipated from the LED and reduce the PN chip junction temperature. In the previous literature on LED lighting [2], it was found that a 1 mm^2 LED dissipated 1 W, corresponding to 100 W/cm^2 of heat flux. This is twice the amount of heat flux generated in a conventional micro-processor chip. Therefore, a huge amount of heat is generated inside the conventional LED flat-panel display as they use LED arrays for the lighting source. In the LED layout, a good design for heat dissipation will increase the device lifetime. As a result, efficient design for LED array thermal management applied to LED flat-panel displays has become significant.

Various studies on thermal management of micro-electronics and LED devices had performed. In early 1981, a proposed micro-channel heat sink was first used for cooling a large-scale integrated circuit [8]. Later a micro channel with diamond-shaped interrupted micro-grooved cooling fins was used to enhance the performance and reduce the LED chip junction temperature [4]. Recently research has suggested that silicon based micro channel coolers with staggered fins have better heat dissipation than continuous fin designs with equivalent geometries [1]. In their study on LED thermal management, Su et al. [7] found that the heat dissipation area on the LED substrate is dominated by the chip temperature and heat dissipation flux. In another recent study, the transient heat measurement results on the heat pipe cooling Metal Core Printed Circuit Board (MCPCB) with a 6-LED array was used to calculate the thermal resistance [3]. They found that the LED array thermal resistance was reduced drastically when cooled with a heat pipe. Heat pipe dissipation efficiency was studied by [5]. It was found that about 44–75% of the heat was dissipated in the heat pipe center section. As LED power increased, the heat pipe circulation could stop and a dry-out phenomenon might occur. Therefore, the amount of heat dissipated would be restricted.

In a small LED space enclosure, such as LED back light arrays, a conventional method to remove heat from the substrate involves passive heat transfer, such as free convection. However the amount of heat dissipated is limited. For the high-power LED array, multi-fins attached to the substrate can be used to improve heat dissipation. Adding a fan to increase the heat transfer coefficient can be an

* Corresponding author.
E-mail address: mingtlin@nchu.edu.tw (M.-T. Lin).

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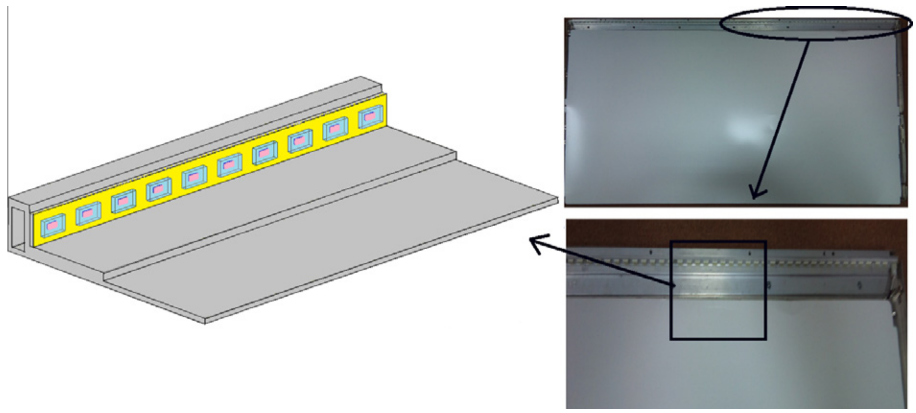

Fig. 1. The LED array stage configuration.

