Paper

Challenges for Measuring Multichip LED Light Engines for Interior Lighting Applications

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Abstract

As LED systems have been evolving today in a great number of niche applications including automotive lighting, water purification, and skin imaging etc., extensive studies of scientists and engineers in the field have been constantly looking for ways to reduce generated heat loads and maximize the light output to reach the highest efficiency ratios. While the current systems developed over the last years achieved to reach even a 40% LED light efficiency, a higher portion of the electrical input energy of LEDs is still produced as heat and it hinders their development potential. In addition, the compact size of the LED systems poses some challenges to the reliable characterization of their performance at low uncertainties. Especially, the performance considerations associated with thermal loads over a limited size of LED chips require the effective characterization of these systems for various operational conditions. One of the techniques used for this purpose is that an LED package is characterized by a decrease in forward voltage with increasing junction temperature. As LEDs are operated at higher junction temperatures, the amount and quality of the light deteriorates significantly, and the less efficient use of the LEDs results in additional operating costs and reduced lifetime of LEDs. In fact, accurate identification of thermal behavior of LED packages is one of the essential tasks towards improving the design of LED systems. If thermal characterization of LEDs is accurately done, performance parameters of LED packages are more reliably optimized to yield the highest possible performance ratios. Thus, this study focused on the design and manufacturing of a thermally improved and fully operational rapid temperature controllable chamber in which calibration and test phases of junction temperature measurements are sensitively conducted under a low uncertainty.

Introduction

Considering the significant amount of heat losses in current single LED chips (approximately 60 to 70% of electrical input power [1]), thermal issues are still significant and better cooling techniques or low power consumption technologies are required since the optical performance of LEDs is directly affected by thermal conditions [2], [3], [4]. Individual LEDs in multi-chip systems are even more affected by the existence of electrical components in the circuits and thermal loads induced by other LED chips. In fact, it has been shown that thermal losses caused by electrical components in a circuit could reach almost the same levels as radiant energy [5]. In the study, it was also shown that conversion efficiency of a multi-chip LED module drops by 6.1% due to the existence of electrical components. In future applications where Internet of Things (IoT) sensors are more included in lighting products, the severity of thermal problems in lighting units is expected to be more sounded as the sensors are placed with additional electrical components. As more and more electronic devices are connected to each other via IoT sensors, human-to-human, human-to-device and device-to-device communication will find a great place in many improved everyday products. Considering the existence of lighting products in many interior, exterior and industrial uses, an LED system will inevitably include various IoT sensors as a future lighting and communication device. On the other hand, some performance parameters of LEDs such as lifetime, efficiency, color and amount of light generation are greatly affected by thermal conditions [6], [7], [8] and the adaptation of IoT sensors to the LED systems may require significant understanding of thermal behavior of LEDs in multi-LED systems. Thus, accurate measurement systems are needed to determine junction temperature of LEDs and improve the performance of high-power LEDs based on thermal data provided at their normal operation. If accurate temperature measurements are performed in this area, then it will be very practical for many industry experts, researchers and engineers to thermally characterize the design of LED systems including IoT sensors and associated electrical components. This will enable them to realize performance optimization of their LED products. In addition, current junction temperature measurement systems are operated using transient measurement methods that require the derivation of a thermal resistance versus thermal capacitance relationship to determine structure function and junction temperature of LEDs over a one-dimensional heat flow path [9], [10], [11]. However, the method with one dimensional heat flux assumption is questioned especially for junction temperature measurements of white LED packages that include phosphor coating over the LED chip. This is mainly attributed to the impact of three-dimensional heat flow on the rise of junction temperature [12]. In junction temperature measurements of multi-chip LED systems, one dimensional heat flux assumption raises even more concerns due to the increased thermal interaction between LEDs and electrical components in the lighting unit, generated local hot spots over the electrical board and three-dimensional heat flow in those systems. Considering alternative cooling systems developed for future lighting systems and the inclusion of IoT sensors in these units, accurate measurement of junction temperature of LED chips will be critical to ensure that the lighting unit is designed to operate in its optimum condition. In addition to the raised concerns about heat flux assumption in measurements, the current measurement systems are not applicable to measure junction temperature of serially connected LEDs in multi-LED systems. Thus, this study primarily focuses on developing a junction temperature measurement system for single and multi-LED system and investigates the challenges behind the accurate measurements of these systems.

