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Design and simulation of solutions to reduce the thermal resistance of lighting systems

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Abstract: The paper focuses on some essential steps in the development of high power line light. The research within the solved project deals with the development of a special extruded profile with a cooling channel and with heat removal by the circulation of the coolant and on the design of a cooling system with all the safety elements. The partial aim of the work is to determine the thermal resistance of individual parts of the device and to design modifications so that the total thermal resistance and maximum temperature are within the limits set by the effort to achieve maximum light output, but also the longevity, economy, safety, and reliability of operation. The analytical calculations, CFD simulations, and real testing were used to determine the required parameters. The main result presented in this paper is a novel developed PCB with a copper core and thermal vias.

Keywords: LED, line light source, line scan camera, computer vision, thermal resistance, light output, PCB, CFD simulation

1. INTRODUCTION

With the advancement of light output and functionality of light-emitting diode, the lights formed by these LEDs are increasingly being used to illuminate interiors, exteriors, and also perform various decorative and design functions. LEDs also have great benefits in computer vision for their properties. It is easy to create lighting systems of various shapes and parameters. Today's very common tasks of computer vision include the control of the production of materials (e.g. nonwovens, foils, paper, etc.) produced in so-called endless belts. The key parameter is the CD (cross direction) and MD (machine direction) resolution of the scan material, where the MD resolution is determined by the speed of the material and the frame rate of the camera. For this purpose, a combination of a line scan camera and a line light source is most commonly used. State-of-art high speed cameras intended for this purpose achieve speeds of up to 250,000 lps (lines per second), so the exposure time is sometimes less than 3 µs. Therefore, there is an increasing demands putted on these lights, especially on luminous flux, but also their overall length, power consumption and other parameters. Nowadays, high-power LEDs capable of creating the line light source with the required intensity are on the market. But even increasing diode efficiency is not enough, and so much waste heat is generated that both the thermal resistance of the device and the cooling system need to be addressed. For such light sources, passive cooling methods are no longer sufficient and active approaches are needed. It is possible to use fans to circulate the air and remove heated air from the device away to the environment. But water cooling is an even more effective solution, so the research project focused on the development of a special extruded profile with a cooling channel and with heat removal through the circulation of the coolant.

However, research also concentrated on the overall thermal optimization of the line light source being developed. The partial aim of the work was to determine the thermal resistance of individual parts of the equipment and to propose modifications so that the total thermal resistance and maximum temperature are within the required limits. First, the PCB itself was analyzed and modifications were made to reduce its thermal resistance. Subsequently, the hydrodynamics of the channel and the heat transfer in it were assessed, especially with regard to ensuring the conditions for turbulent flow. The overall thermal resistance of the profile with the cooling channel was determined and the total thermal resistance of the entire device was then established. On the basis of performed calculations and simulations and proposed modifications, a design of a powerful cooling device with the optimum inlet temperature was subsequently carried out. Also, a hydraulic calculation was made for all important system components and regulation was designed to ensure economical and reliable system operation. The present paper focuses primarily on the part of the research concerning the determination of the thermal resistance of the printed circuit and suggestions for adjustments that could reduce it.

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2. LINE LIGHT SOURCE WITH WATER COOLING

2.1 Individual parts

In the development of the light with an effort to maximize the light output, it is necessary to pay attention to all details of its individual parts. The entire line light system consists of four main parts:

- the diode itself,
- PCB carrying a larger number of diodes,
- supporting profile with optical part, printed circuit and cooling channel,
- cooling system with pump and water-air cooler.

Diode: For its performance, the XLamp XP-L High Density LED diode from CREE (Cree® XLamp® XP-L LEDs, n.d.) was selected to provide the light output. At the moment, it is probably one of the most powerful commercially available diode on the market with huge light (but also thermal) performance. Its basic parameters are: power 10 W, maximum current 3 A, maximum luminous flux 1150 lm, thermal resistance 2.2 °C/W.

