THERMAL DESIGN OF LED BY DOE

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ABSTRACT

The article analyses the influence of the design parameters of the structure of the heat sink with round pins on the junction temperature of the LED system. The study uses design of experiment (DOE) and thermal simulations to determine the factors that have the greatest impact to improve the cooling capacity and finding the optimal heat sink design. The results of thermal design and simulation of the LED system have been validated experimentally using a thermocouple and they show that the error between the experimentally measured and simulated temperature value of optimized heat sink structure is below 6%.

KEYWORDS

Thermal design, Design of experiment, Heat sink design, Thermal simulation, LED application

1. INTRODUCTION

The LED technology is developing rapidly and more powerful LED devices placed in smaller packaging appear on the market, which must effectively dissipate large amounts of heat. [1] Heat negatively affects the performance and is a prerequisite for the emergence of failure, so proper thermal management is essential for the design of each LED device or system [2].

Management of heat transfer in powerful LED systems in most existing studies focus on heat dissipation through MCPCB (Metal Core Printed Circuit Board) and IMS (Insulated Metal Substrate) to improve the heat transfer in the design [2], [3], [4].

Usually powerful LED systems use heat sinks of different materials and different sizes for better heat dissipation. The effectiveness of the heat sink, however, does not depend only on the dimensions and the material from which it is made, and is largely determined by its structure. Different design requirements are placed to meet the operating conditions and installation of each LED application, which requires the development of customized solutions for cooling design of the final product.

The problems associated with the design of heat sinks are discussed by many researchers. H. Fengze and Y. Daoguo and others in [5] studied the thermal behaviour of designed by them LED array and a heat sink with flat fins and pin type fins. Using a 3D model in ANSYS the temperature distribution of a LED system is simulated, taking into account the impact of the heat sink construction. Analyses show that the junction temperature of LEDs in the array is the lowest when the structure of the heat sink has pin type fins and are arranged so that the fins alternate every other. P. Huang, Kailin Pan and others in [6] apply thermal modelling and simulations to optimize the entire design of multi-chip LED lighting module. To optimize the LED structure are

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used statistical analysis and thermal simulations by ANSYS software to evaluate the factors influencing the productivity - output of chips, layout of chips, the size of MCPCB and heat sink.
T. Kobayashi, S. Ishikawa, R. Hashimoto and others in [7] study the thermal effects of a heat sink with a round base and flat fins designed for LED bulb. In the analysis of heat transfer they use FEM (Finite Element Method) and are in the model are included thermal convection and radiation. By applying the design of experiments (DOE) there are determined the parameters of the heat sink, affecting the temperature of the heat sink and the best and worst construction is evaluated. Results from the simulation model of the heat sink are validated by measurements with thermocouples and thermal camera.

A. Mahalle and M. Shende in [8] numerically analyse the heat flow of a star heat sink with a round base and flat fins in natural convection. Research is done in three geometric parameters of the heat sink for finding the optimal structure. The effects of changing the geometric dimensions and the effects of heat flow on the heat resistance and the coefficient of heat exchange are analyzed. The results show that with an increase in the geometric dimensions of the heat sink, the heat resistance and the coefficient of heat transfer are usually reduced.

Although there are studies that examine different structures of the heat sinks, there are still enough challenges in their design. A good heat sink must maintain low junction temperature of the LED devices at different operating conditions; it must be compact and with an easy installation.

This article presents a study of a passive heat sink for a powerful LED module. For optimization of the geometric dimensions of the heat sink, a design of experiments is used. To assess the thermal efficiency of the optimized structure the temperature of junction of the LED source is monitored.

2. HEAT SINK DESIGN METHODOLOGY

2.1. Choice of structure

The basic structure of the heat sink has a square horizontal base and circular pin type fins arranged in line. This type of construction offers a minimum resistance and high efficiency [9] and allows more flexible installation and use. As a heat sink material aluminium alloy is used, because of its low price, good thermal conductivity and a heat sink with enough complex geometric shape can be easily molded. The structure of the heat sink and the geometry of the fins are shown in Fig. 1.

