Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Conduction-driven cooling of LED-based automotive LED lighting systems for abating local hot spots

Ferina Saati
Mehmet Arik

Ferina Saati, Mehmet Arik, "Conduction-driven cooling of LED-based automotive LED lighting systems for abating local hot spots," *Opt. Eng.* **57**(2), 025102 (2018), doi: 10.1117/1.OE.57.2.025102.

Optical Engineering 57(2), 025102 (February 2018)

Conduction-driven cooling of LED-based automotive LED lighting systems for abating local hot spots

Ferina Saati[a] **and Mehmet Arik**[b,*]
[a]Technical University of Munich, Department of Mechanical Engineering, München, Germany
[b]Ozyegin University, EVATEG Center for Energy Efficient Electronics and Lighting Technologies, Istanbul, Turkey

Abstract. Light-emitting diode (LED)-based automotive lighting systems pose unique challenges, such as dual-side packaging (front side for LEDs and back side for driver electronics circuit), size, harsh ambient, and cooling. Packaging for automotive lighting applications combining the advanced printed circuit board (PCB) technology with a multifunctional LED-based board is investigated with a focus on the effect of thermal conduction-based cooling for hot spot abatement. A baseline study with a flame retardant 4 technology, commonly known as FR4 PCB, is first compared with a metal-core PCB technology, both experimentally and computationally. The double-sided advanced PCB that houses both electronics and LEDs is then investigated computationally and experimentally compared with the baseline FR4 PCB. Computational models are first developed with a commercial computational fluid dynamics software and are followed by an advanced PCB technology based on embedded heat pipes, which is computationally and experimentally studied. Then, attention is turned to studying different heat pipe orientations and heat pipe placements on the board. Results show that conventional FR4-based light engines experience local hot spots ($\Delta T > 50°\mathrm{C}$) while advanced PCB technology based on heat pipes and thermal spreaders eliminates these local hot spots ($\Delta T < 10°\mathrm{C}$), leading to a higher lumen extraction with improved reliability. Finally, possible design options are presented with embedded heat pipe structures that further improve the PCB performance. [DOI: 10.1117/1.OE.57.2.025102]

Keywords: automotive lighting; light-emitting diode; local hot spots; double-sided printed circuit board; thermal resistance.

Paper 171768 received Nov. 8, 2017; accepted for publication Jan. 10, 2018; published online Feb. 12, 2018.

1 Introduction

Recent developments in light-emitting diode (LED) technologies enable high lumen extraction for many desired colors, such as blue, violet, amber, orange, green, and yellow. Display-like technologies heavily utilize LEDs for backlighting units and offer many benefits, such as slim designs, no mura effect (clouding), high refresh rates, and enhanced resolution. LEDs in automotive exterior lighting date back to the early 2000s, and, recently, many more vehicles are leveraging LEDs for interior and exterior lighting systems.

The potential of solid-state lighting (SSL) technology has been studied for reducing lighting energy consumption by a considerable amount. In particular, automotive lighting has received higher attention in recent years due to light quality, compact optically controlled light beams, and long life that offer significant energy savings and economic benefits in the long run.[1] One of the most challenging obstacles in LED maintenance is thermal management due to the fact that about 80% of the input power to an LED may be converted to heat, which can cause a shift in color, shorter device life, and reduced light output when exceeding a certain limit of junction temperature. Subsequently, optical and mechanical failures are probably due to thermal problems. An appropriate thermal design enhances the reliability of LED lighting systems due to high thermal conductivity of LED components and the heat transfer path of the heat spreader extending ultimately to external ambient. The board resistance is very sensitive to components and materials, so the ones with low conductivity cause thermal efficiency to be very low and have a significant impact on the performance.[2,3] A good design of the board must take thermal management into account. In the design process, there is a limitation on LED junction temperature, and the light intensity has an inverse relationship with chip temperature. In other words, a lower LED die temperature means a higher light intensity and a higher reliability.

Automotive lighting is considered a harsh environment application for LEDs. LED junction temperature on flame retardant 4 (FR4) board may exceed the thermal limits locally as imposed by design requirements (i.e., intensity). This, of course, is dependent on the component heat generation and heat density distribution on both the front side and back side of the board. Adjusting the density by optimizing the configuration and choosing the most efficient components is a possible solution, but local thermal problems, causing high losses in total efficiency of the lamp, may still remain as a potential issue.

A propitious solution for thermal obstacles of SSL is using a metal clad board instead of an FR4 printed circuit board (PCB). This solution may offer an efficient solution in lowering the junction temperature. Insulated metal substrate may help in shrinking form-factor of the LED product with increasing power requirements. Effective heat management then emerges as a critical issue.[4] Better thermal efficiency in thermal clad boards compared with FR4 boards can be due to a number of factors:

---

*Address all correspondence to: Mehmet Arik, E-mail: mehmet.arik@ozyegin.edu.tr

0091-3286/2018/$25.00

- Thermal conductivity of the material for each layer of the board, which is higher in thermal clad boards.
- Aluminum- or copper-based metal substrate is a better heat spreader compared with FR4 materials; therefore, the spreading resistance is significantly lower.
- Thermal behavior of the board, which depends on the solder pad layouts, contact resistance of components' placements, and thermal vias.

Thermal via technology can improve thermal performance for a structure special design.[5] Various cooling options have been investigated in different studies. A specific optimal heat sink design and thermal conductivity of the chip substrate are studied in detail in Ref. 6. According to Ref. 7, a synthetic jet is a possible example of a thermal performance-enhancement method for heat transfer in electronics and LEDs. Alternative active cooling approaches, such as piezo fans, direct liquid cooling,[8] and high heat flux heat pipe embedded in a metal-core printed circuit board (MCPCB) for high-power LED cooling,[9] have been proposed. Also, direct and indirect liquid cooling methods exist, with indirect liquid cooling and microchannels being mainly inefficient due to the added interfaces. On the other hand, direct liquid cooling provides contact with the chip and, thus, is less dependent on the interface resistance.[10]

In this study, a numerical and experimental study has been performed to abate the local hot spots for a compact LED automotive lighting system. Due to aggressive thermal problems that lead to quick decay of LEDs in the harsh environment (>80°C), being close to the vehicle engine, cooling technologies are proposed. The system is first introduced, and baseline models and results of numerical models are demonstrated in detail. Finally, an experimental investigation with a set of local enhanced conduction models are proposed and discussed comparatively.