Printed circuit board: PCB are used for mechanical attachment and electrical connection of components. There are different types of sheet materials with different properties on the market. The analysis of the PCB prototype using calculations and CFD simulations and suggestions for improvement are described in the following chapters.

Profile: The skeleton of the entire line light source is an extruded profile (Fig. 1). Its function is primarily carrying and cooling. At its top, optical elements are fixed to maximize the concentration of light in the desired area. Below are printed circuit boards with diodes. The channel through which the refrigerant flows is located at the bottom.

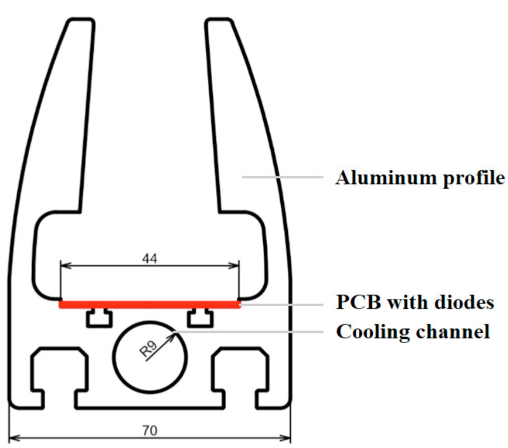

Fig. 1. Simplified side view of profile

Cooling system: An earlier design of the entire cooling system with an inlet temperature of 50 °C was considered for PCB analysis. However, the project proposed a new system with the coolant inlet temperature of 30 °C. The complete cooling system consists of a circulation pump, coolers, safety valves, expansion and storage tank, thermostatic mixing valve and cooling channel itself. The cooling channel is placed in an aluminum profile, and here the heat from the system is removed. An important parameter is the safe crossing of the boundary between the laminar and turbulent behavior of the coolant. It is a classic case of forced internal convection with constant heat flow. To save operating costs, the system was divided into operation in winter and summer, when the design of coolers that cool the liquid to the desired level differs.

2.2 System requirements

When designing a high power light source, it is important to consider mainly two parameters. Firstly, it is the maximum temperature of the diode that is important for its proper operation and which should not be exceeded during operation, otherwise the required luminous intensity, efficiency and diode life would decrease. The second important monitored parameter is the total thermal resistance of the device, which gives an idea of the temperatures on the individual components of the system and the requirements for the coolant with which the system can still be operated without any negative effects on its functionality.

The light output of each diode is dependent on its temperature. The maximum temperature that XLamp XP-L is capable of withstanding is 150 °C (critical junction temperature, JT). However, at this temperature it does not reach its maximum light output. Based on the relative luminous flux dependence on the junction temperature given by the manufacturer (Cree® XLamp® XP-L LEDs, n.d.) and as a compromise between the maximum luminance and the real temperature that can be achieved by the diodes under such conditions, the maximum diode temperature requirement for the proposed light source was set to 120 °C.

Knowing the thermal resistance of the system is crucial for the correct determination of the maximum cooling temperature at whitch the diodes are still running at full power. The smaller the thermal resistance the system is designed for, the less requirements can be placed on the coolant. Thus, by optimizing the thermal resistance correctly, the energy required to cool the coolant can be saved and the cost of the complete cooling system can be reduced too. The required maximum thermal resistance of the system 10 K/W was determined based on the maximum current versus ambient temperature indicated by the manufacturer (Cree® XLamp® XP-L LEDs, n.d.) and the liquid inlet temperature that the current cooling system is capable of achieving at least favorable ambient temperature.

3. SINGLE-DIODE PCBS

Printed circuit boards are distinguished primarily by the material used to make their core - the PCB with the laminate or metal core. When using high-power light emitting diodes, a large amount of waste heat is generated and the PCB has to meet high demands on the overall heat conduction resistance. This chapter focuses on calculating these factors. The following chapters then deal with suggestions for improving the design solution and CFD simulations of the individual printed circuit types to determine the most suitable.