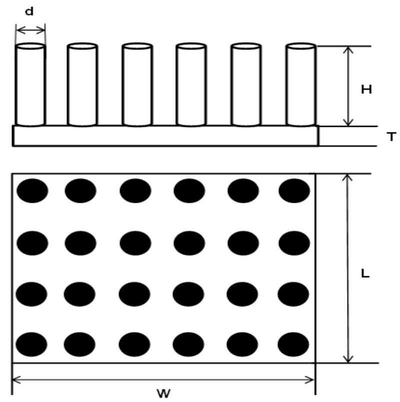

Fig. 1. Heat sink construction

2.2. Thermal modelling

For the design and testing of the thermal behaviour of the heat sink structure CFD software Flotherm is used. Fig. 2 shows the heat-modelled structure of the heat sink fitted with LED module, situated in the centre, which thermal power to be dissipated.

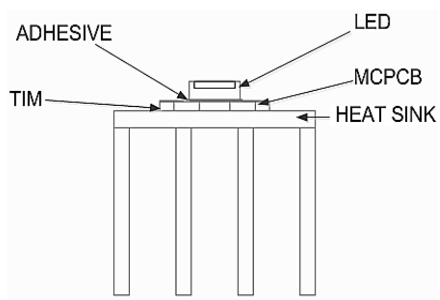

Fig. 2. Heat modeled LED system construction

The maximum heat power set at the thermal modeling of LED (at maximum operating voltage U_f = 4.1V, maximum current I_f = 700mA and conversion of electrical energy into heat H = 75%) is calculated by the formula [8]:

$$P_{th} = U_f I_f H = 4{,}1V \cdot 0{,}7A \cdot 0{,}75 \approx 2{,}15W \qquad (1)$$

Table 1 shows the physical characteristics of the materials constituting the LED system.

Table 1. Physical characteristic of the materials

Material	Conductivity [W/m·K]
Heat Sink – Aluminum 6061	180
GaN Chip	130
SnAgCu Solder	58
FR4 – Dielectric Layer	0.2
Top Layer Copper	385
MCPCB – Aluminum Plate	150
TIM – Silver grease	3

When creating a geometric model of the different variants of heat sink, the length *L*, width *W* and the thickness of the base of the heat sink *T* do not change with thermal modeling and simulations, because of the specific requirements of LED application.

The heat sink is modeled with a length *L* = 40mm, width *W* = 40mm and thickness of the base *T* = 3 mm.

In order to optimize the fins parameters - the height of the fin, the fin diameter and the number of fins in the design of the heat sink, a design of experiments (DOE) is used.

2.3. Use of DOE in the heat sink design

To obtain optimum thermal characteristics in the design of the heat sink there must be identified the factors having the greatest impact on improving the capacity for heat dissipation.

The geometry factors of the heat sink structure, which are selected as design parameters, are the height of the fins (*A*), the fin diameter (*B*) and the number of fins (*C*) of the heat sink.

Full Factorial Experiment for three factors for each one on two levels is used as a tool for the realization of DOE. Table 2 shows the three design parameters, whose influence is analyzed.

Table 2. Parameters and levels of experiments

Factor	Factor Latter	Level	
		Low	High
Height of Fins, [mm]	A	15	30
Diameter of the Fin, [mm]	B	3	4
Number of Fins, [mm]	C	24	42

Eight possible experiments and configurations of the design parameters are shown in Table 3.

Table 3. Combination of design parameters

Experi-ment №	Height of Fins [mm]	Diameter of the Fin [mm]	Number of Fins
1	15	3	24
2	15	3	42
3	15	4	24
4	15	4	42
5	30	3	24
6	30	3	42
7	30	4	24
8	30	4	42

In Full Factorial Experiment can be estimated all main effects and interactions, since the method has full resolution.

3. ANALYSIS AND DISCUSSION

The study of impact of design parameters on the thermal characteristics of the LED system is performed by thermal simulations. All thermal simulations are conducted at specified ambient temperature of 25^0C.

Fig. 3 shows the distribution of heat and the maximum temperature of the LED system at the first design configuration (with a height of the fins 15mm, diameter of the fin 3mm and 24 fins), and the Fig. 4 of the latter configuration (with a height of the fin 30 mm, a diameter 4 mm, and the number of the fins - 42) of Table 3.