2 LED Automotive Lighting System

Understanding the thermal performance to design a robust system is critical. Developing an analytical approach to understand board thermal resistance for the conductivity range of typical boards can also be useful for predicting the sensitivity of each part, as will be discussed below. An idealized analytical network of thermal resistances was developed for automotive lighting as shown in Fig. 1. The calculations are done using the values provided by the manufacturing company. Typical LEDs are used, and commercially available components shape the system. The electronics include resistors, diodes, and transistors, and how they are placed is part of the design of the circuit. In this network, the top surface of LEDs and components are considered to be at temperatures of interest, which provide information for comparison between technologies, and the only cooling method is natural convection. The board is a double-sided multilayer, modeled with no enclosure around the board (open air) in an ambient of 25°C. Double-sided PCB technology is used in special consumer and defense electronics where the space is premium. Components are placed at both sides of the PCB for compact packaging. Although spreading resistance is excluded in this 1-D simplified analytical modeling, sensitivity of the system to the board resistance is found to be several times higher than to the other components of the LED system, i.e., solder pads, die or convective, and radiative resistances, when all conduction parameters are swept within the range.

A first-order thermal resistance network can be helpful for understanding the sensitivity of the system to subcomponents. The results of a resistance network for an automotive LED lighting system presented by Saati show that an LED chip is most sensitive to die attach conductivity. In the same paper, the sensitivity of a single-LED package to the board is shown to be the highest among other resistances playing part in the system total sensitivity. The importance of a low-resistance board appears at this point with common board technologies being: (1) FR4 PCB, which is either a two-layer PCB with thermal vias or a one-layer FR4 with aluminum or copper leading to a thermal resistance range within 0.2 to 0.6 W/mK and (2) metal-core PCB, which is either aluminum or copper with proper electrical isolation over the surface. Two- or one-layer boards use the same technologies, but proper electric isolation techniques are included in the two-layer designs to avoid any short-circuit situation. The metal-core technologies normally use a thermally conductive dielectric layer, ranging from 0.8 to 3 W/mK with low spreading resistance. According to Ying and Toh,[11] thermal conductivity of a PCB may not be uniform since it consists of layers pressed together. Insulator layers are low conductors, while the others are highly conductive. Overall temperature distribution and the junction temperatures (reference temperatures on the surfaces that are readable from the infrared camera measurements) are the parameters we consider to compare the efficiency of two different boards.

The computational fluid dynamics (CFD) models in this paper consider all heat transport modes in an LED: conduction, convection, and radiation. The exit path for the energy in such a system is known to be mainly through conduction and convection.[12] The heat flow path must be kept short as

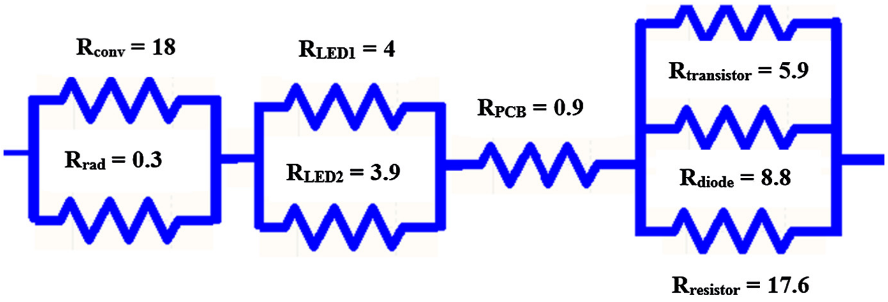

Fig. 1 A sample thermal resistance network for the automotive lighting system board in free space (unit is K/W).

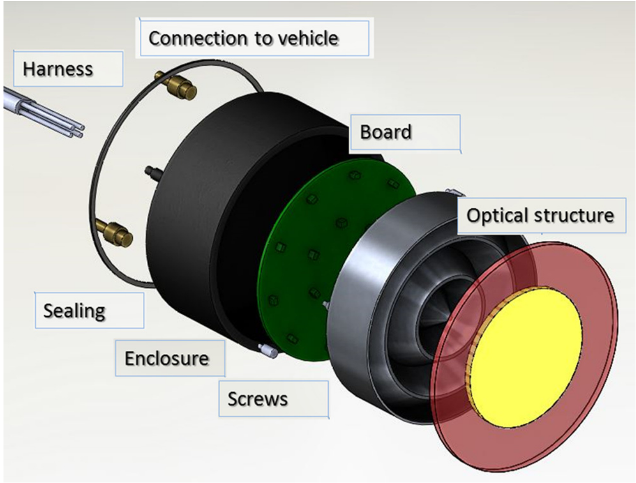

Fig. 2 Exploded view of the automotive LED rear lighting concept.

possible to transfer the junction heat to the ambient at a much lower temperature. Therefore, the temperature distribution and junction of the same board at different conductivities are compared in the computational models. The LED automotive lighting system must operate safely in a range of environmental temperatures much higher than the self-heated air temperature created by low-efficiency electronics and LEDs. System-level thermal management should be supported by a screening of cooling methods, and the thermal solution must be all-inclusive, taking device, package, and board- and system-level aspects into consideration.