Methodology

Junction temperature measurement technique

Junction temperature measurements are conducted based on the improved version of forward voltage change technique introduced by [5]. Measurements are initiated with the calibration of each LED located on the PCB. In calibration, the relationship between junction temperature and forward voltage is set with the use of a temperature controllable oven system. The oven system provides steady state and thermal equilibrium conditions in which junction temperature of an LED chip can be regarded as the oven temperature. In the second phase of the measurements, an LED unit is operated with its normal operation current or voltage until it reaches steady state condition. Then, the junction temperatures of individual LEDs are determined with the multi-channel sourcemeter system. The technique requires the separate application of electrical input power to the LED board and an individual LED whose junction temperature is to be determined. Applying energy to the LED board from the first channel enables each LED to reach their junction temperatures at steady state during their normal operation. Once this is achieved, the first channel is turned off for 1 millisecond (ms) pulse duration and the second channel is simultaneously turned on and the pulse current of 1 milliampere (mA) is applied on the individual LED whose junction temperature is to be measured. The forward voltage drop on the LED is also measured by the second channel after applying 1 mA pulse current. The procedure is repeated ten times and the forward voltage readings are evaluated to ensure the range of results is within 0.1 mV. This ensures that junction temperature measurements were conducted at steady state operation of the LED board since 0.1 mV change in forward voltage readings of the pulse current application corresponds to the change in the results of repeated junction temperature measurements by around 0.07°C as shown in the Results section of study. Before conducting measurements, the electrical wires were soldered to the LED leadframes in order to apply pulse current to the individual LED chips and measure the forward voltage from the second channel of the sourcemeter system. The LED board after additional wires are soldered and the test phase of the introduced technique are seen in Figure 1.

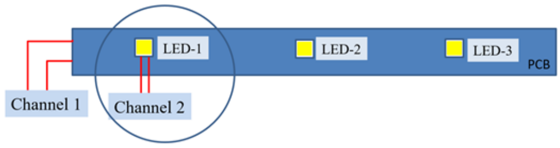


Figure 1: Electrical connections of two channels of a source-meter device for junction temperature measurements of LEDs [5]

In order to conduct junction temperature measurements of LEDs described above, a sourcemeter integrated test chamber (oven system) was developed to provide steady state and thermal equilibrium conditions in calibration phase, apply electrical power to the LED system and measure junction temperature at normal operation of the LED product.

Computational analysis and test chamber (oven system) design

This study requires a robust and reliable thermal chamber with precise temperature conditions in order to determine the calibration data (junction temperature versus forward voltage) for an LED chip. Thermal steady state must be achieved for each measurement point. Thermal equilibrium is considered as a temperature change of no more than 0.1°C for minimum of 10 minutes, in every temperature readings of the system. These values are picked from the previous studies performed by Tamdoğan et. al. [13]. The objective was to design a heating and cooling chamber with a high temperature change speed and uniformly distributed temperatures. Operating conditions are determined as shown in Table 1.

Table 1: Operating Conditions for Measurement Device

Temperature range	+25°C – 100°C
Chamber dimensions	110mm x 110mm x 110mm
Temperature gradient	±0.5 °C
Heating and cooling rate	1.5 °C/min
LED chip connector amount	6 chips
Cooling liquid	Water

According to the operating conditions, an aluminum oven design is considered for a chamber enclosure. Proposed design consists of aluminum walls with embedded cylindrical heaters and liquid cooling path to ensure a rapid heating and cooling cycle to reach a certain temperature set. That said, 15 mm thickness aluminum plates with drilled holes for circulation of the coolant is designed for a compact design. The model is manufactured by conventional manufacturing methods and does not require numerous piping and clamping systems that increase the number of defect points.