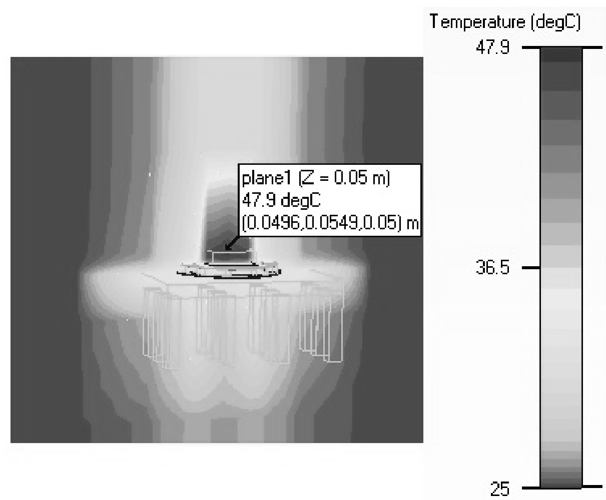

Fig. 3. Temperature distribution in the design configuration of the fins with a height of 15mm, a diameter of 3mm and 24 fins

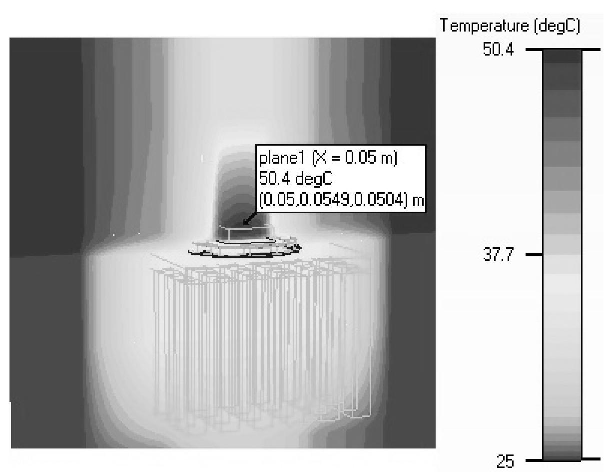

Fig. 4. Temperature distribution in the design configuration of the fins with a height of 30mm, a diameter of 4mm and 42 fins

The effects of various configurations of heat sink design parameters on the maximum temperature of the LED system simulations are shown in Table 4.

Table 4. Thermal simulation results

№	Height of Fins	Diameter of the Fin	Number of Fins	Max. Temp. [^{0}C]
1	15	3	24	47,9
2	15	3	42	47,1
3	15	4	24	49
4	15	4	42	51,9
5	30	3	24	45,4
6	30	3	42	45,7
7	30	4	24	46,1
8	30	4	42	50,4

After analyzing the results Fig.5 graphically shows the influence factor of each parameter and combination of heat sink parameters of the LED system maximum temperature.

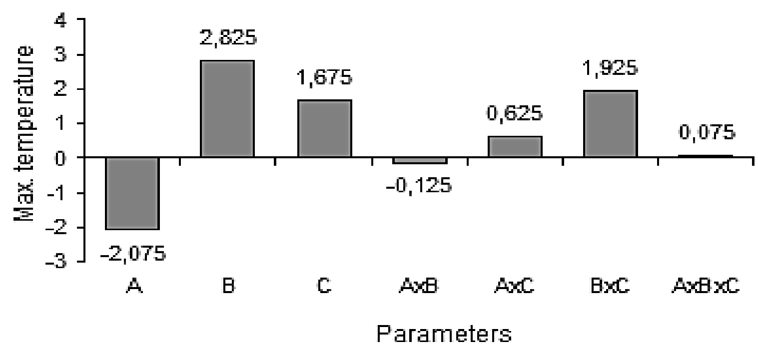

Fig. 5. Factor of influence of each parameter on the maximum temperature

From fig.5 it is seen that out of the separately considered parameters *A* (fins height) has the greatest influence on lowering the temperatures, and *B* (fins diameter) has the greatest negative influence and leads to a temperature increase. Parameter *C* (fins number) also has a negative effect, but to a lesser extent.