A typical automotive LED rear lighting system may run at around 24 V and generates <10 W of heat. A representative system is shown in Fig. 2 in an exploded view of the various parts of the prototype system. Electronic concepts of common international standards and customer performance expectations are important factors to take into account. Both sides of the PCB are utilized to create a compact design capability.

In the FR4 board used in this study, copper-rich areas are denser to enhance the thermal performance by getting a more uniform temperature distribution in the circuit board. The PCB that has LEDs on its surface is concentric with the optical structure that is aluminum coated, optically reflective, and fixed on the board by means of mechanical fasteners. The enclosure is assembled screw-fixed to the PCB. Thereafter, the lens is glued onto the outside of the lamp housing. The original lamp essentially consists of the following components:

- optical structure, includes two-color transparent outer lenses and a reflector,
- carrier housing (enclosure),
- PCB,
- connection and cable, and
- screw, ventilation, and lower parts, such as gaskets.

In this system, thermal resistance of the LEDs and electronic components along with the size of their footprints are determined according to maximum allowable operating temperature. The thermal stack-up is calculated considering all materials and interfaces. Various materials are substituted in the models to determine the best performance at the lowest cost. The appropriate thermal interface material is also another important step in the design of the board, for which electrical and mechanical requirements are considered to minimize the thermal resistance. In the next part, a design approach with no apparent exit path for waste heat will be discussed (no heat spreader used). A close to isothermal temperature distribution technology is the goal of the modeling. It is expected that lowering the thermal resistance (specifically spreading resistance) and by making direct connection between lead frame of LED to the board, the thermal path will decrease. Therefore, thermal resistance will be reduced significantly. Thickness of the dielectric layer in FR4 is also nearly 70 μm to withstand the breakdown voltage and is, therefore, a limit to decreasing this thermal path.

To confirm the improved thermal performance of new board technology, a double-sided metal-core PCB, which has a shorter path for conduction in comparison with conventional structure of metal-core PCB, is first studied. Thermal models and experimental measurements are conducted with an LED module consisting of 16 midpower LED packages and electronic components as listed in Table 1, which presents the system major components. Although the number of transistors is fewer than that of the other components, they have the highest heat generation rates. Details of the computational study and the results are presented in Sec. 3 and are followed by the experimental analysis. According to optical tests in an integrated sphere, LED lamps emit 90 lumens of light as a mixture of red, amber, and yellow. LEDs are modeled as they are on one side of PCB and electronic components on the opposite side.

Total current supplied to the board is close to 400 mA. LEDs power input is up to 400 mW, and transistors and resistors are 840 and 200 mW, respectively. Details of electrical and thermal power are summarized in Table 2. In this table,

Table 1 Each component of the system by quantity.

Name	Quantity
Transistor	5
Resistor	18
Diode	8
LED of type 1	10
LED of type 2	6

Table 2 Power rate and heat dissipation for each function.

Function system	Consumed energy (W)	Heat dissipation (W)
Function 1	0.43	0.39
Function 2	2.98	2.58
Function 3	4.22	3.78
Total	7.63	6.75

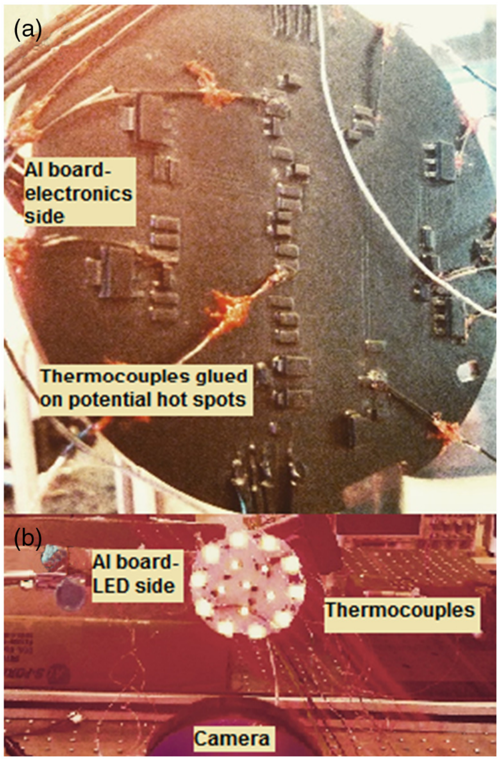

Fig. 3 Multifunctional LED backlight board with thermal vias: (a) electronics side and (b) LEDs side.

function 1 means "tail light on only," function 2 means "side light on only," and function 3 means "brake light on only." Thermal vias are covered by a copper layer of 70-μm thickness, playing an important role in enhancing board spreading conductivity. The board geometry used in the experimental study is shown in Fig. 3. The system is expected to operate in an aggressive environment of over 80°C in a tight thermal envelope.

3 Computational Study

Computational models were developed in a finite element-based commercially available software named ANSYS.[13] First, the FR4 PCB and then the metal-core board were modeled with the same boundary conditions. In the simulation model, the components' legs are attached directly on one of the metallic layers of board. Thermally, such consideration is supposed to be the closest model of reality. Since in the ANSYS software thermal modeling module has been used, the electric functioning is not playing the role in the simulation, and, therefore, no short-circuit is an important role in the thermal aspect of investigation. The thermal part of the software is called Icepak. Heat created in each component is applied using the power source feature.

After creating the geometry of FR4 and thermal clad board, for the computational study, a mesh grid is generated. The simulation model should ideally be insensitive to the number of elements used. For this purpose, mesh sensitivity of the Icepak model was studied. This means that, by increasing the number of elements, the temperature results were sensitive up to a certain number of elements and not above that limit. This number is 500,000 as seen in Fig. 4. A higher number of elements was used to derive results for further comparisons.