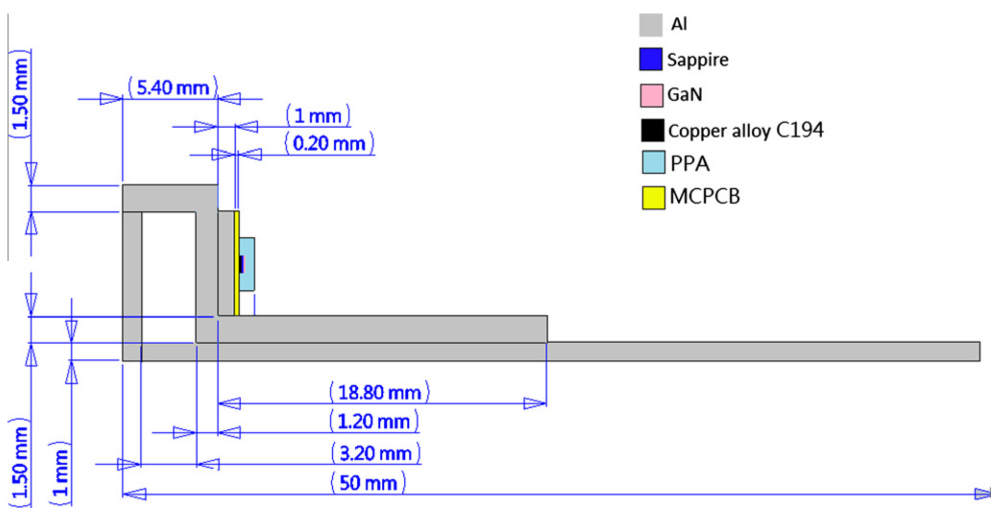

Fig. 2. The LED array stage dimensions.

alternative. High-power LED array heat dissipation using multiple fins is studied in this research using a three-dimensional finite element simulation with ANSYS 11. The objective is to explore fin geometry design and different heat transfer coefficients to reduce the LED junction temperature on a Metal Core Printed Circuit Board (MCPCB) applied to LED flat panel displays.

2. Analysis

The conventional LED flat panel display consists of an 80-LED chip array in line used for the bottom lighting. Because there are 8 sets of 10-LED arrays and the LED array arrangement is symmetrical, shown in Fig. 1, the thermal behavior study can be simplified into a 10-LED in line array. We conducted a model to simulate the temperature distribution of a high-power LED array applied to a LED flat panel display, shown in Fig. 2. The LED chip (GaN) is on a 0.25 mm thick sapphire (Al_2O_3). The Al_2O_3 is attached to a copper alloy C194 covered by transparent Polyphthalamide (PPA). Copper alloy C194, MCPCB and aluminum (Al) are used under the LED base assembly as a heat sink. The material properties of the LED chip and heat sink are listed in Table 1. Here, we study different heat dissipation methods and compare their results. In Fig. 2 a longitudinal rectangular cross section channel design is used for the LED array heat sink. We designed multi-fins attached to the rectangular channel to study the heat dissipation efficiency, as shown in Fig. 3.

Heat is dissipated from the LED substrate and heat sink. The steady-state heat transfer governing equation is written as

Table 1
Conductivities of materials.

Material	Conductivity k (W/m K)
Sapphire	40
GaN	130
Copper alloy C194	260
PPA	0.3
Al	237
MCPCB	2

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+Q=0 \quad \text{in R} \tag{1}$$

where T and Q represent the temperature and heat source from a chip, and k_x, k_y, k_z are the thermal conductivities of the material in the x, y, and z directions. The region R at the x and y directional boundaries is subjected to convection heat transfer in the ambient environment as follows

$$q_x|_{at\ wall}=h\cdot(T_s-T_\infty),\ q_y|_{at\ wall}=h\cdot(T_s-T_\infty) \tag{2}$$

In the surrounding area, in (2) h is the convection heat transfer coefficient, T_s for the surface temperature, and T_∞ for the surrounding temperature. In the z direction, since the LED array arrangement is symmetrical, it has insulated boundary conditions as