3.1 Basic types of printed circuit boards

The most used and cheapest types of PCB are those whose construction consists of a laminate board (FR4 - cuprextit), a thin layer of copper and a layer of solder. In Fig. 2 is a cross-sectional view of the PCB. The bottom layer which is formed by a heat-conducting paste, will be placed on an aluminum profile. The diode will be soldered to the upper solder layer. The materials and properties of the individual layers are in the following table.

Fig. 2. Cross-section of laminated PCB

Table 1. Laminate PCB materials

Material	Thickness (mm)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
SnAgCu solder	0.100	58
Copper	0.035	398
Laminate core	1.600	0.2
Heat conducting paste	0.100	8.5

With increasing diode performance, it was necessary to replace the insulating laminate with materials with better thermal properties. Two seemed appropriate - aluminum and copper. The function of electrical insulation was taken over by a thin dielectric layer. The section of the aluminum core joint is shown in Fig. 3. The properties of the materials of the individual layers are shown again in the table (Table 2).

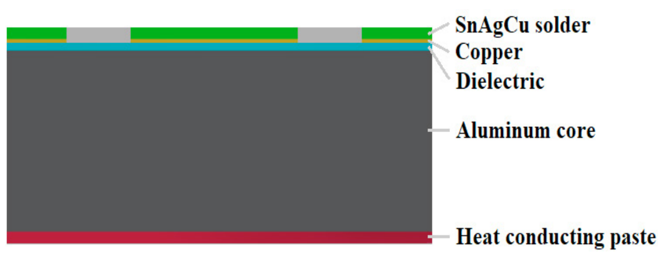

Fig. 3. Cross-section of aluminum PCB

Table 2. Aluminum PCB materials

Material	Thickness (mm)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
SnAgCu solder	0.075	58
Copper	0.035	398
Dielectric	0.076	2.4
Aluminum core	1.600	150
Heat conducting paste	0.100	8.5

An even better PCB, with better thermal properties than aluminum, is formed by replacing the aluminum core (in Fig. 3 and Table 2) with a copper core (thickness 1.6 mm and thermal conductivity 398 $W \cdot m^{-1} \cdot K^{-1}$). Other layers and their properties remain the same.

3.2 Thermal flow through anode and cathode

Because both calculations and simulations need to know how the heat generated on the chip heats the area beneath it, a test was performed to monitor the underside of the diode while gradually heating it. An infrared camera was used for this purpose. The aim was to find out the temperature distribution on the individual parts of the diode.

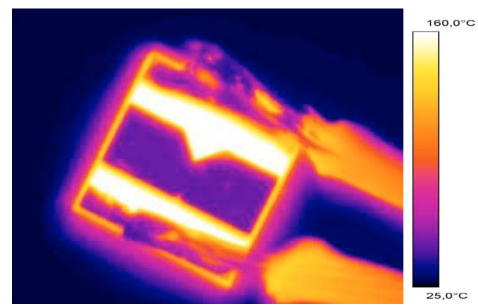

Fig. 4. Infrared camera image - temperature distribution at the bottom of CREE X-lamp XP-L

It was found out from the test that the whole underside of the diode is heated by the chip in the middle approximately equally over the entire cross section. Thus, it can be assumed that the heat flows through the anode, cathode and center will depend only on the size of their surfaces. Thus, the percent flow distribution by individual diode portions is 22% both by anode and cathode and 56% by centered.

