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Innovative heat transfer analysis of LED modules by thermal simulations

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A critical analysis of the heat transfer processes in LED module via 3D CFD thermal modeling is made in the current work. A 3D thermal model of LED matrix is created and its thermal efficiency is investigated. The thermal stresses in the structure are derived from the thermal simulations and approaches for optimization of the design and increase of the reliability are proposed. For this purpose digital models of structures of the printed circuit board with various configurations of thermal vias were created. An analysis of FR4 PCB with 4, 5 and 9 thermal vias is made and the effect of different filling materials - air, copper and SnAgCu is made, in order to clarify the complex interrelationships of heat transfer in the structure.

Key words: heat transfer, LED modules, CFD simulations, thermal management, thermal via, reliability

INTRODUCTION

Despite its high efficiency power LEDs produce large amounts of heat during operation. The large amount of heat, together with the small dimensions of the LED chips results in an increase of the operating temperature. Prolonged operation at high temperature has a negative impact on the reliability and lifetime. The operating temperature should not exceed the maximum allowable temperature of the junction T_j of the chip. Heat dissipation from the LED structure to the environment is a task in which there are many complex connections between the components [1, 2]. This requires the use of innovative techniques for the analysis of heat transfer in order to optimize the structure and improve the reliability. This paper deals with some innovative techniques for fast and reliable study of heat transfer processes in the LED modules to optimize the design and increase reliability.

This article addresses some innovative techniques for fast and reliable study of heat transfer processes in the LED modules for optimization of the design and increasing of the reliability.

For the heat transfer analysis a CFD (Computational Fluid Dynamics) software FloTherm, by Mentor Graphics is used. 3D models of LED matrix, consisting of 3×4 (12) white LEDs mounted on a printed circuit board are created in the software. To create the reference 3D model of the LED matrix a LED matrix with known electrical parameters and physical dimensions of the LED chip is used, as well as the circuit board on which they are mounted. The internal structure of the circuit board is knows, as well as the materials of the constituent layers and their size (width, length and thickness).

The thermal stresses in the structure of the reference model are detected by the conducted CFD thermal simulations and approaches to improve heat transfer are proposed. For that purpose 3D models are generated, which include variations of the circuit board structure of the circuit board with thermal vias.

PCB structures with different configurations of thermal vias (4, 5 and 9 respectively) in the insulating FR4 material of the PCB and also in the FR4 bilateral copper foil are tested. An analysis of the impact of different filling materials for the thermal via (air, copper and SnAgCu) on the structure heat transfer is made.

Data, obtained from the simulations is summarized and can be used by engineers, dealing with the problems of thermal design.

DESIGN OF THE REFERENCE LED MATRIX

The LED matrix, which we will use to create a reference digital model represents an array of 3×4 (total 12) white SMD LEDs located on a FR4 PCB.

The LEDs are model PLCC6 (5050) with three chips in one case and have the following dimensions: $5 \times 5 \times 1.6$ mm. Fig. 1a shows what the LED looks like (PLCC6 (5050)), and Fig. 1b shows the entire LED matrix.

Some technical features of the LEDs in the matrix are shown in Table 1.

The PCB, on which the LEDs of the LED array are mounted, has the dimensions $220 \times 290 \times 1.07$ mm.

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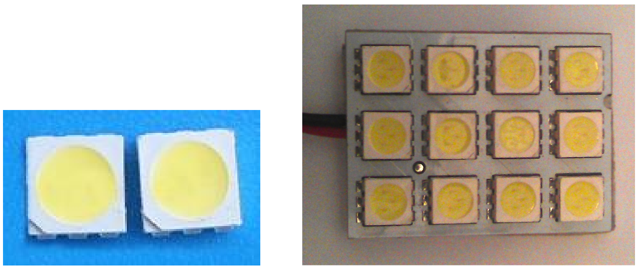


(a) **(b)**

Fig. 1. (a) SMD LED (5050); (b) LED matrix.

Table 1. Specifications of SMD LED series PLCC6 (5050)

Parameters	**Value**
Materials of the LED	InGaN
Viewing angle	120°
Forwarding voltage	3.2 V
Forward current (typ/max)	3 x 20 mA / 3 x 25 mA
Power dissipation	0.3 W
Operating temperature range	-40°C ∼ 100°C
Storage temperature	-40°C ∼ 100°C
Soldier temperature range	260°C (3 sec.)