$$\left.\frac{dT}{dz}\right|_{z=wall.}=0 \tag{3}$$

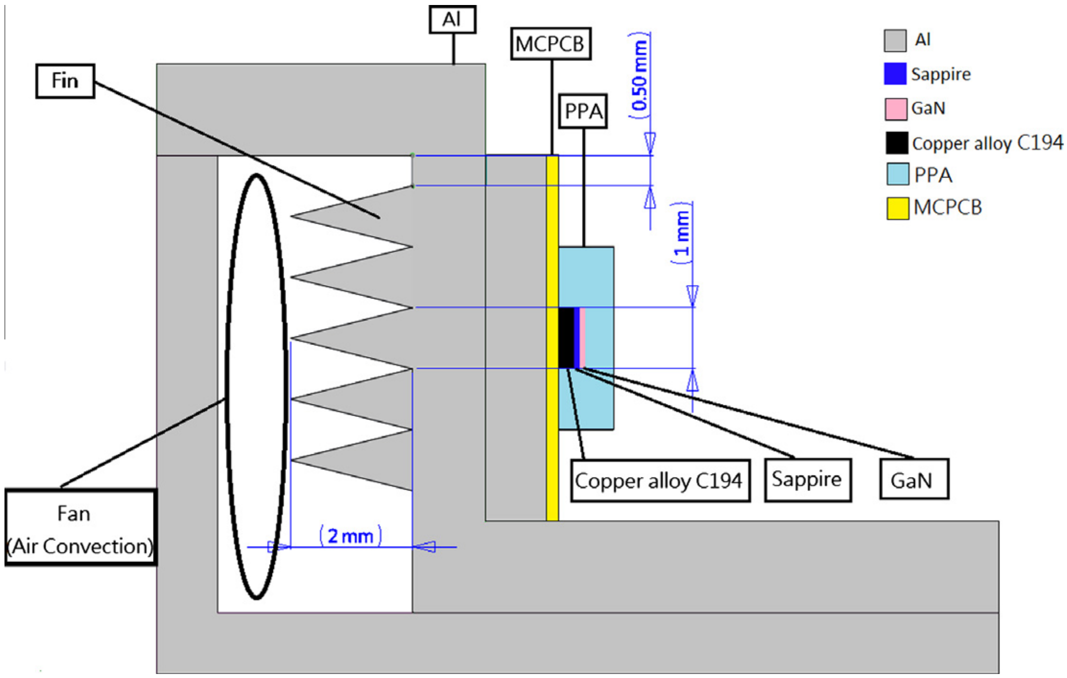

Fig. 3. The heat sink with fins profile dimension.

The LED array stage geometric configuration was meshed using hexahedral elements for computation. A total number of 323,371 elements are meshed for simulation. The mesh size independent analyses were performed prior to the simulation. Free convection occurs at the boundary, in which the surrounding temperature is 25 °C. Heat is generated from the P–N junction and dissipated through the heat sink. We assumed that 80% of the heat flux energy is transferred from the LED chip junction and sapphire substrate.

A finite element method using the Galerkin approach with hexahedral elements for the heat transfer governing equation

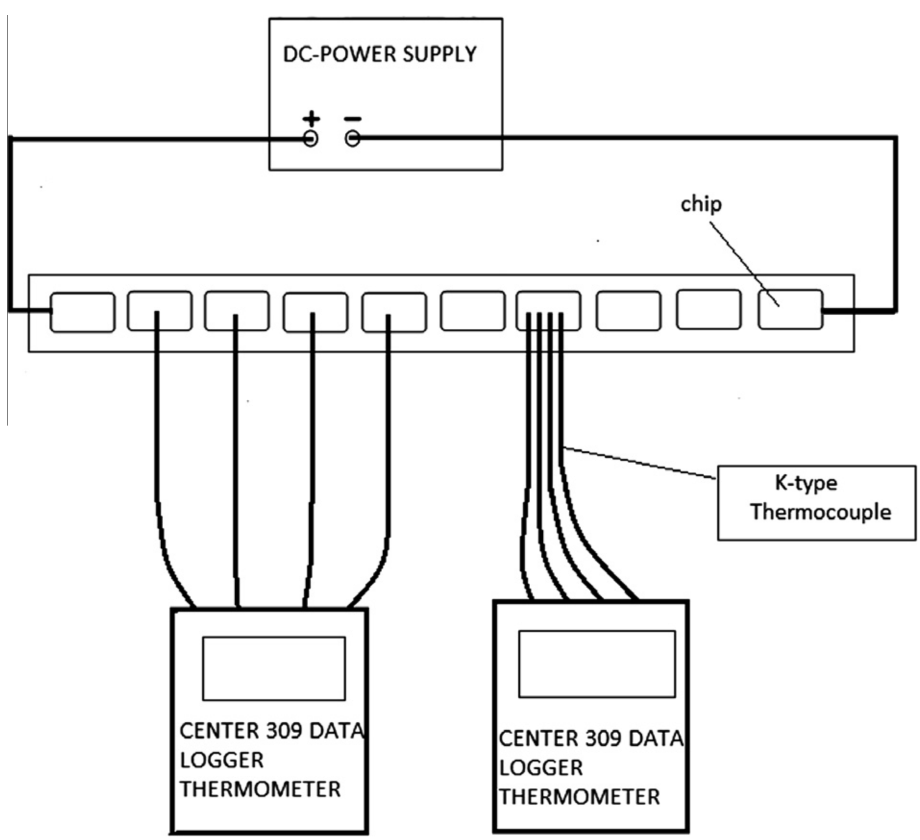

Fig. 4. The experimental measurement setup.