A collector is designed for connecting inner channels of the coolant in order to have one inlet and one outlet for the whole measurement chamber. These collectors are used for transferring the fluid from one channel to another while maintaining the sealed foundation with sealing rings conforming to the temperatures more than 200°C. Figure 2 shows the assembled measurement chamber structure.

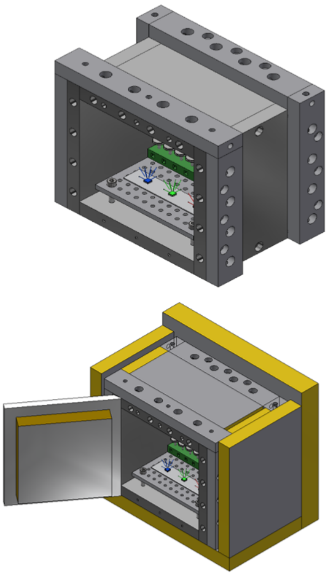
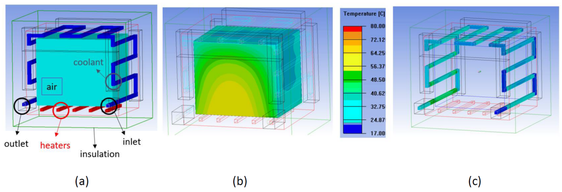


Figure 2: Measurement chamber aluminum structure

Transient thermal analysis was made to determine design parameters that result in a desired heating and cooling rate of the test chamber. Thus, the oven model was created in ANSYS Icepak [14] (see Figure 3) including heating and cooling subsystems. The change of air and water temperature in the system was monitored in simulations. It was aimed to achieve over 1.5°C/min heating and cooling rate of the air.

After the analysis, it was decided that 6 mm diameter drilling holes that the coolant water passes through, three 225 W capacity heaters, 17°C inlet water, 11x11x11 cm^3 internal volume chamber and 15 mm thickness insulation layer satisfy the heating and cooling rates over 1.5°C/min. The details of the selection process and other units of the system are described as the following.



(a) (b) (c)

Figure 3: ANSYS Icepak model of the oven system (a), the change in temperature distribution of air inside the oven system during transient simulations (b), the change in temperature distribution of cooling liquid inside the drilled holes in the oven walls (c)

Circulation pump for cooling fluid (water) is selected depending on the rate of the mass needed for optimum heat transfer from aluminum walls to the water. 4 L/min water at 25°C is needed as flow rate from the circulation pump. Local pressure losses decrease the flow rate of circulation pumps, which is why pressure required at the inlet is calculated with the number of bends in connectors and plates. 1.3 bar of pressure is required for the water to be pushed to the other side. Then, according to the operating pressure-flow rate, the nominal flow rate of the circulation pump was determined. A circulation pump with nominal flow rate of 18 L/min and working pressure of 4.2 bar is selected. Cooling is done with the help of a fan driven plate type heat exchanger, of which the plate distance and dimensions are determined from the required cooling capacity of the chamber to operate with a rate of 1.5°C/min (see Figure 4 for the cooling subsystem of the measurement device). Since the temperature of the measurement device will be reaching 100°C, stone wool is used for insulation instead of polyurethane panels, which are observed to be melting at temperatures more than 80°C. On top of the insulation, a 1 mm thickness of powder painted sheet metal bent structure is installed.

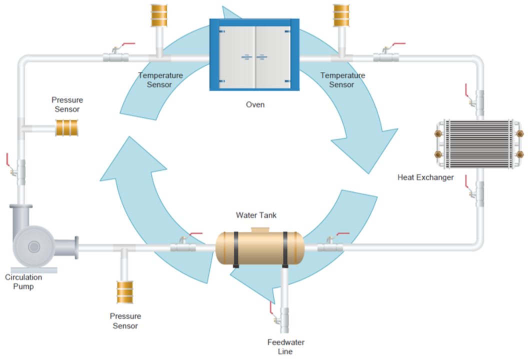


Figure 4: The cooling subsystem of the measurement device

Manufacturing of the oven system

After determining measurement methodology and conducting computational analysis to achieve a preferred heating and cooling subsystem of the measurement device, the oven system was manufactured to enable a temperature controllable environment with heating and cooling control on the oven walls. The manufactured oven system is seen in Figure 5 without inlet and outlet connections and the LED mount attachment. In Figure 6, the assembly of all test unit in a compact measurement system is observed. It includes a heat exchanger, circulation pump, reservoir, sourcemeter and oven system as main components.