At determining the influence factor of multiple design parameters it is seen that *AxB* (interaction between fins height and diameter) has the greatest influence for lowering the temperature. A big negative influence has *BxC* (interaction between fins diameter and number), and with less negative influence is *AxC* (interaction between fins height and number), which leads to a temperature increase.

The interaction of all three parameters *AxBxC* has a low negative influence.
Fig. 6a to 6f graphically show the basic effects from the interaction of the design parameters in terms of their temperature influence.

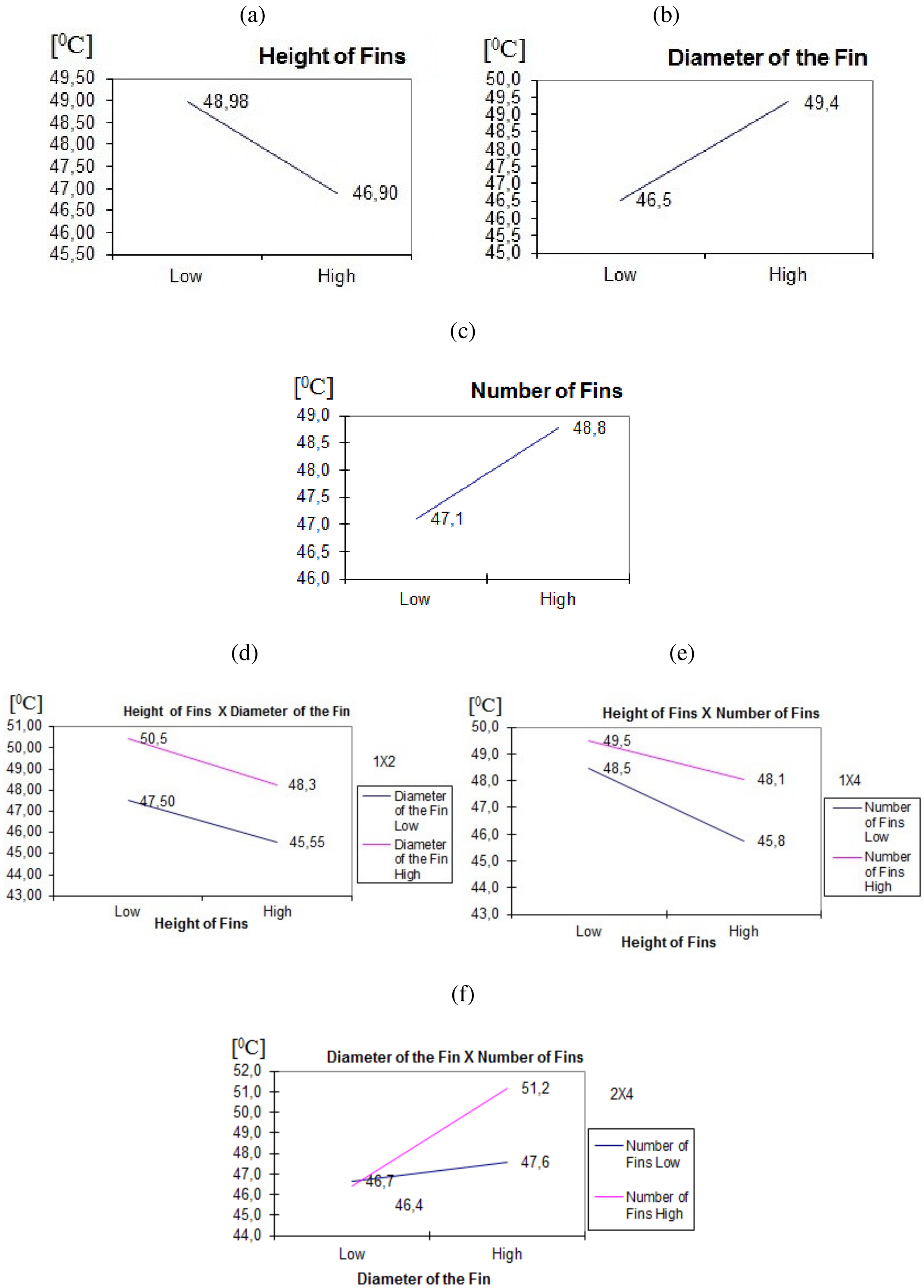

Fig. 6. Graph of interaction between: a) low value versus high value of the fins height; b) low value versus high value of fin diameter; c) low and high values of fins number; d) the height of the fins X versus the diameter of the fins; e) the height of the fins X versus the number of fins; f) the diameter of the fins X versus number of fins

Fig. 6a shows how the temperature varies in relation to the height of the fins at a low value of the height of the fin (15mm) and at a high value of the height of the fin (30mm). The graph shows that at a high value of the height of the fin the temperature decreases, due to the better heat dissipation.