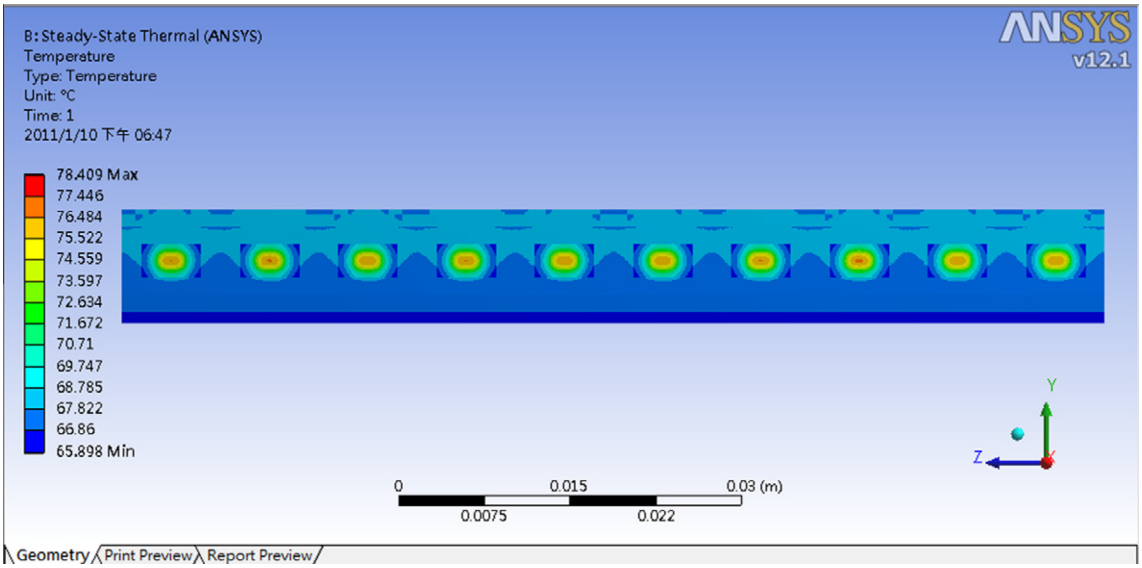

Fig. 5. The LED array stage temperature distribution for 0.54 W.

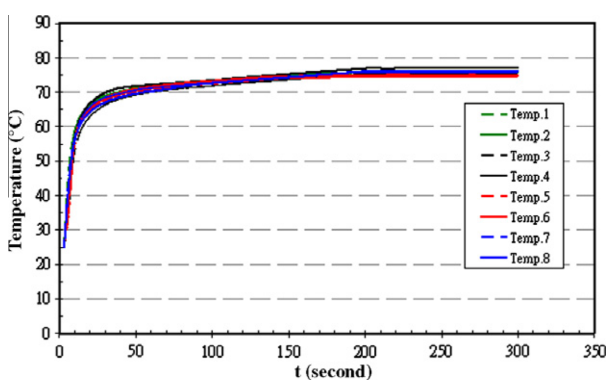

Fig. 6. The LED surface temperatures obtained from experimental measurement.

was then applied using ANSYS 11. Experiments were conducted to measure the LED surface temperature on 0.54 W LED arrays to compare those results with the simulation results. The experimental measurement setup is shown in Fig. 4. Eight K-type thermocouples were attached at the chip surface. The temperatures were acquired using a Center 309 data logger thermometer as the steady-state condition was reached after 5 min. The electrical power was regulated using a DC voltage meter. The LED array power was calculated using the following equation.

$$P = I \cdot V \tag{4}$$

3. Results and discussion

In LED back lighting applications free active heat convection is a major method for heat dissipation. However, the efficiency is limited, which results in LED lifetime reduction. To solve this problem increasing the convective areas, such as adding fins, is one of the solutions. The passive type of force convection, for example fan installation in the back lighting panel, may be one of the most