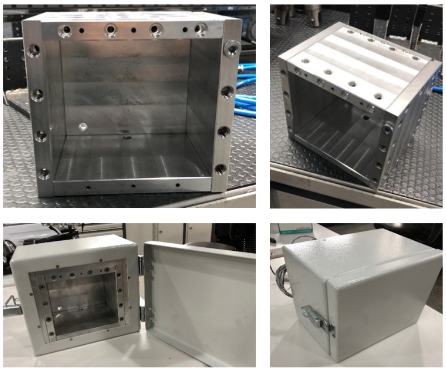


Figure 5: The manufactured oven system

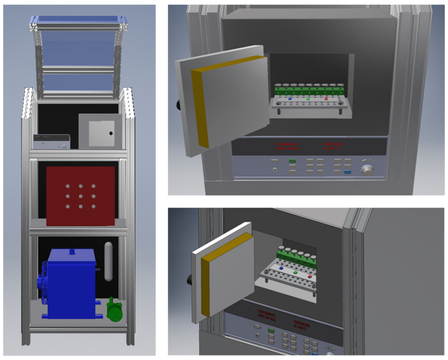


Figure 6: The assembly of all test unit

The oven system as in Figure 5 has drilled through holes on their walls and coolant liquid is circulated in these holes from inlet to outlet position. The circulation of cold liquid reduces the temperature of the oven walls and ultimately drops the ambient temperature. On the other hand, the heating of the oven walls and air in the test chamber is provided with the cylindrical rod heaters tightly embedded in the bottom wall of the oven to adjust a certain air temperature. The heating of the ambient air is facilitated by the movement of heated air particles to the upper positions of the test chamber as a result of natural convection currents. Temperature sensors (J type sensors) are also embedded in the heating and cooling walls to keep track of thermal condition of the oven system and provide uniformly distributed temperature profile at steady state condition during the junction temperature tests. As an attachment to the test chamber, an LED mounting table is created with multiple electrical connectors and extension cables properly taken out from the back wall of the oven system. The oven system is also insulated with an insulation material (stone wool) durable at the operating temperature range of the system (maximum 100°C).

Results and Discussions

In this study, junction temperature measurements of a single blue LED and white multi-chip LED system (see Figure 7) were realized with the proposed measurement technique in a novel measurement device.

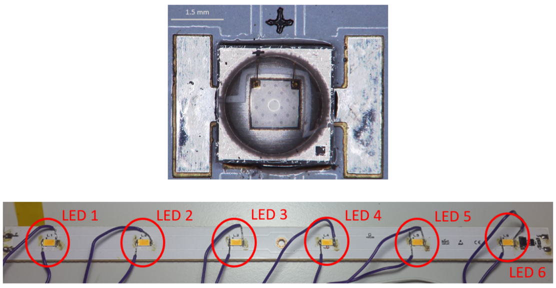


Figure 7: A single blue LED chip and a white multi-chip LED system for junction temperature measurements

The calibration of LEDs was conducted with 1 milliampere (1 mA) pulse current for 1 millisecond (1 ms) pulse duration to prevent additional heating over the LED chip at a certain stabilized oven temperature. Junction temperature of LEDs was assumed to be equal to the oven temperature once steady state and thermal equilibrium conditions were satisfied in the oven. Then, calibration phase of measurements was conducted as described in Methodology section. The relationship between junction temperature versus forward voltage was created individually for multi-chip LED system from the soldered wires using the pulse current application channel of the sourcemeter system. The relationship between two parameters are demonstrated in Figure 8 and Figure 9 respectively.