The basic material, from which the board is made is FR4, and has a thickness of 1 mm. The FR4 insulating material on the top and bottom plate is covered with a copper foil, which has a thickness of 35 μm.

The adhesive for soldering the LEDs on the board is H2OS and has a thickness of about 50 μm. Fig. 2 shows a cross-sectional view of the entire structure (PCB and LEDs).

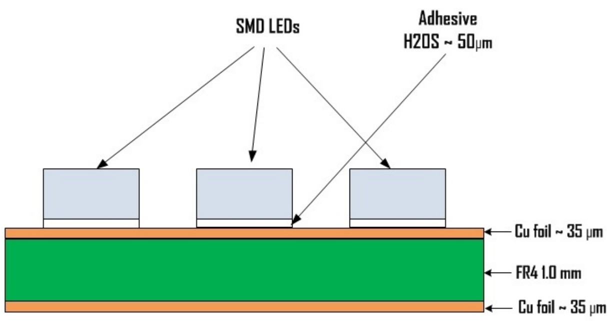


Fig. 2. Cross-section of the circuit board and LEDs - PCB base of FR4, which is bilateral copper foiled, H2OS glue to attach the LEDs, the material of each LED chip is InGaN.

ANALYSIS OF HEAT TRANSFER OF THE REFERENCE LED MATRIX

To create the digital 3D model a for thermal simulation software FloTherm, by Mentor Graphics is

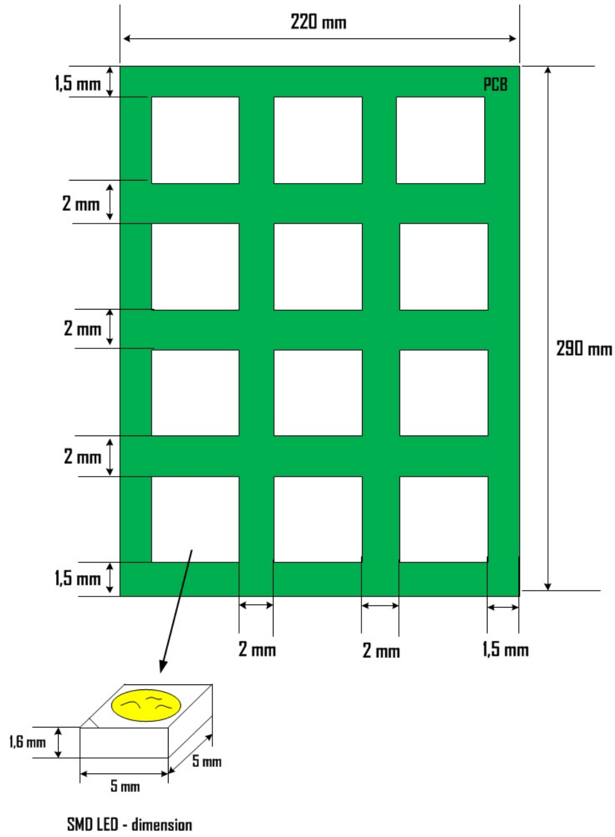


Fig. 3. Geometry of the LED array, which will be used to create a digital 3D model.

used. Flotherm is a powerful CFD tool with the help of which airflow, temperature, and heat transmission of electronic components and whole systems can be predicted [3].

Fig. 3 shows the geometry of the reference LED matrix that is used to create the digital model. The digital model is a simplified model of the LED matrix structure, with the help of which its thermal behavior is examined.

Each LED is modeled as a separate heat source and dissipates power of 0.13W. Due to the complex structure of the LEDs, they are presented as cubes with their real sizes. As it is known the heat, released by the junction of the LED chip is dissipated mainly through the PCB by conduction and from the free surfaces to the environment by radiation and convection [4].

It is therefore of extreme importance the correct modeling of the circuit board for the analysis of heat transfer processes in the LED array.

Table 2 shows the thermal characteristics of the materials, making up the PCB, which are used in the digital simulation.

Table 2. Characteristics of the PCB materials.

			Thermal
Layer	**Material**	**Thickness**	**conductivity**
Layer	**Material**	(μm)	(W/m.k)
Adhesive	H2OS	50	3.25
Top-layer foil	Cu	35	400
Dielectric layer	FR4	1000	0.8
Bottom-layer foil	Cu	35	400

Results of the thermal simulations made by FloTherm, via the instrument Visual Editor are shown in Fig. 4 and Fig. 5.