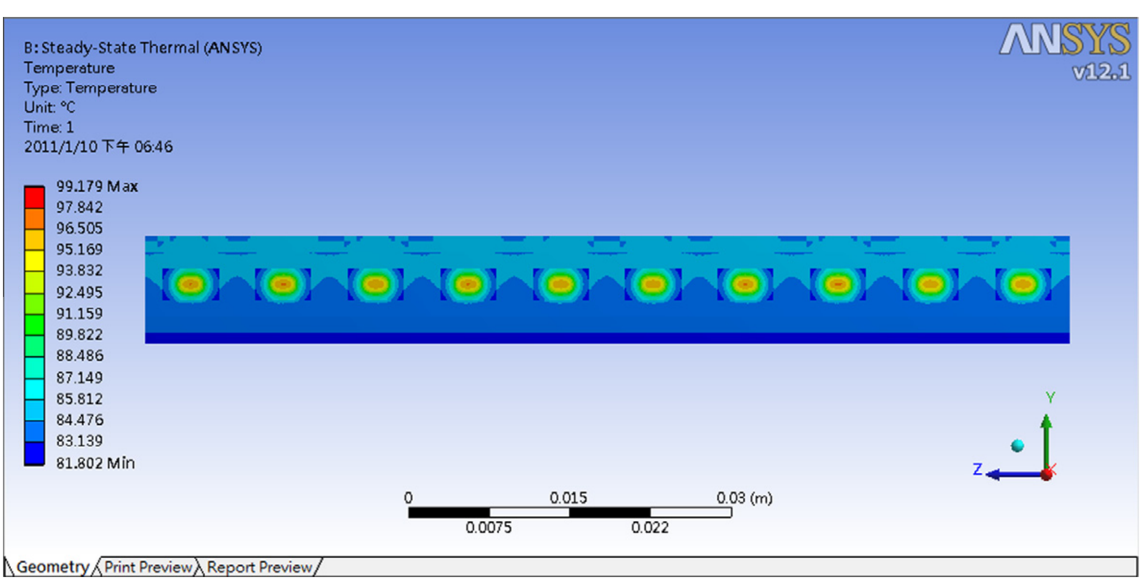

Fig. 7. The LED array stage temperature distribution for 0.75 W.

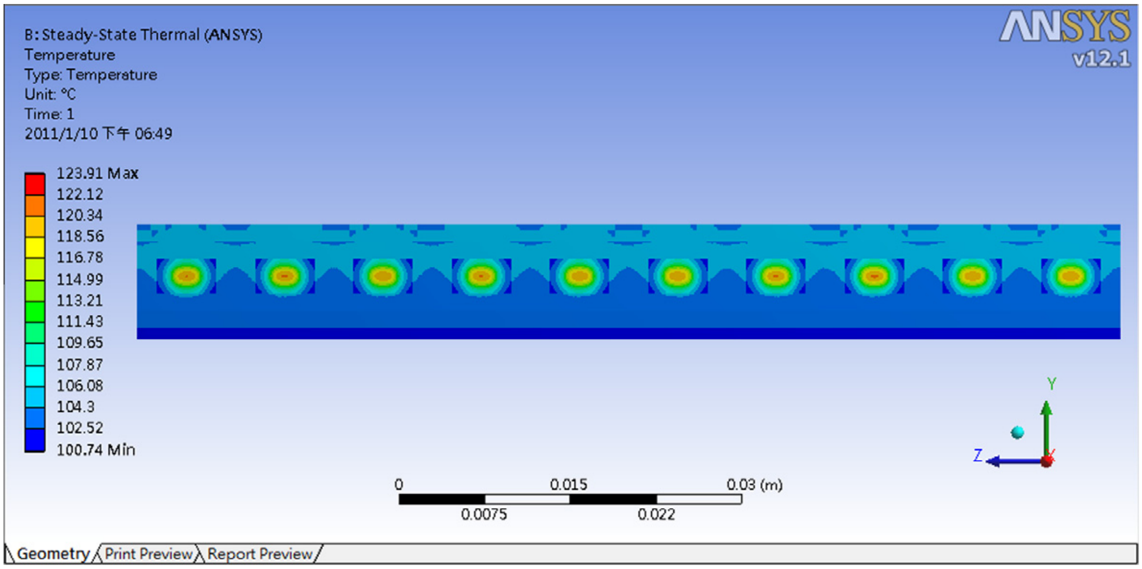

Fig. 8. The LED array stage temperature distribution for 1 W.

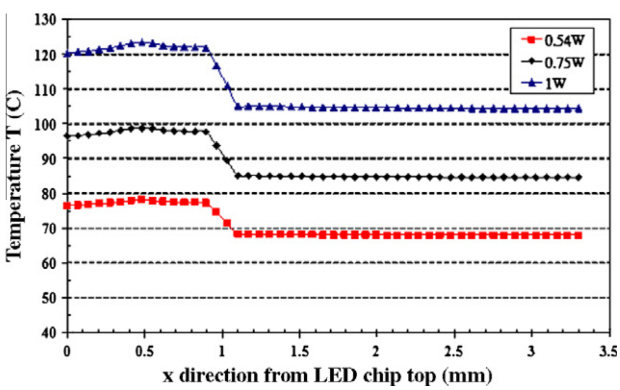

Fig. 9. The LED chip temperature change along the longitudinal direction.

efficient methods. The following study results support the back lighting equipped with fan design.