3.3 Calculation of PCB thermal resistance

For optimum function and selection of suitable joints (materials and distribution of individual layers) it is necessary to know its ability to dissipate the heat generated on the diode chip into the aluminum profile and cooling channel. Heat conduction through a wall is given by Fourier's low, where q is the heat flow (W/m^2), λ is the thermal conductivity ($W/(m \cdot K)$), t_h is the thickness (m) and ΔT is the temperature difference (K) (Lampinen, Assad and Curd, 2001).

$$\dot{q} = \lambda \frac{\Delta T}{t_h} \tag{1}$$

The ability of the material layer to conduct heat depends on its thermal conductivity, cross-sectional area and thickness. This property can also be characterized by the thermal resistance of the material, and after the previous equation has been edited, a relation (2) is created (R is the thermal resistance (K/W), S is the area (m^2)).

$$R = \frac{t_h}{\lambda \cdot S} \tag{2}$$

The material properties required to calculate the total thermal resistance of single-diode PCB according to equation (2) are shown in the previous tables. The required dimensions are derived from the recommended dimensions of the XLamp XP-L solder plate and are shown in Fig. 5. (Cree® XLamp® XP-L LEDs, n.d.).

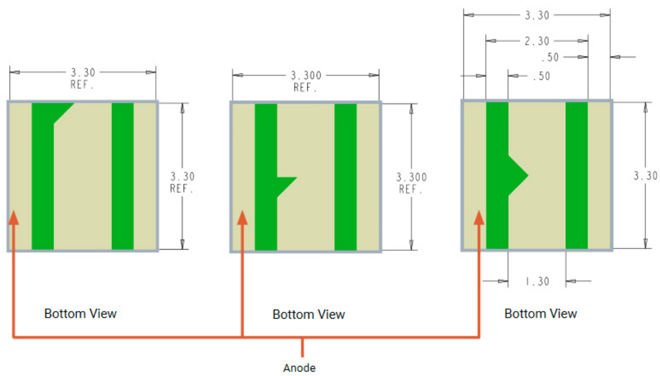

Fig. 5. Alternative bottom views of the XP-L High Density LED (Cree® XLamp® XP-L LEDs, n.d.)

By replacing the individual layers of the joint with partial resistors, a resistivity scheme shown in Fig. 6 is produced. The + sign represents the anode, - the cathode, and C the center. Due to the analogy between the heat flow and the electric current, the same rules can be used for composing the thermal resistances as for composing the electrical ones, serial and parallel connections.

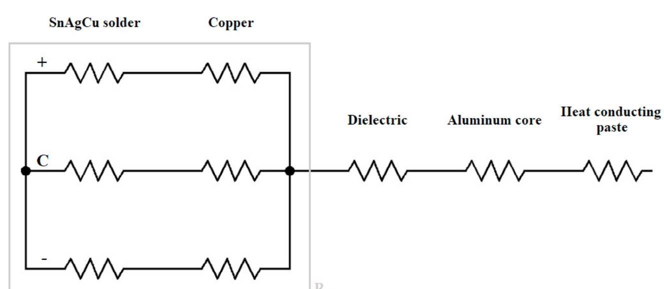

Fig. 6. Resistance scheme of aluminum printed circuit board

3.4 Resulting total thermal resistance of the PCB

Laminate PCB: In this type of joint, the laminate thermally non-conductive core has a decisive influence on the overall thermal resistance. Its resistance is so great (R = 734 K/W) that it will not be considered further.

Aluminum PCB: The thermal resistances of the individual parts and layers of the joint with the aluminum core and the procedure for calculating the total thermal resistance are shown in Table 3, where R_p is the thermal resistance of the parallel portion of the resistor scheme in Fig. 6 and R is the total thermal resistance of the printed circuit.

Table 3. Thermal resistance of individual parts of aluminum PCB

Part	SnAg Cu	Cu	R_p	Diele ctric	Al core	Past e	R (K/W)
+	1.04	0.05					
C	0.40	0.02	**0.24**	4.17	0.98	1.08	**6.47**
-	1.04	0.05					

Copper PCB: When replacing the aluminum core with the copper core, the overall thermal resistance of the joint is reduced. In Table 3, the core resistance decreases from 0.98 (Al) to 0.37 (Cu) and thus the total thermal resistance decreases from 6.47 to 5.86 K/W.