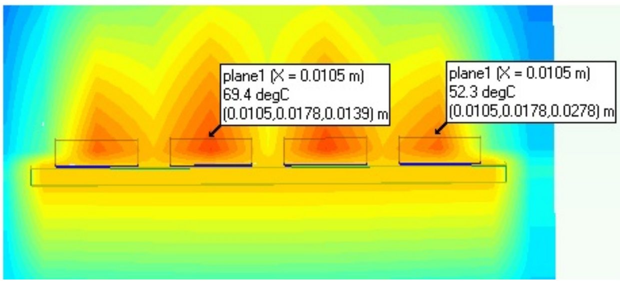


Fig. 4. Distribution of heat in the structure of the LED matrix.

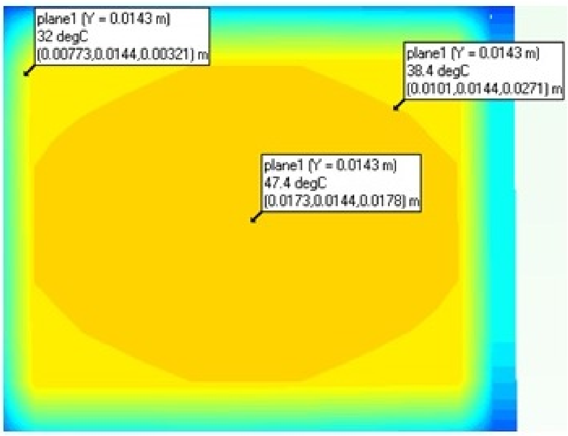


Fig. 5. Distribution of heat on the underside of the circuit board.

For the simulation the thermal behavior of LED matrix at a supply voltage of 12 V and current of 130 mA is studied. The maximum power P_D of a LED is a product of the multiplication of the forward voltage U_F and the current I_F. Thus by substituting the appropriate values for voltage and current, the power P_D of the LED matrix is

$$P_D = U_F I_F = 12\text{ V} \times 0.130\text{ A} = 1.56\text{ W} \quad (1)$$

Simulations are made at an ambient temperature of 25°C. They show that the temperature of LEDs, which are located closer to the center of the PCB is 69.4°C, and the temperature of LEDs at the periphery of the PCB is 52.3°C. The high temperature of the LEDs in the center is due to their great proximity to one another, a relatively high power, which is dissipated, compared to the size of the PCB, and the poor thermal conductivity of the PCB.

The distribution of heat on the bottom of the circuit board shown in Fig. 5 demonstrates the thermal load around the center of the board. It is seen that the temperature in the center is 47.4°C, by increasing the distance from the center temperature rapidly decreases to 38.4°C, and at the very end of the PCB, where there is more space, the PCB temperature is 32°C.

From the conducted simulations and the analysis of the results it can be concluded that despite the small power of the LED matrix it releases large amounts of heat, which may have negative impact on its reliability. Therefore an optimization needs to be done, in order to improve the heat exchange in the matrix structure.

In the next section methods to improve the heat transfer of the LED matrix by using thermal vias in the PCB are proposed.

OPTIMIZATION OF THE REFERENCE LED MATRIX MODEL

The simulations in the previous section show that FR4 circuit boards have very low thermal conductivity and cannot dissipate heat efficiently. One method for improving heat transfer of FR4 boards is by adding thermal vias in the PCB layers. Using thermal vias is common in thermal design, but still there is no exact method of where to place them or what their configuration must be [5].

In this point there are studied various structural modifications of the already created digital model of LED matrix. The studies include various configurations of PCBs with various locations of the thermal vias, which are most commonly used. The effect of thermal vias on the heat transfer on the board at configuration with 4, 5 and 9 vias, located beneath each of the LEDs, and different filling material are analyzed [6, 7]. In all simulations the thermal vias have a diameter of 0.5 mm.

Fig. 6 show various configurations of the thermal vias and the distance between them.