Fig. 6b shows the opposite - at the low value of the diameter of the fins (3mm), the temperature decreases, at the high value (4mm) the temperature increases significantly with $\Delta T = 2{,}9^0C$. This effect is explained by the decrease of the circulation of warm air around the fins as a result of the closer spacing of the fins with the increasing of the diameter.

The graph of fig. 6c shows that at the smaller value of the number of fins (24 fins) the temperature decreases, and at the high value (42 fins) it increases by $\Delta T = 1{,}7^0C$. The increase in temperature is due to reduced circulation of the heat due to the more adjacent fins.

Fig. 6d shows that at fins height of 15mm and fins diameter of 3mm (the lower design parameters) the temperatures are higher than fins height of 30mm and fins diameter 4mm (the higher design parameters). This effect is explained by the increased surface area of the sink, which helps for a more efficient heat dissipation.

The graphic on fig. 6e shows effects, similar to those on fig. 6d. In this case the bigger fins height - 30mm leads to a temperature variation of $\Delta T = 1{,}4^0C$. The number of fins - 42 has a greater effect and a temperature variation of $\Delta T = 2{,}7^0C$, because by increasing the fins number heat sink area is significantly increased.

Fig. 6f shows a strong interaction between the design parameters, especially at the point of intersection between the two lines. In this case at lowest value of fins diameter - 3mm and a small number of fins - 24 the lowest temperatures with respect to the design parameters are observed. From here we can conclude that the lower value of fins diameter (3mm) and the lower number of fins (24) provide optimal project results and lead to a temperature decrease.

The carried out studies show that the optimal design parameters of the heat sink are – fins height 30mm, fins diameter 3mm and 24 fins. The LED system temperature after simulation is the lowest - $45{,}4^0C$ with these values of design parameters . Very low temperature - $45{,}7^0C$ shows the heat sink with fins height 30mm, fins diameter 3mm and 42 fins, but it is more expensive to make. The worst design parameters shows the heat sink with fins height 15mm, fins diameter 4mm and 42 fins, in this case the highest LED system temperature is recorded - $51{,}9^0C$.

4. RESULTS VALIDATION

To validate the results of thermal simulations there is used a prototype of the heat sink, which is made with the optimal parameters and has a mounted a LED module on it supplied by 3,6V DC voltage. Temperature measurement using K-type thermocouple, which is connected to the data acquisition system (UNI-T UT804) and fully dedicated computer with software for data processing are performed.

Fig. 7 shows the place of the thermocouple on the LED structure during the measurements.

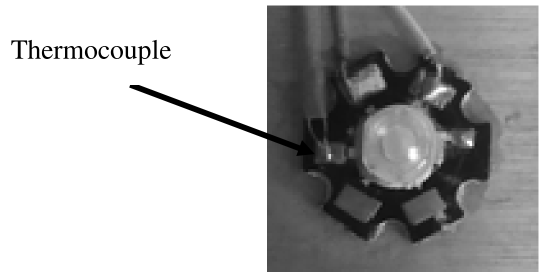

Fig. 7. The place of the thermocouple for measuring the temperature of the module

During the measurements, the ambient temperature is 24^0C and the LED works without interruption for 30min. By substituting the measured temperature at the solder T_s and other thermal parameters of the LED package, for the transition temperature T_j we get:

$$T_j = T_s + (R_{j-s})P_d = 33^0 C + (8^0 C/W \cdot 1{,}89W) = 48{,}12^0 C \qquad (2)$$

The resulting temperature of the LED junction of $48{,}12^0$C is very similar to that obtained by the thermal simulations - $45{,}4^0$C. The relative error between the simulated and measured temperature is about 5.6%, which demonstrates accordance of the results.