As is clear from the previous text, the use of the copper core PCB would be most appropriate for the overall thermal resistance of the joint. To optimize the entire system consisting of diodes, PCB, aluminum profile and cooling channel so that the total thermal resistance is less than the required 10 K/W, when the board itself has the thermal resistance of around 6 K/W and the LED has the resistance of 2.2 K/W, there are not many options left for the thermal resistance of the aluminum profile and the cooling channel. On the basis of these facts, it was decided to create a study dealing with the possibilities of reducing the thermal resistance of the PCB in order to design the most suitable printed circuit (material, construction) for the line light source.

4. SUGGESTIONS FOR MODIFYING THE DESIGN SOLUTION TO REDUCE PCB THERMAL RESISTANCE

It is evident (from Table 3) that the dielectric layer has a major influence on the overall thermal resistance. If the total heat resistance is to be reduced, it is necessary to pay the most attention to this layer. Another option is to modify the metal core.

4.1 Change the thickness of the metal core

The standard thickness of the metal PCBs is 1.6 mm. Some manufacturers offer the possibility to reduce this parameter and thereby reduce the thermal resistance of the metal layer. As can be seen from (2), the thermal resistance is directly proportional to the material thickness. By reducing the thickness to half, we also reduce the resistance by half, for example, for an aluminum core, the total resistance is reduced from 6.47 to 5.98 K/W.

4.2 Creating a thermal vias

A way to improve the heat transfer of the PCB is to add thermal vias - plated through-holes (PTH) between the conductive layers as shown in Fig. 7 (Optimizing PCB Thermal Performance for Cree® XLamp® LEDs, n.d.). The vias are created by drilling holes and and copper plating them or filling them with heat conducting material. This will result in thermal transitions formation and the overall resistance of the dielectric layer will decrease. The technology and materials for drilling and filling holes can be different.

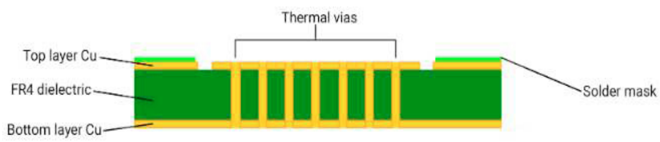

Fig. 7. Cross-section geometry with thermal vias (not to scale) (Cree® XLamp® XP-L LEDs, n.d.)

When designing this solution, attention should be paid to the accomplishment technology, as different metals have different thermal expansion and not all metals should be combined. For example, a combination of aluminum and copper is not recommended because of the high corrosion effect, while a combination of copper and tin is very suitable. A CFD simulation of temperature distribution for this design is given in the following chapter.

4.3 *Creating a thermal bridge*

An even more effective solution is offered by the American manufacturer Cofan USA (COFAN USA, 2019), where the dielectric layer under the middle of the solder pad is completely removed and replaced by the so-called thermal bridge (see Fig. 8). This thermal bridge will cause the temperature difference between the heat transfer paste and the solder layer to fall to a minimum, resulting in a PCB with the lowest thermal resistance on the market.

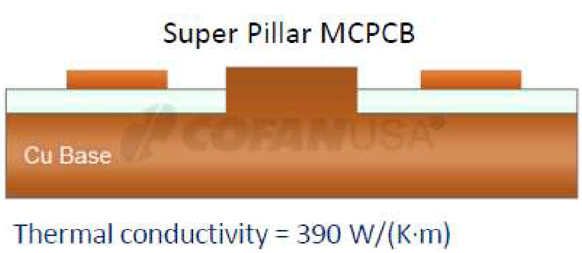

Fig. 8. Super Pillar MCPCB (COFAN USA, 2019)

5. CFD SIMULATION OF SINGLE DIODE PCBS

Based on the dimensions and features listed above, a single diode model was created in Autodesk Inventor in three variations:

- PCB with aluminum core,
- PCB with copper core and thermal vias,
- PCB with copper core and thermal bridge.