3.1. Simulation results without fins

We first compare the simulation results for the original design, shown in Fig. 2. This design used a longitudinal rectangular channel without fins with free convection, 8.4 W/m^2 C, as the LED array heat sink. Fig. 5 shows the simulation result for 0.54 W LED array stage temperature distribution. The temperature was higher at the peripheral LED chips than the rest of the area. For this experiment the surface temperature of the 0.54 W LED array was measured. Fig. 6 shows the surface temperatures of different LED positions for the 0.54 W LED array in 5 min. The result demonstrated that the LED surface temperatures were between 75.0 °C and 76.1 °C. Compared with the simulation results, the LED surface temperatures were from 75.5 °C to 76.5 °C. Both results were in agreement.

Figs. 7 and 8 show the simulation temperature distribution for 0.75 W and 1 W LED array stage. The maximum temperature reached 99.18 °C and 123.91 °C for 0.75 W and 1 W respectively.

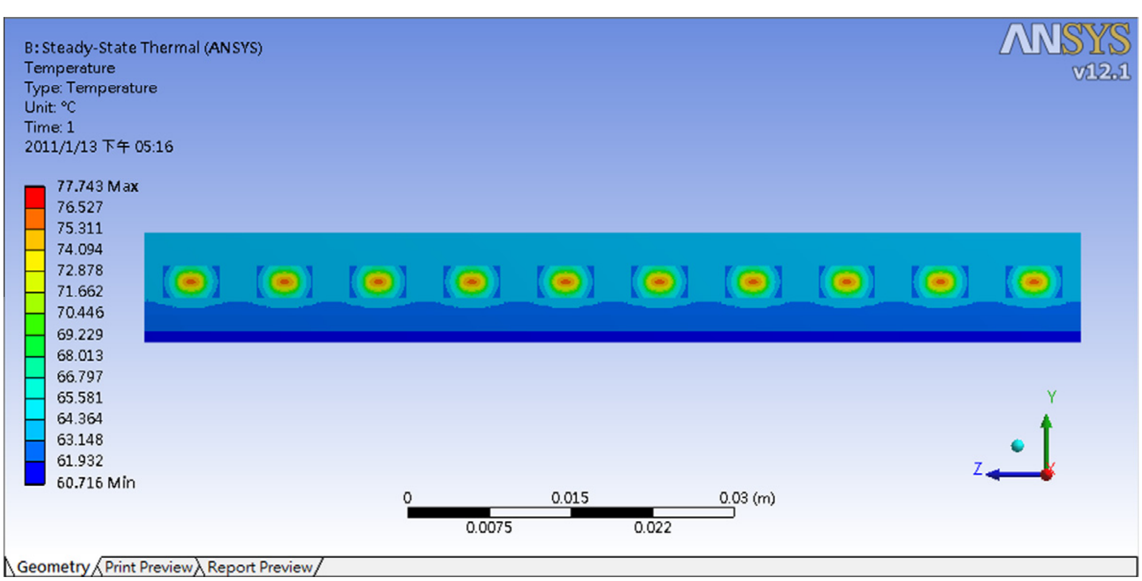

Fig. 10. The LED array stage with fins temperature distribution for 0. 54 W.

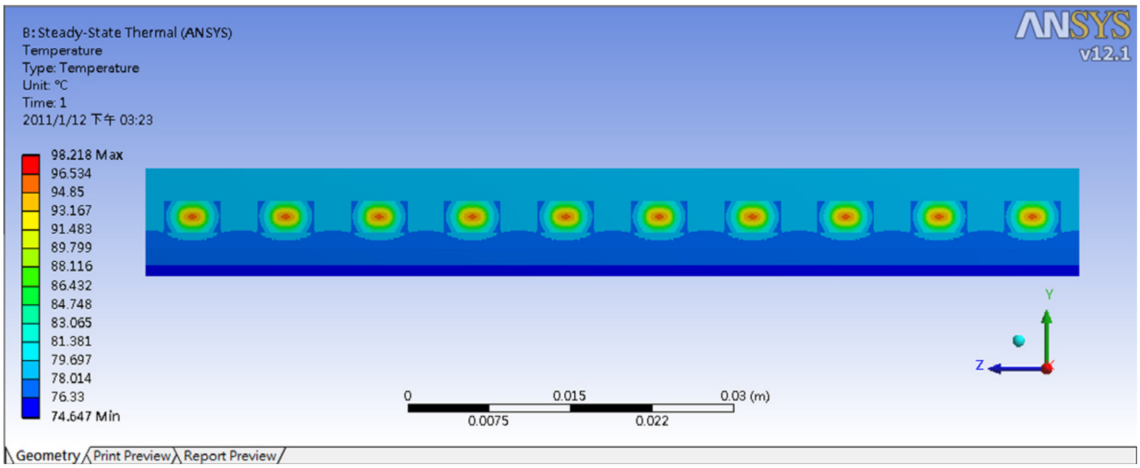

Fig. 11. The LED array stage with fins temperature distribution for 0.75 W.