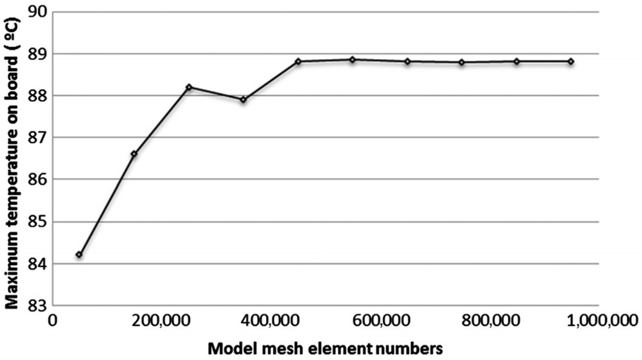

Fig. 4 Mesh sensitivity plot for Icepak model.

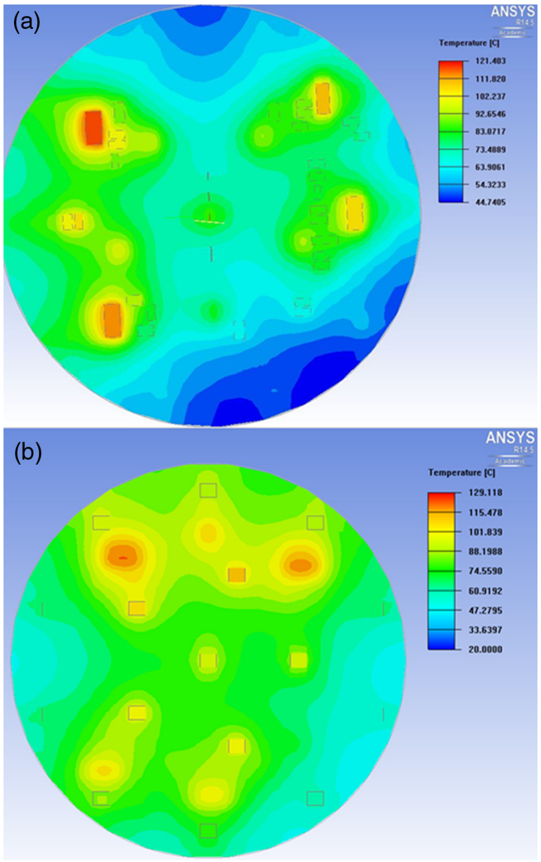

Fig. 5 Baseline simulation model results giving temperature findings for FR4: (a) electronics side and (b) LEDs side.

Temperature results are then derived as demonstrated in Fig. 5. First, the computational study is solved for each board without any enclosure, using all three functions of lighting together, thus, the maximum heat power. Then, a plastic enclosure along with a simplified optical structure is modeled to represent the thermal behavior of these parts in the tightly packed system. Temperature results for the double-sided FR4 board show that maximum local temperature occurs on the electronics side [Fig. 5(a)], where the high flux components are densely populated. This configuration is also related to the structure at the other side of the board [LEDs side, Fig. 5(b)] where the maximum local temperature (which is less than the total $T_{\max}$) happens about the same

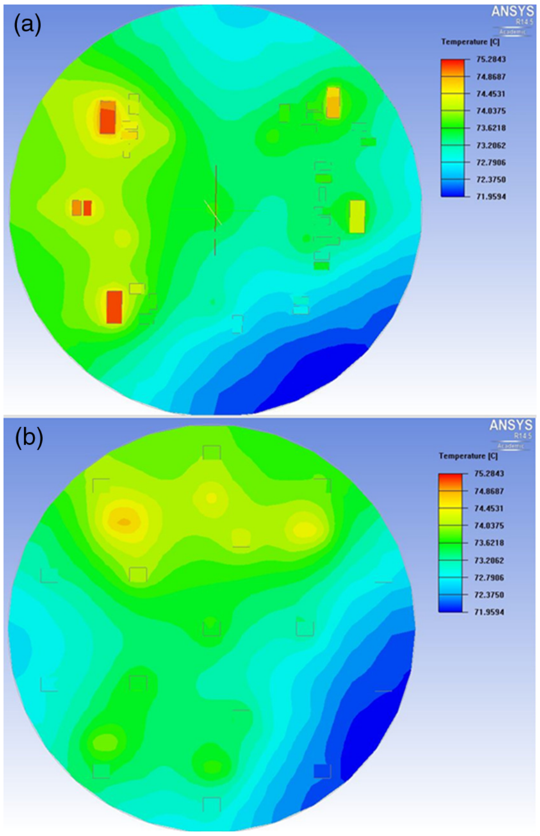

Fig. 6 The simulation model temperature contour results of MCPCB CFD: (a) electronics side and (b) LEDs side.

place; hence, on both sides of the board, there is a high-temperature region. The orientation of the boards is the same in all simulations and measurements throughout this paper, and it exactly matches the placement in the vehicles. Overall, hot regions locally vary strongly and are more on the electronics side due to higher heat generation power per surface area. The maximum temperature is found to be 110°C, and the minimum is 46°C.

Double-sided thermal clad technology of this study is then tested, so we compare FR4 results with findings of a compact LED lighting system that is suitable for a high-performing economical automotive exterior lighting system. Thermal clad board model results demonstrate a more uniform temperature distribution on both electronics [Fig. 6(a)] and LEDs [Fig. 6(b)] sides. These results show that metal-core board clearly has a more uniform distribution with a maximum temperature of 70°C and a minimum of 63°C compared with FR4 technology.

According to temperature findings, maximum junction temperature is decreased by 34°C only by changing the board from FR4 to thermal clad material. We have observed that local hot spots are dependent on orientation and heat flux density of both sides (LEDs, transistors, resistors, etc.). But this sensitivity is decreased when using thermal clad board since the distribution is uniform (temperature gradient on the board is <7°C). Due to the fact that electronic component suppliers estimate doubling the rate of failure for each 10°C rise in the junction temperature, thermal clad board is a more promising approach here with <10°C all through the board, which means that the generated heat in each component is efficiently removed and resulted in a higher reliability. These computational results will be verified with the experimental results in Sec. 4.