A network with a corresponding base cell size was set to each model part. The solid-state physics for heat transfer calculation in programme STAR-CCM+ is given by computational models and material properties, in particular thermal conductivity λ, of the substance. It is therefore necessary to create a physical model for each material with the following parameters: Steady, Segregated flow, Constant density and Solid. The mentioned material properties are prescribed by the parameter "Solid". The boundary conditions must also be determined.

Fig. 9. Computational network of printed circuit model with thermal vias

After all three single diode PCB simulations were created, the average temperature of the upper and lower side of the joint (tin and heat conducting paste) was evaluated. With a known difference in temperature and heat flow, the thermal resistance according to formula (3) can be determined. The results for all variants are shown in the following table.

$$R = \frac{\Delta T}{\dot{q}} \tag{3}$$

Table 4. Results for three variants of single-diode PCB

PCB type	Avg. temperature (K)		ΔT (K)	R (K/W)
	Top	Bottom		
Al core	325.8	280.0	45.8	6.1
Cu core with thermal vias	318.1	286.2	31.9	4.3
Cu core with thermal bridge	312.7	288.9	23.8	3.2

As can be seen by comparing Tables 3 and 4, the difference between the analytical calculation of the thermal resistance of the aluminum PCB and its derivation from the average wall temperatures from the simulation is approximately 6%. The resulting deviation is caused by the fact that the relationships for the one-dimensional heat conduction were applied to the analytical calculation. However, as can be seen from the following figure, the heat-affected region is slightly larger than the dielectric-copper contact area. Therefore, the relationships for 1D heat conduction cease to apply, since the heat flux also propagates in the transverse direction of the material.

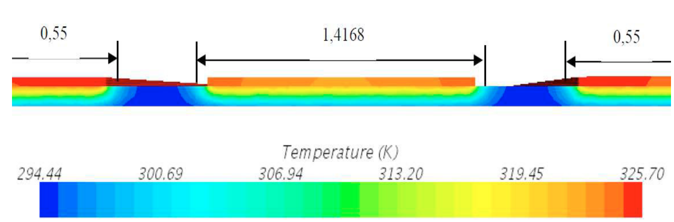

Fig. 10. Detail of temperature distribution of dielectric layer of aluminum joint

In this case, the book VDI Heat Atlas (VDI, 2010) talks about 2D heat conduction and introduces the notion of shape factor k, which extends the known equations 1D heat conduction by the coefficient of heat propagation in the cross direction. It represents the ratio between the area really affected by heat S_2 and the contact area of the walls S_1. On the basis of measuring the dimensions of the affected area S_2 (S_2 = 8.32 mm^2) from the simulation and determining the area S_1 (S_1 = 7.59 mm^2) from the solder pad dimensions (see Fig. 5), the factor k = 1.1 was calculated. As a result, the dielectric layer resistance changes to 3.8 K/W, and the total resistance of the aluminum board changes to 6.1 K/W. Considering 2D conducting and shape factor, the analytical calculation of the thermal resistance corresponds to the value obtained from the simulation.

6. SELECTION OF THE MOST APPROPRIATE PCB SOLUTION

The new type of PCB must be designed with regard not only to the overall thermal resistance but also to other parameters. Since the PCB must also be sufficiently rigid to not bend due to thermal expansion, the change in core thickness is unacceptable (the change leads to only a small reduction in thermal resistance but to a great reduction in overall stiffness). The creation of thermal transitions, either by drilling the dielectric layer or by the copper thermal bridge, faces the lack of experience of the companies that produce printed circuit boards. However, the drilling and copper plating of the dielectric layers are technologically easier than milling the copper core to form a thermal bridge. And so it was decided to the second variant, i.e. the copper PCB with three copper-plated holes in the dielectric layer subsequently filled with brazing mixture CuSnAg during the soldering process. Despite this, the reduction in thermal resistance should be enough distinctly and sufficient.