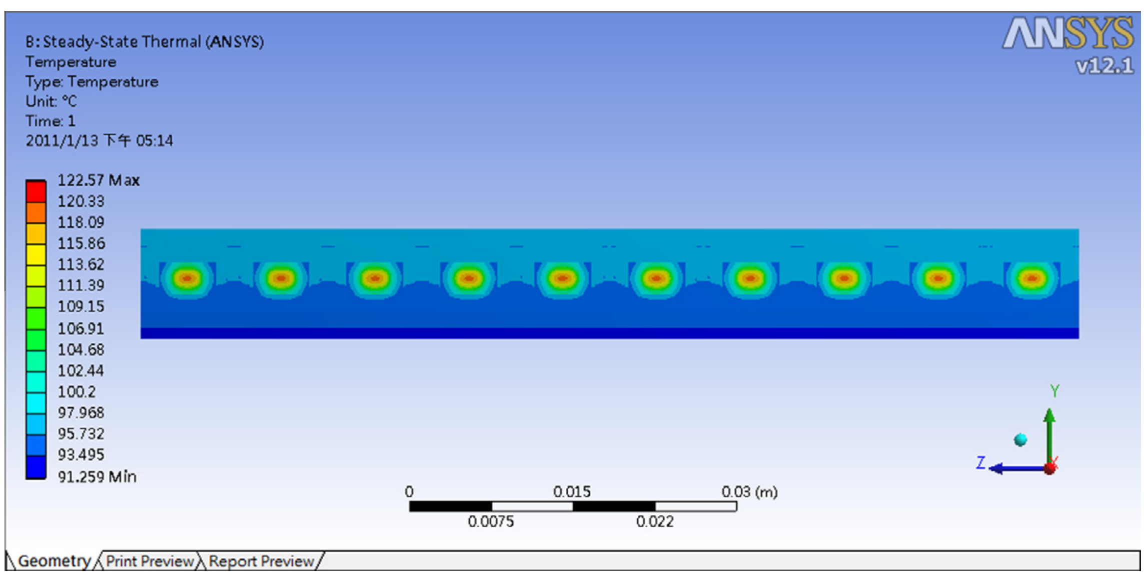

Fig. 12. The LED array stage with fins temperature distribution for 1 W.

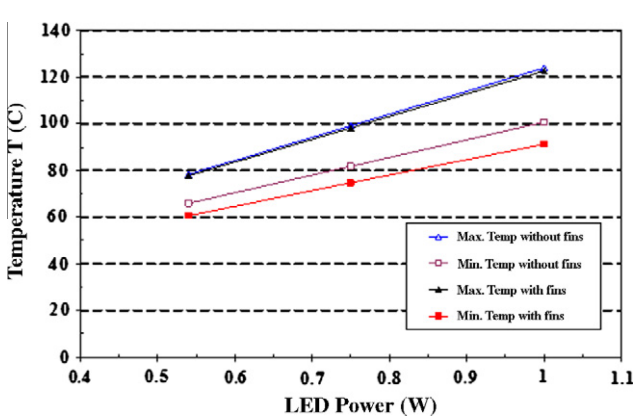

Fig. 13. The fin effect temperature comparison.

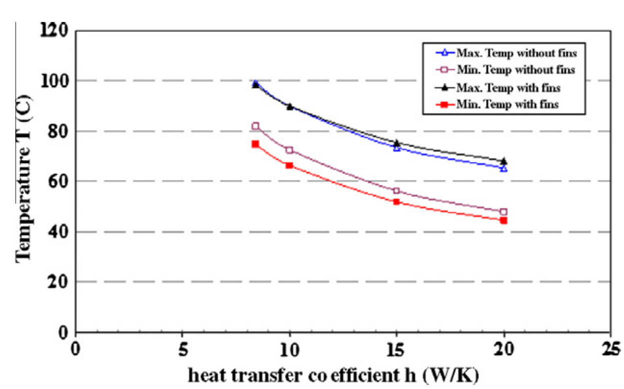

Fig. 14. The wall heat temperature distribution.