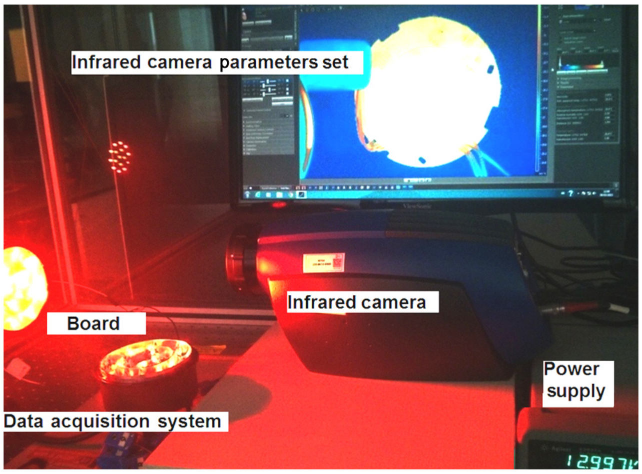

Fig. 7 Experimental setup.

4 Experimental Study

An experimental system has been designed and built for the current study. The experimental apparatus (as shown in Fig. 7) is set in the same conditions as in the simulation. T-type thermocouples were first used for calibrating the surface parameters for the infrared camera measurements. The surface is covered with a layer of black paint with a calibrated emissivity, so temperature results are comparable for local points. For a sample point chosen on the surface of MCPCB, emissivity values of 0.98, 0.99, 0.83, and 0.96 were found for four different points, front and back. Emissivity is, therefore, calculated as an average of these four points of 0.94, similar to prior publications (Refs. 14 and 15). The system was designed and tested as a conventional FR4 PCB in the first part of this study and then thermal clad board was tested.

Numerical findings agree well with the experimental results as shown in Table 3 depending on the location of the board. Maximum deviation of the agreements was 10%. The data are the average of the same point in three repeated experiments. The results are compared both when the board is inside a plastic enclosure and when there is no enclosure. This variation is due to unknown interfaces, exact heat generation rates, and experimental and computational uncertainties. Temperatures are measured by T-type thermocouples with an Agilent data acquisition system.

To reduce the uncertainty, tests are repeated at least twice in the same ambient condition. After averaging the results for certain chosen spots, the hot spot temperatures are compared as presented in Table 4.

Figures 8 and 9 show the temperature distributions obtained with an infrared (IR) camera (FLIR SC5000). The LEDs side temperature distribution is shown in Fig. 8(a). The hot spots are clearly observed and similar to the numerical results with a 3% standard deviation. On the other hand, thermal clad board has a more uniform temperature distribution as previously discussed [Fig. 8(b)].

Table 3 Measured and modeled temperature differences for an FR4 prototype circuit board both in free space and in the enclosure. The results are given as temperature differences from the ambient temperature.

	Model	Board in free space		Board in the enclosure	
	Flux[a] (10^6 W/m^2)	Measured[a] ΔT (K)	Modeled[a] ΔT (K)	Measured[b] ΔT (K)	Modeled[b] ΔT (K)
R1	50.3	60	67	—	—
R4	50.3	58	60	—	—
R6	78.4	74	78	100	108
R12	78.4	104	110	117	126
R18	134	87	93	118	123
R19	134	88	89	111	115
R22	50,3	66	72	—	—
Q1	127.3	63	65	100	110
Q2	127.3	46	46	—	—
Q3	127.3	53	59	—	—
Q4	1.178	45	46	—	—
Q5	153.9	73	82	117	128
Q6	159.6	75	80	—	—
Q7	2.3	48	51	—	—

[a] When board is not inside any enclosure.
[b] When board is inside an enclosure.

Table 4 Verification of thermal camera data by thermocouple readings. The thermocouple temperatures deviate from the IR temperatures by (-0.6 ± 2.7)°C.

Component	IR temperatures (°C)	Thermocouple temperatures (°C)
R13	63.0	61.6
R16	63.5	62.0
Q5	61.7	64.9
R19	62.7	64.5
R22	62.6	61.8
R2	62.0	62.0
Q1	60.5	62.1
Q6	61.6	64.1
LED5	60.1	56.1
LED14	60.6	57.4
Ambient	25.4	25.4
Maximum	70.4	65.0

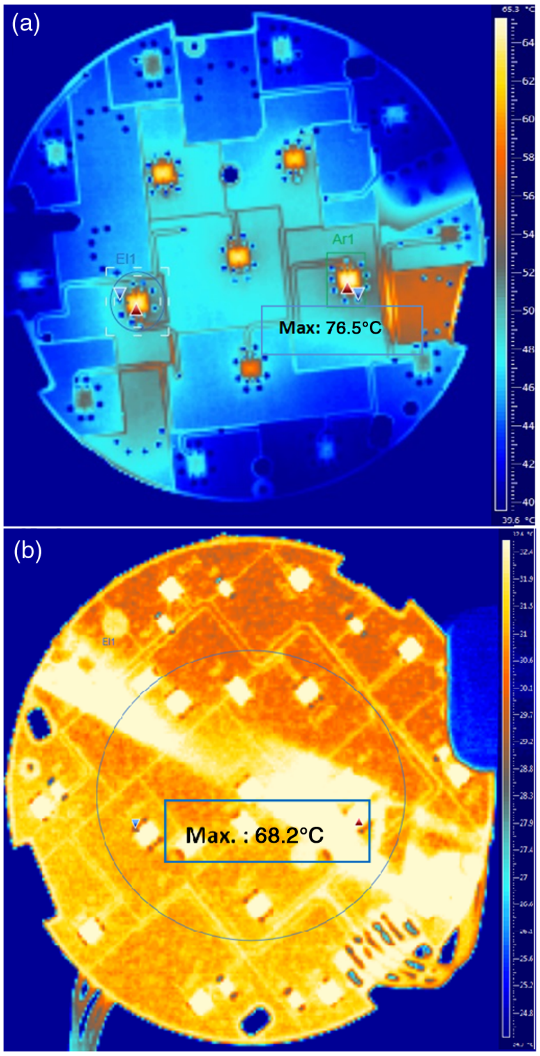

Fig. 8 LEDs side of temperature distribution in (a) FR4 prototype and (b) thermal clad prototype, measured with a thermal camera.