5. CONCLUSION

The application of the design of experiment in the process of heat designing of LED modules leads to a reduction of the number of thermal models and simulations to find optimal design parameters of the cooling system, which helps to reduce the design costs and leads to more rapid arrival of the final product to the market.

The results of the study lead to the following conclusions from the analysis:

- Studies analysis show that at the design of heat sinks with circular pin type fins a key role for increased cooling capacity plays the fins height. At smaller fins height a temperature increase is observed, due to the retention of heat around the heat sink base and its low dissipation into the environment. By increasing the fins height a temperature decrease is observed, because the heat sink areas is increasing and the heat is dissipated faster in the surrounding space.
- For obtaining a better heat flow dissipation by the heat sink, the fins diameter must be carefully selected. The larger fins diameter increases the heat dissipation area, but at a large number of closely situated fins the circulation of hot air to the environment is impeded, leading to a temperature increase. A good heat dissipation with a bigger diameter fins is achieved by a lower number of high fins, but situated further apart from each other. In this way a sufficient effective and a good circulation of the air flow area is achieved, which helps for a better heat dissipation..
- The results show that the increased number of fins is not a leading factor for increasing the efficiency of heat dissipation. Although by increasing the number of fins the heat dissipation area is also increased, but if the fins are not far apart enough or have shape which impedes the hot air movement, the heat stays around the heat sink and is dissipated more slowly. This leads to a temperature increase.

- The analysis have shown that the most effective heat dissipation by the heat sink and lowest temperature are achieved by a small fins diameter and a small number of high fins, situated at an appropriate distance from one another.

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REFERENCES

[1] G. Langer, M. Leitgeb, J. Nicolics, M. Unger, Hans Hoschopf, F. Wenzl, (2015) "Advanted Thermal Management Solutions on PCB for High Power Applications", *SMT Magazine*, Vol. 29, Number 6, pp12-32.

[2] H. Rainer, (2008) "Thermal Management of Golden Dragon LED - Application Note", Osram Opto Semiconductors.

[3] E. Juntunen, O. Tapaninen, A. Sitomaniemi, M. Jamsa, V. Heikkinen, M. Karppinen and Penttti Karioja, (2013) "Copper-Core MCPCB with Thermal Vias for High-Power COB LED Modules", *Power Electronics*, Vol. 29, Issue 3, pp1410-1417.

[4] T. Jeong, K. H. Kim, S. J. Lee, S. H. Lee, S. R. Jeon, S. H. Lim, J. H. Baek, and J. Lee, (2009) "Aluminum Nitride Ceramic Substrates-Bonded Vertical Light-Emitting Diodes", *IEEE Photonics Technology Letters*, Vol. 21, pp890–892.

[5] H. Fengze, Y. Daoguo and Z. Guiqi, (2011) "Thermal Analysis of LED Lighting System with Different Fin Heat sink", *Journal of Semiconductors*, Vol. 32, Issue 1, DOI: 10.1088/1674-4926/32/1/014006.

[6] P. Huang, K. Pan, S. Wang, S. Chen, (2012) "Study on Packaging Structure of High Power Multi-Chip LED", *International Conference on Electronic Packaging Technology and High Density Packaging*, DOI: 10.1109/ICEPT-HDP.2012.6474895.

[7] H. Kobayashi, S. Ishikawa, R. Hashimoto, H. Kanematsu and Y. Utsumi, (2014) "Effect of Heat Link Structure on Cooling Performance of LED Bulb", *International Conference on Design Engeneering and Science*, Pilsen, Czech Republic, pp171-174.

[8] Application Note AN30, (2013) "Thermal Management for Bridgelux Vero Series LED Array", pp3-8.

[9] R. Mendonca, S. Yalamarty, C. Kini, (2015) "Numerical Analysis of Heat sink for LED Lighting Modules", *IJRIT*, Vol. 4, Issue: 03, pp142-149.

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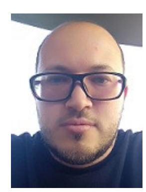

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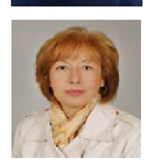

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