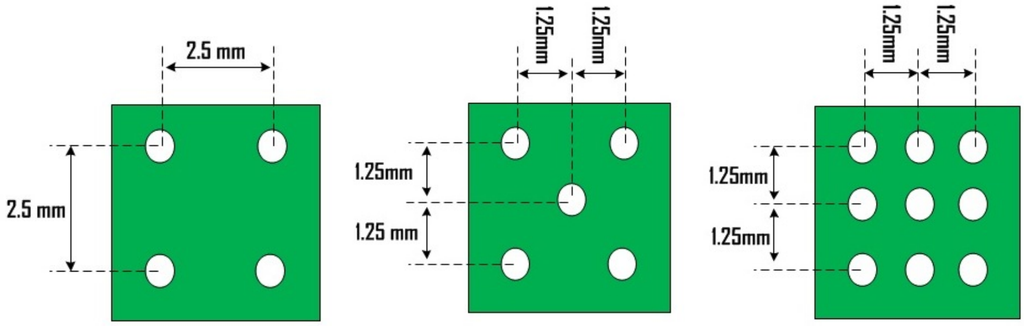


Fig. 6. a) 4 vias configuration; b) 5 vias configuration; c) 9 vias configuration.

Different configurations and parameters for CFD simulations are shown in Table 3.

Table 3. Parameters for thermal simulations.

PCB parameters			
PCB dimensions: 22×29 mm; Thickness: 1.07 mm			
LED parameters			
LED dimensions: 5×5 mm; Thickness: 1.6mm			
Power dissipated per a LED: 0.13 W			
PCB via configuration			
Diameter of the via,mm		0.5	
Via configuration	4	5	9
Filled via (Material)	Air Cu SnAgCu	Air Cu SnAgCu	Air Cu SnAgCu
Thermal conductivity of the via, (W/m.k)			
Material of the via	Air Cu SnAgCu		0.0261 400 58

The geometry of the PCB and the location of the LEDs remain the same as the reference LED matrix model. The physical dimensions and properties of the PCB materials and LEDs also remain unchanged.

The results of the conducted thermal simulations of the created LED matrix model with configuration of 4 thermal vias at a different filling material are shown on Fig. 7.

The geometry of the PCB and the location of the LEDs remain the same as the reference LED matrix model. The physical dimensions and properties of the PCB materials and LEDs also remain unchanged.

The results of the conducted thermal simulations of the created LED matrix model with configuration of 4 thermal vias at a different filling material are shown on Fig. 7

From the simulation of the 4 thermal via model it is obvious that the temperature of the LED close to the center of the PCB is the highest when the thermal vias are filled with air - 59.5°C. In the first case, in spite of the presence of thermal vias in the structure of the LED matrix the heat cannot be dissipated effectively due to the low thermal conductivity of the air ($K_{\mathrm{air}} = 0.0261$ W/m.k). However, the dissipation of heat from the structure of the 4 thermal via model, filled with air is significantly better than the reference model without thermal vias. This can be seen from the temperature markers, placed on the LEDs of the simulated models on Fig. 4 and Fig. 7.

As expected, the temperature of the copper filled vias model is the lowest - 57.8°C and the heat dissipation throughout the structure of the circuit board is most effective. This is confirmed by the markers, placed at the same places on the circuit board in the three examined cases. There it is clearly seen that the PCB with copper filled vias is the coldest. This is due to the good thermal conductivity of the copper ($K_{\mathrm{copper}} = 400$ W/m.k), which effectively channels the heat from the source through the PCB to the surrounding area.

In the case of 4 thermal vias, filled with soldering paste SnAgCu the temperature of the LEDs and the bottom side of the board is close to those, filled with copper. The difference in the temperatures of the LEDs near the center of the structure is $\Delta T_d = T_{d_{\mathrm{SnAgCu}}} - T_{d\_\mathrm{Cu}} = 58.6 - 57.8 = 0.8$°C, and the temperature on the bottom side of the circuit board is in the center $\Delta T_{\mathrm{pcb}} = T_{\mathrm{pcb}_{\mathrm{SnAgCu}}} - T_{\mathrm{pcb}_{\mathrm{Cu}}} = 40.9 - 40 = 0.9$°C. These results show that the temperature distribution in the structures of the two examined models is with a very similar behavior.