Figure 9 shows that local hot spots are similar to hot spots in the thermal clad board prototype at the electronics components side. Overall temperature distribution is close to uniform within 3°C, whereas in FR4 board, there exists a temperature gradient of almost 50°C. This temperature difference is more than 10 times of the temperature difference found in the thermal clad prototype board.

To see the temperature over the hottest and coldest points on the thermal clad board, a temperature line function is created (see Fig. 10). With a close examination of this distribution, a possible best placement for the heat pipe embedded board structure is determined. According to experimental results, in the state when hottest spot of the thermal clad board is standing in the highest point against gravity (in that case, the heat pipe will also be at its maximum efficiency), maximum temperature difference is achieved, and the embedded heat pipe is expected to be of the optimum efficiency in that orientation.

The experiment was performed inside a clean and stable setup inside the laboratory. Temperature-wise, the uncertainties were avoided by choosing appropriate and similar time frames for measuring and repeating the same test several times.

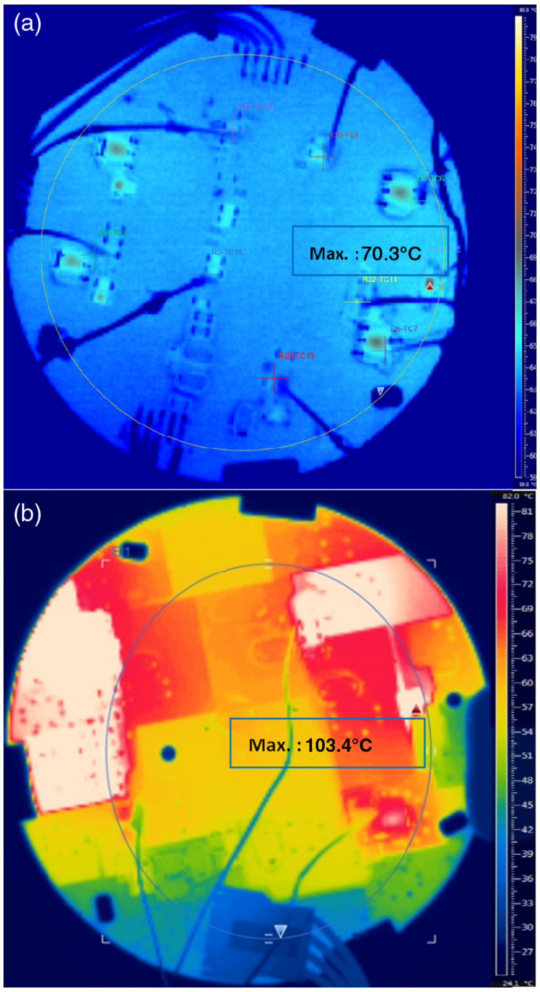

Fig. 9 Temperature contours comparison for the electronics side for (a) FR4 versus (b) thermal clad board, measured with a thermal camera.

5 Local Enhanced Conduction Designs as an Idea

While the metal clad board provided a better heat spreading, an innovative idea is further presented to obtain a uniform temperature on the board. The idea is to include a highly conductive structure, such as a heat pipe into or attached to the circuit board. The heat pipe, on its own as a type of heat transporting system, has been developed remarkably over the last 60 years, appearing in a large number of practical applications and research studies. The ease of design and simplicity for production, as well as the fact that it can drop the temperature gradient between two local hot spots and transport high heat fluxes at even high-temperature gradients, makes heat pipes interesting for such purpose.[16] Most heat pipes are produced from either aluminum or copper, although there are some other choices such as plastics or recent exotic materials. Embedded heat pipe technology has been of interest for the last decade, and some government agencies (DARPA) are highly interested in it for its high flux, tight environment applications. Therefore, a heat pipe is purchased from commercially available sources for low cost. To present this idea, a typical standard heat pipe is simulated as a conductive structure in the simulation model with arbitrary thermal conductivity (including the range of low/conductive cases, such as FR4, to highly conductive cases, such as thermal clad board). In the model, the heat pipe is simplified as a highly conductive block. Figure 11 shows this in a computer-generated model for better understanding. The ideas are not yet on the prototype level.

The computational solution includes two short, highly conductive bars between several hot spots. Different models were then created in terms of quantity, shape, and position according to the board geometry (either embedded inside it, placed on its surface, connecting several components, or acting as a spreader between system parts). Figure 12 shows the results for one of these cases.

When comparing temperature results of all the mentioned models, the best performance and the lowest temperature difference on the board (most uniform distribution) occurred when a highly conductive geometry was embedded inside the board and was circular (which could be related to the circular geometry of the board).