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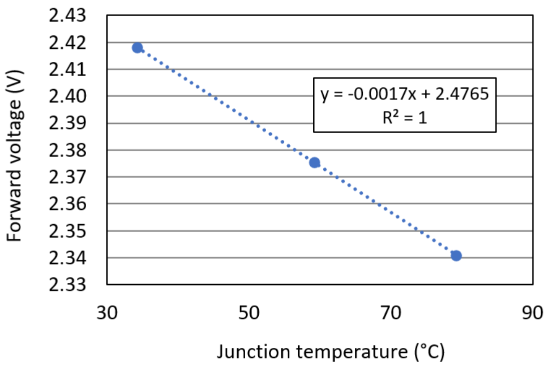

Figure 8: Relationship between junction temperature and forward voltage for a single blue LED chip

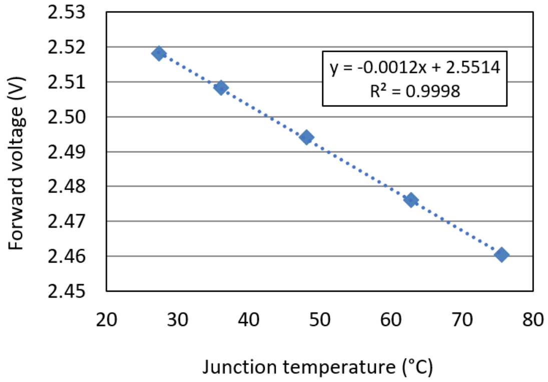

Figure 9: Relationship between junction temperature and forward voltage for the LED-1 in a white multi-chip LED system

Sensitivity Analysis

Calibration and test phase of junction temperature tests were conducted with repeated forward voltage measurements to increase the reliability of the results. To ensure that the measurements were conducted after steady state condition was reached, the variation between forward voltage measurements and its effect on junction temperature results were examined. According to the analysis, a variation criterion was determined between repeating forward voltage measurements to minimize measurement uncertainty of junction temperature results based on the allowed resolution of the measurement equipment. The variation between repeated forward voltage results and the corresponding junction temperature measurement sensitivity with this variation are shown in Table 2. The analysis was made based on a calibration equation of a single LED derived with 1 mA pulse current application for 1 ms pulse duration (V_f = -0.0013*T_j + 2.5939). Based on this analysis, measurement uncertainty of junction temperature tests was limited to 0.1°C in test phase and the LED was operated at its driving current until steady state is reached and maximum variation of 0.1 mV between ten repeated measurements is achieved. The overall analysis and the relationship between variation in repeated forward voltage readings and junction temperature sensitivity is given in Figure 10 and Table 2.

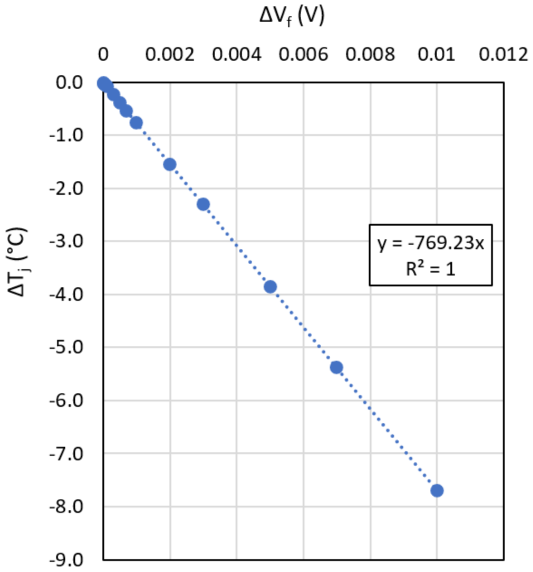

Figure 10: Junction temperature sensitivity of a single blue LED with the variation in repeated forward voltage readings