7. MULTI-DIODE PCBS

Previous calculations and simulations were performed for a single diode on the PCB. In the design of the linear light, however, is obviously calculated with multiple LEDs. To achieve the desired luminous flux, the spacing between the LEDs was determined to be 4 mm. In order to obtain a light total length of 4 m, when the printed circuit design is largely determined by the series connection of individual diodes, and when trying to maintain a reasonable voltage, the PCB was arranged in 4 parallel circuits, each with 13 series-connected diodes. Then, 16 such PCBs connected in parallel were ranged behind each other (250 mm each). The electrical parameters of the proposed line light are then: 832 diodes, 48 V voltage, 192 A current, and 9216 W power.
The task of the next research was to create the CFD simulation again and to determine the thermal resistance of the printed circuit with more diodes and to compare the results with the results in the previous chapters to determine the effect of adding diodes to the overall resistance. The simulation was based on an earlier simulation of a single diode PCB. However, more diodes and the actual width of the heat conducting paste, metal core, and dielectric layer were simulated. The power loss of the PCB was also considered. As a sufficiently representative sample to determine the overall thermal resistance of the printed circuit, a model with ten diodes and dimensions of 44.6 x 44.0 mm was chosen. The results of the simulation are evident from Fig. 11 and Fig.12 of the distribution of horizontal and vertical temperatures in the printed circuit. The average temperature of the bottom and top of the joint in the simulation was then evaluated by the appropriate report. The simulation result is a determinated temperature difference ΔT = 29.6 K.

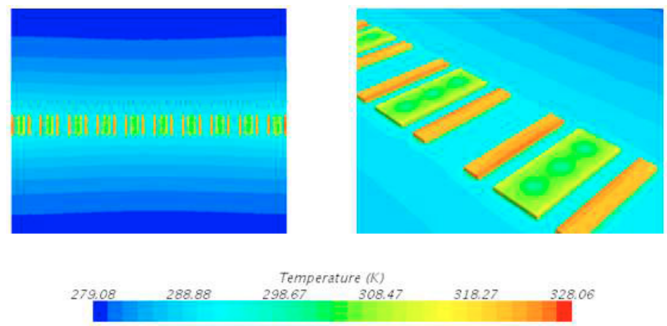

Fig. 11. Horizontal temperature distribution and detail of solder pads in the middle of the joint

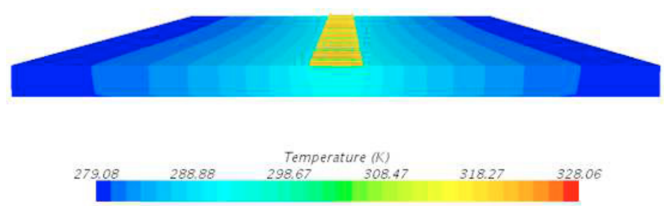

Fig. 12. General view - horizontal and vertical temperature distribution in printed circuit boards

The equations for one-dimensional heat conduction show that the adding of diodes increases the heat flux flowing into the system and reduces its thermal resistance, but the temperature difference ΔT between the top and bottom remains the same. However, in simulations, heat conduction is considered in all directions. By spreading the heat flow not only in the vertical direction to the cooling channel but also in the horizontal to the surroundings of the individual diodes, the thermal resistance decreases due to the enlargement of the "active area of material". The resulting thermal resistance was calculated to 4 K/W (versus 4.3 K/W of one diode).

8. RESULTS AND FULFILLMENT OF ESTABLISHED REQUIREMENTS

Based on the study of possible solutions for reducing the thermal resistance of the printed circuit and after verification by calculations and simulations, the PCB with copper core and thermal vias was chosen with respect to several parameters (described in chapter 6). The electrical calculation led to the design of a partial PCB with 52 diodes arranged in 4 parallel circuits, each with 13 series connected diodes. The dimensions of this PCB are 250 x 44 mm. The photograph of the produced and mounted PCB can be seen in Fig. 13. The next figure shows the X-ray image of the PCB part.