6 Conclusions

One of the main challenges in thermal management of LEDs is the power density to available surface area ratio leading to high heat flux rates that create high-temperature gradients even across a few hundred microns-thick layers. While conventional plastic PCB technology is still widely used in LED systems, it may lead to local hot spots and temperature nonuniformities. The current analysis shows that local hot and

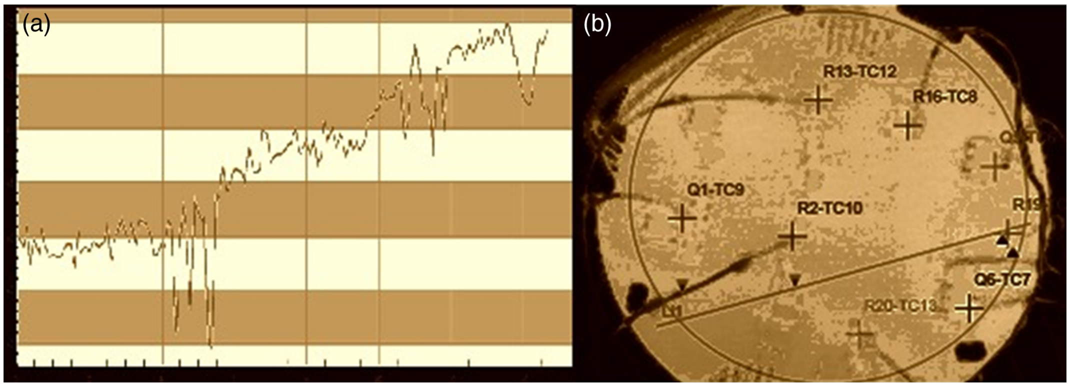

Fig. 10 Using line function to determine the maximum temperature difference on thermal clad board [line that is drawn on thermal image in (a) Local temperature distribution and (b) PCB with identified line for temperature difference].

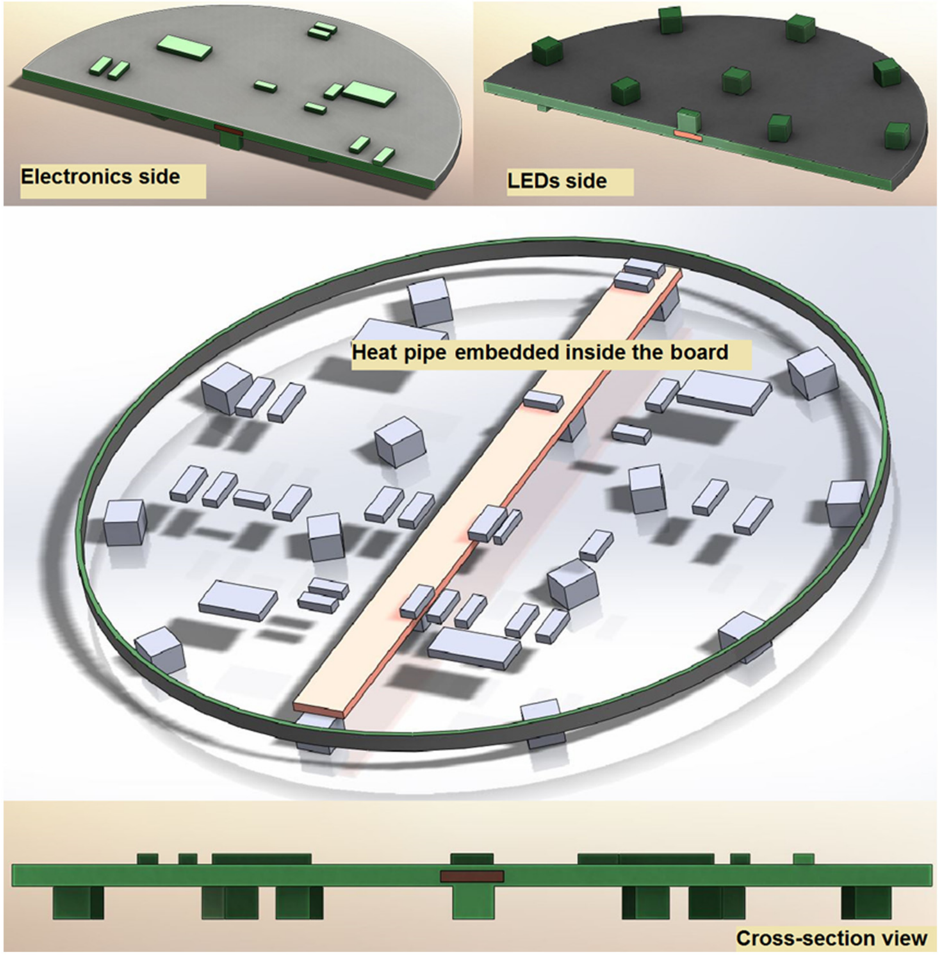

Fig. 11 Embedded highly conductive plate analogous to heat pipe in the model and cross sections from different views of computer modeling of the design idea.

cold spots occur even in conventional designs with thermal vias. In particular, this happens in harsh environments where the LED junction has high potential to lead to failures if temperatures rise above the safe limits.

The LED lighting system with double-sided FR4 board was closely examined for the sensitivity of the system to thermal conditions computationally and experimentally. It was found that the maximum temperature gradient on the board was 35°C and 48°C for LED and driver circuit sides, respectively. The maximum temperature on the board was found to be 104°C. Next, a double-sided metal board was studied computationally and experimentally validated. It was

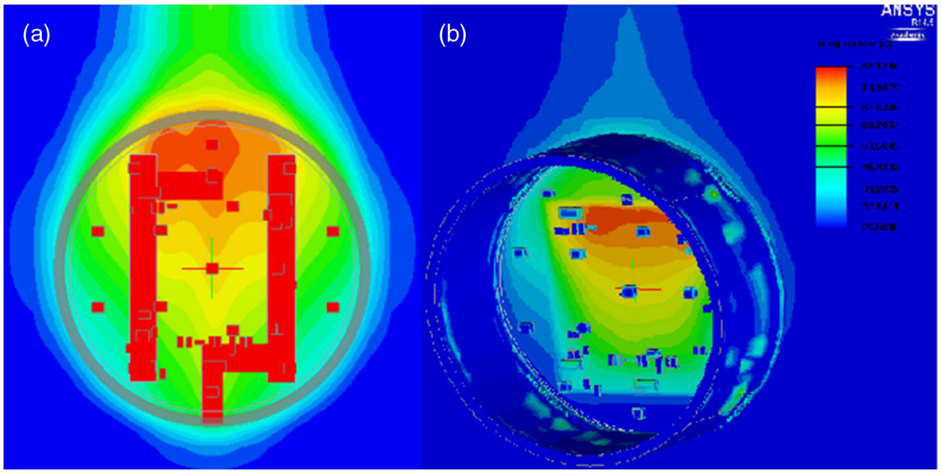

Fig. 12 Temperature distribution of several high-conductive plates embedded in board: (a) components: LEDs and electronics components, plates and (b) board and plastic enclosure around it.