It was found that the junction temperature increased with LED power. For 1 W LED, the junction temperature reached 123.91 °C, which influences the light intensity and LED lifetime significantly.

Fig. 9 shows the temperature on the top of LED along the longitudinal direction. From this figure there is a larger slope between 0.6 to 1 mm on the LED. This means that the packaging materials attached to the LED possess a large thermal resistance around 0.6–1 mm at the LED top. From the physical model, low thermal

Table 2
The maximum temperature for different design.

Different designs	Max. Temp. (°C)		
	0.54 (W)	0.75 (W)	1 (W)
Without fin and fan (free convection, $h = 8.4\ W/m^2C$)	78.41	99.18	123.91
Without fin and with fan ($h = 10\ W/m^2C$)	71.67	89.82	111.43
Without fin and with fan ($h = 15\ W/m^2C$)	59.88	73.45	89.59
Without fin and with fan ($h = 20\ W/m^2C$)	53.98	65.25	78.67
With fin but no fan (free convection $h = 8.4\ W/m^2C$)	77.74	98.22	122.57
With fins and fan ($h = 10\ W/m^2C$)	71.76	89.91	111.50
With fins and fan ($h = 15$)	61.27	75.35	92.10
With fins and fan ($h = 20$)	56.01	68.05	82.38

conductivities exist at the sapphire and MCPCB, which causes the heat to not dissipate well from the chip. Increasing the material thermal conductivity attached to the chip is a key factor to improving LED heat dissipation.

3.2. Simulation results with fins

Figs. 10–12 show the LED array stage temperature distribution with 5-fins attached to the rectangle channel in the longitudinal direction as the heat sink using free convection. The simulation results illustrated that the maximum temperatures were 77.73 °C, 98.22 °C, and 122.57 °C for 0.54 W, 0.75 W, and 1 W, respectively. Fig. 13 shows the maximum and minimum temperature on LED array compared with and without fins. Note that we simulated the LED array thermal behavior based on free convection boundary conditions for both cases. It seems that the maximum temperatures are not obviously different. However, the minimum temperatures around the LED array stage edge are improved. For a 0.75 W LED array with fins, the maximum temperature is 1 °C lower than that without fins, but the minimum temperature can be 7.2 °C lower than that without fins.

3.3. LED array with fins for different convective heat transfer coefficients

Instead of free convection cases, a small fan with various rotation speeds is designed at the force convection on the side wall of the channel to increase the convective heat transfer coefficient. Based on this design, the different heat transfer coefficients, which mean different fan rotation speeds, were studied using FEM. Fig. 14 shows the maximum and minimum temperatures of 0.75 W LED array stage with and without fins corresponding to different convective heat transfer coefficients. The results demonstrated that the temperature was decreased with the increase in convective coefficient. From the simulation results, it was found that LED array stage with fan heat dissipation was dramatically improved. Comparing the heat transfer coefficients, 8.4 and 15 W/m^2C, the maximum temperature was reduced to 73.45 °C from 99.18 °C. The results demonstrated that the fan caused force convection in the duct channel which contributed to heat dissipation.

For the different heat dissipation situations and back lighting designs, the maximum LED temperatures are shown in Table 2. With a fan design the maximum temperature can be reduced at least 10 °C depending on the fan revolution speed. For a multi-fin design only 1–2 °C temperature decrease occurred.

4. Conclusions

For heat dissipation improvement in a 10-LED array stage with an enclosed channel, a longitudinal multi-fin heat sink with different heat transfer coefficients was studied in this paper. Our conclusions are summarized as follows:

1. FEM can be used to analyze LED array heat dissipation. From the simulation results there is a larger thermal resistance on top of the LED MCPCB. For a 1 W LED array stage the junction temperature of LED chip reaches 123.91 °C, which will reduce the LED efficiency.
2. For a LED array stage with a longitudinal multi-fin design in an enclosed air channel as a heat sink without force convection, the heat dissipation improvement is limited. Only the heat dissipated with a fan enhances that with multi-fins.
3. Using a fan at the side wall of the heat sink channel to increase the convective heat transfer coefficient is an effective method to reduce the LED chip junction temperature.

In summary, a back lighting panel equipped with a fan contributed to increasing LED lifetime. The results from this study can provide the LED industry with improved heat dissipation designs.

Acknowledgment

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