Table 2: ΔV_f versus ΔT_j

ΔV_f (V)	ΔT_j (°C)
0.00001	-0.0077
0.00003	-0.0231
0.00005	-0.0385
0.00007	-0.0538
0.0001	-0.0770
0.0003	-0.2308
0.0005	-0.3846
0.0007	-0.5385
0.001	-0.7692
0.002	-1.5385
0.003	-2.3077
0.005	-3.8462
0.007	-5.3846
0.01	-7.6923

Junction temperature measurements

Test phase of the junction temperature measurements were carried out in various ambient conditions and the LED system was operated at a steady state condition defined as the change in board temperature by 0.1°C in 15 minutes. Junction temperature measurements of a single blue LED was conducted two times at different ambient conditions from 30°C to 80°C with 10°C increments and at various driving currents (300, 400 and 500 mA) to observe the repeatability of tests. The results have shown a good agreement with a maximum variation of 1.6°C between two series of measurements (see Figure 12, 13 and 14).

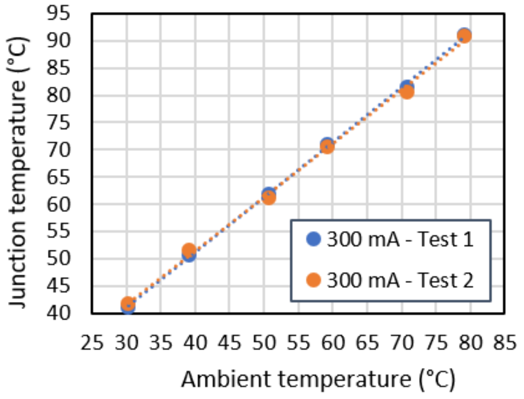

Figure 11: Evaluation of repeatability tests with a single blue LED driven at a 300 mA operating current at different ambient temperatures

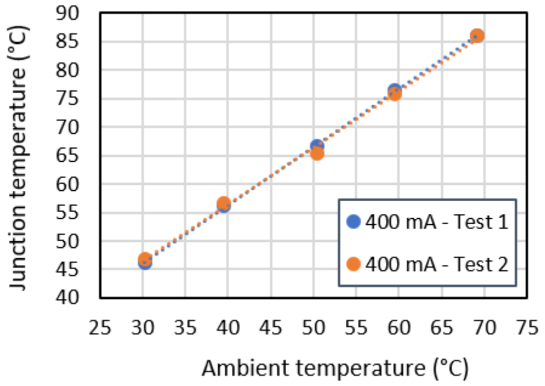

Figure 12: Evaluation of repeatability tests with a single blue LED driven at a 400 mA operating current at different ambient temperatures

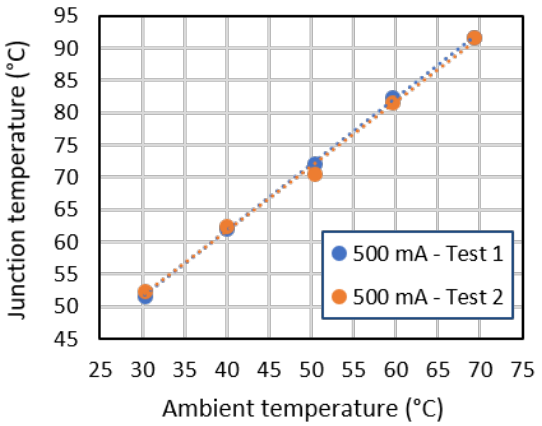

Figure 13: Evaluation of repeatability tests with a single blue LED driven at a 500 mA operating current at different ambient temperatures

A multi-chip LED system was also operated with the application of 24V at 23°C ambient temperature and thermal behavior of individual LEDs was determined with junction temperature measurements to characterize thermal condition of the LED system as seen in Figure 15. It was noticed that the LED 6 has the highest temperature since it is located in a very close position to electrical components in the lighting unit. As the distance from the electrical units increases, junction temperatures of LEDs are observed to be gradually decreasing; however, the junction temperature of LED 2 is measured to be the second highest. This is also supported by solder point measurements with a T-type thermocouple and may be attributed to the inappropriate packaging of the LED 2 on the circuit board since this could contribute to the increase in total thermal resistance of the LED package.