found that the maximum temperature gradient on the board was 6°C and 9°C for LED and driver circuit sides, respectively. The maximum temperature on the board was found to be 70°C. The uniform temperature distribution as a result of this change in the board is reported as highly critical and trustable in terms of eliminating possible thermal failures, especially for high-brightness LEDs. Even further, the local hot spots were also abated by means of embedding a conductive structure with the example of heat pipes as potential options of embedding inside the board for which the models show that homogeneity is even higher. The thermal study of heat pipe embedded board gives promising results that a potential prototype is worth producing to further take the measurements in real time.

Acknowledgments

The authors would like to thank Turkish Ministry of Science, Industry and Technology, Grant No. 01464.STZ.2012-2, for their support and for funding this project. The authors also would like to acknowledge FARBA Corporation, Bursa, Turkey, and Mr. Ulas Yildirim of Ozyegin University for partial financial support and help in the experimental study.

References

1. F. S. Khosroshahi, C. S. Tufekci, and M. Arik, "A computational and experimental study on a harsh environment LED system for vehicle exterior lighting applications," in *IEEE Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, IEEE (2014).
2. M.-H. Lee et al., "Design and fabrication of metal PCB based on the patterned anodizing for improving thermal dissipation of LED lighting," in *5th Int. Microsystems Packaging Assembly and Circuits Technology Conf. (IMPACT)*, IEEE (2010).
3. M. Arik et al., "Energy efficiency of low form factor cooling devices," in *ASME Int. Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers (2007).
4. M. de Vos, "The cooling of high-power LEDs: effective solution for rapidly dissipating heat," Power Systems Design, Europe (2004).
5. P. Wilkerson, A. Raman, and M. Turowski, "Fast, automated thermal simulation of three-dimensional integrated circuits," in *Ninth Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems*, IEEE (2004).
6. M. Arik et al., "Thermal management of LEDs: package to system," *Proc. SPIE* **5187**, 64–75 (2004).
7. M. Arik, "Local heat transfer coefficients of a high-frequency synthetic jet during impingement cooling over flat surfaces," *Heat Transfer Eng.* **29**(9), 763–773 (2008).
8. E. Tamdogan and M. Arik, "Effect of direct liquid cooling on light emitting diode local hot spots: natural convection immersion cooling," in *Proc. of the 15th Int. Heat Transfer Conf.*, IHTC (2014).
9. D. Pounds and R. W. Bonner, "High heat flux heat pipes embedded in metal core printed circuit boards for LED thermal management," in *IEEE Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, IEEE (2014).
10. E. Tamdogan and M. Arik, "Natural convection immersion cooling with enhanced optical performance of light-emitting diode systems," *J. Electron. Package* **137**(4), 041006 (2015).
11. T. M. Ying and K. C. Toh, "A heat spreading resistance model for anisotropic thermal conductivity materials in electronic packaging," in *Seventh Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems*, Vol. 1, IEEE (2000).
12. M. Arik et al., "Thermal management of LEDs: package to system," in *Third Int. Conf. on Solid State Lighting*, SPIE, Bellingham, Washington (2004).
13. ANSYS Icepak, "14.0 documentation," ANSYS Inc. (2012).
14. M. Arik and S. Weaver, "Chip-scale thermal management of high-brightness LED packages," *Proc. SPIE* **5530**, 214–223 (2004).
15. Y. Utturkar, M. Arik, and M. Gursoy, "An experimental and computational sensitivity analysis of synthetic jet cooling performance," in *ASME Int. Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers (2006).
16. A. Faghri, *Heat Pipe Science and Technology*, Global Digital Press, 2nd ed., (2016).

Ferina Saati received her BSc and MSc degrees in mechanical engineering, from the University of Tehran and Özyegin University in 2012 and 2016, respectively, and currently she is pursuing her PhD in mechanical engineering from Technical University of Munich. Her PhD research focus is on porous material modeling and characterization, using acoustic models, experimental techniques and finite element method.

Mehmet Arik is a professor and director of EVATEG Center for Energy Efficient Electronics and Lighting Technologies, Ozyegin University. He obtained his BSc degree in mechanical engineering from İstanbul Technical University, İstanbul, Turkey. He completed his MSc degree at the University of Miami and his PhD was awarded at the University of Minnesota focusing on the thermal management of advanced electronic components and Microelectromechanical systems (MEMS) in 2001. He worked at the General Electric Global Research Center in Niskayuna, New York, on the thermal management of electronics as a senior research scientist and program manager between 2000 and 2011. He joined the Department of Mechanical Engineering at Ozyegin University as a full-time faculty member in 2011. His current research focuses on energy, medical, electronics, defense, and solid state lighting technologies. He established the EVATEG Center (Energy Efficient Electronics and Lighting Technologies Research, Development, and Demonstration Center). EVATEG is a scientific partner for Luger Research and Lighting Professional Symposium. Currently, he leads EVATEG, which has over 50 global collaborators from academia, industry, and government entities. He has published over 150 research papers in conferences and journals and owns over 120 patents. He serves as an associate editor for *IEEE Components and Packaging Technologies* and the *ASME Journal of Electronics Packaging*. He also serves for the *Journal of Solid State Lighting* editorial board, *ASRO Journal of Applied Mechanics* and as a scientific committee member for International Center for Heat and Mass Transfer. He is an ASME fellow.