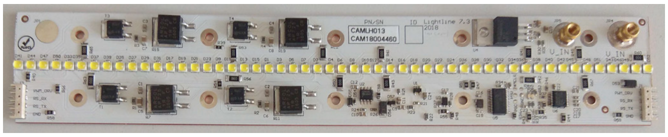

Fig. 13. The resulting PCB assembled with components.

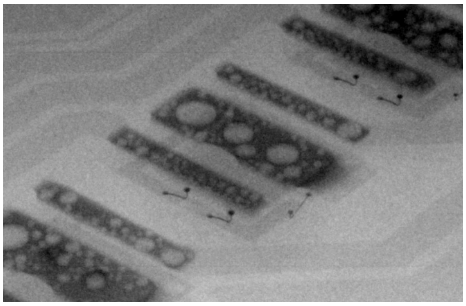

Fig. 14. Control X-ray image of PCB with soldered diode

The total thermal resistance of the system is given by the sum of the partial thermal resistances of the diode, the printed circuit and the carrier profile with the cooling channel. The manufacturer specified that XLamp XP-L diode resistance is 2.2 °C/W. The thermal resistance of the proposed PCB with vias in dielectric was determined to be 4.0 K/W (see previous chapter). The profile resistance was determined based on calculations and simulations to 1.5 K/W (not subject to this article). The total thermal resistance of the system is therefor 7.7 K/W, so the requirement for the maximum thermal resistance of less than 10 K/W has been met.

Thanks to the knowledge of individual thermal resistances, it is possible to determine the temperatures in the whole system. Temperatures were calculated at the most telling places - at the inlet, at the center and at the outlet of the system. The results for the inlet coolant temperature 50 °C are shown in Table 5. The highest system temperature reaches 112.9 ° C for the last diode at the system output. The total temperature difference between the inlet fluid and the last diode is 62.9 °C. The second requirement, the diode temperature of less than 120 °C was also met. Possibilities to further decrease the temperatures in the system or to provide a larger reserve with respect to using more powerful diodes in the future is to reduce the inlet coolant temperature. Therefore, the project proposed a new cooling system with the coolant inlet temperature of 30 ° C.

Table 5. Partial system temperatures

Position of the measured temperatures		Teperature (°C)		
		start	means	end
Liquid – Profile R = 1,5 K/W	liquid	50,0	52,5	55,0
	channel wall	54,5	57,0	59,5
	bottom of the PCB	60,6	63,7	66,8
PCB R = 4,0 K/W	bottom of the PCB	60,6	63,7	66,8
	upper side of PCB	90,2	93,3	96,4
Diode R = 2,2 K/W	bottom side of diode	90,2	93,3	96,4
	upper side of diode	106,7	109,8	112,9

9. CONCLUSIONS

The presented paper focuses primarily on the part of the research concerning the determination of PCB thermal resistance and suggestions for adjustments that could reduce it. The subject of interest was mainly the core material of the PCB, since the most commonly used classic laminate core has low thermal conductivity and is thus unsuitable for heat dissipation. Therefore, the aluminum and copper core was also considered. By replacing the individual joint layers with partial resistances in the overall resistance scheme, the total thermal resistance of the joint was determined. Because the results have shown that thermal resistance, even when using the aluminum or copper core, is still unacceptably large, three modifications to the design have been proposed to reduce it. Suggestions were submitted to CFD simulation. With regard to other parameters, e.g. board stiffness and technological complexity, the solution with copper core and with three thermal vias was chosen. This innovative solution reduces the thermal resistance of the PCB by 30% compared to the classical aluminum core. The results were then transferred to multi-diode PCBs. Combined with other parts of research related to the design and simulation of the profile and to heat transfer to the cooling channel, the overall thermal resistance and the maximum temperatures in the individual parts of the device were determined (for the inlet temperature of coolant 50 °C). The total thermal resistance of the system is 7.7 K/W compared to the required up to 10 K/W. The highest temperature of the system reaches 112.9 °C, when the demand was set at the maximum of 120 °C.

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