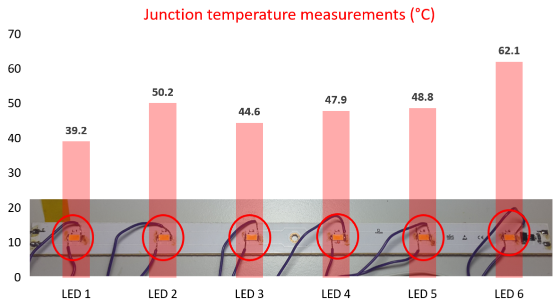

Figure 14: Junction temperature distribution of LEDs in a white multi-chip LED system

Conclusions

In this study, junction temperature of a single blue LED and multi-chip white LED was measured with a proposed junction temperature measurement device. The measurement method applied with the introduced device does not include the transient measurement technique with one dimensional heat flow assumption. Instead, steady state junction temperature measurements are carried out with a pulse current application and two-channel simultaneous operation and measurement technique. The measurement system could play a significant role in reliable measurements of junction temperature that directly affects the optical performance and lifetime of LEDs and offer a practical solution to the determination of junction temperature of individual LEDs in multi-chip systems. These measurements are believed to be even more significant in future applications when Internet of Things (IoT) sensors and associated electrical components are more frequently included in LED lightings units. Thus, the measurement system can characterize the thermal condition of an LED unit and allow researchers, engineers and experts to optimize the design of their LED products considering various heat generators in their modules.

Author's CV

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M. Muslu received the B.Sc. degree in mechanical engineering from Ozyegin University, Istanbul. He is currently pursuing his M.Sc. Degree in mechanical engineering in Ozyegin University. Mr. Muslu was a member of a competition team who received the “Best Commercial Potential Award” in developing a novel thermal connector design sponsored by U.S. Defense Advanced Research Projects Agency (DARPA) in 2015. From 2014 to present, he is a research assistant in EVATEG (Energy Efficient Lighting Technologies Research, Development, Education and Demonstration Center). His research interests include optoelectronics and thermal management of electronics.

Onuralp ISIL

Onuralp Isil was born in Istanbul (Turkey) in 1994. He completed his undergraduate education at Ozyegin University, Department of Mechanical Engineering (2017). He continued his graduate studies at Ozyegin University, Department of Mechanical Engineering. His current study field is in the alternative cooling, specifically cooling with synthetic jet actuators. Along with the Graduate Program working in heat transfer studies, he works at Rota Teknik, an engineering company in hydraulic, pneumatics and automation sector, as a mechanical design engineer and project manager.

Mehmet ARIK, Prof. Dr.

Dr. Arik received the B.Sc. degree in mechanical engineering from Istanbul Technical University, the MSc degree in mechanical engineering from University of Miami, and the PhD degree in mechanical engineering from the University of Minnesota in 2011. He has worked at the General Electric Global Research Center in Niskayuna, NY, on thermal management of electronics as a senior research scientist and program leader between 2000 and 2011. Dr. Arik is currently Professor of Mechanical Engineering at Ozyegin University. He is also the independent member of the board of directors at ASELSAN (Turkish Military Electronics Industry).

Organisation

Ozyegin University

The university was founded by the Hüsnü M. Özyeğin Foundation, and its establishment was approved by Foundation Act No. 5656, published in the Official Gazette No. 26526 on May 18, 2007.

Özyeğin University admitted its first class of students to the department of Business Administration and started its education in September, 2008.

According to the "Most Popular Universities" survey conducted by Bloomberg Business Week in 2014, Özyeğin ranked 3rd among foundation universities, following Sabancı and Koç universities, respectively. Özyeğin University was also placed 4th among all universities in the online survey conducted with 15.700 students from 89 universities between January and May 2014.

Özyeğin University ranked 6th among the Most Entrepreneurial and Innovative Universities of Turkey and rose in the ranking compared to 2013.

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