No. **Thermal simulation by Flotherm of the whole structure of the LED matrix** **Temperature distribution on the underside of the circuit board**

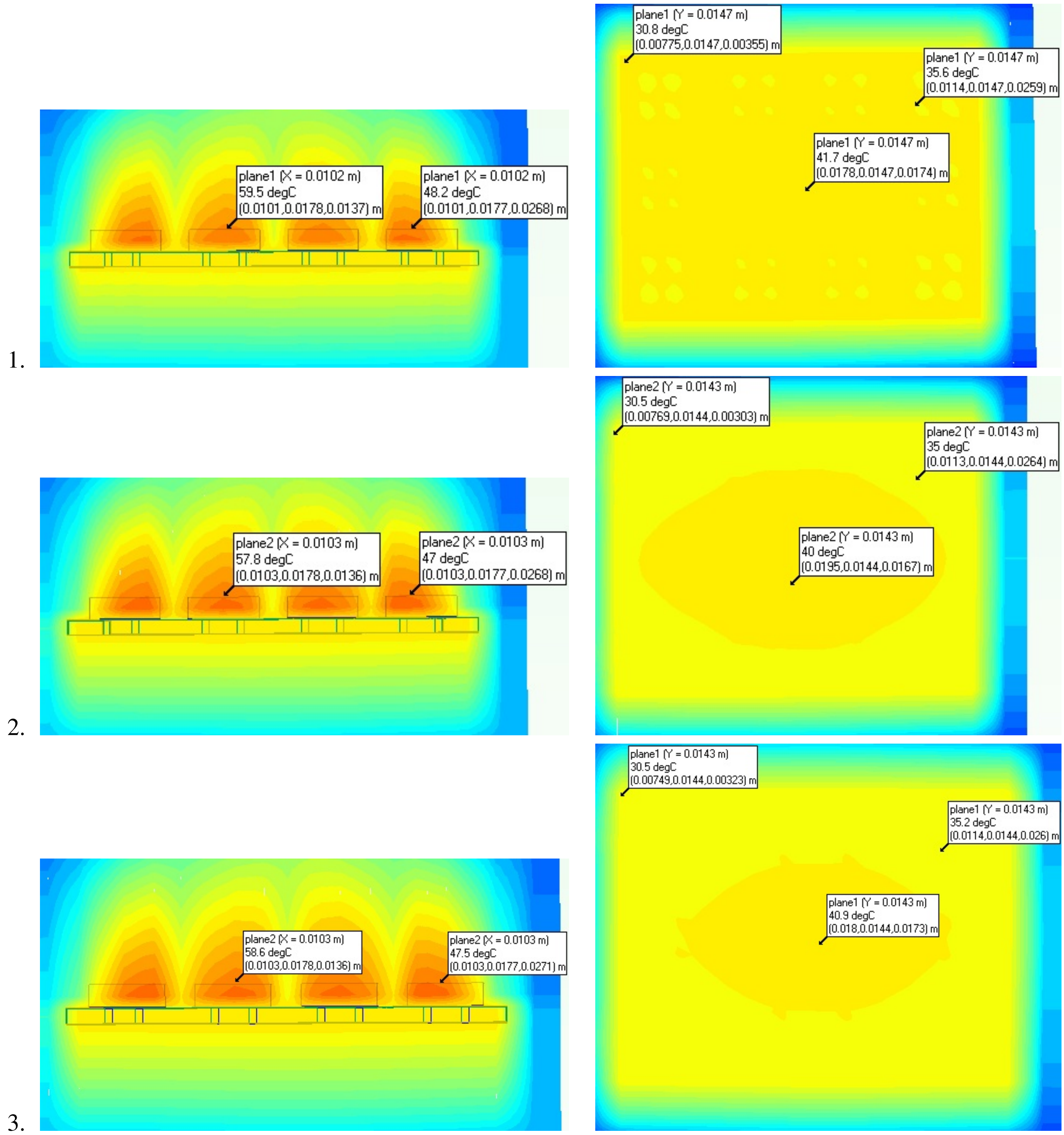


Fig. 7. Simulations with 4 thermal vias filled with different material: 1) filled with air; 2) filled with Cu; 3) filled with SnAgCu.

The simulation results from a configuration with 5 thermal vias, filled with different filling materials are shown in Fig. 8.

The simulation shows that the temperatures of the LEDs and the circuit board of each of the models with 5 thermal vias drops by a few degrees. Again the temperatures of the models with vias, filled with copper and those filled with SnAgCu paste are very

No.	Thermal simulation by Flotherm of the whole structure of the LED matrix	Temperature distribution on the underside of the circuit board

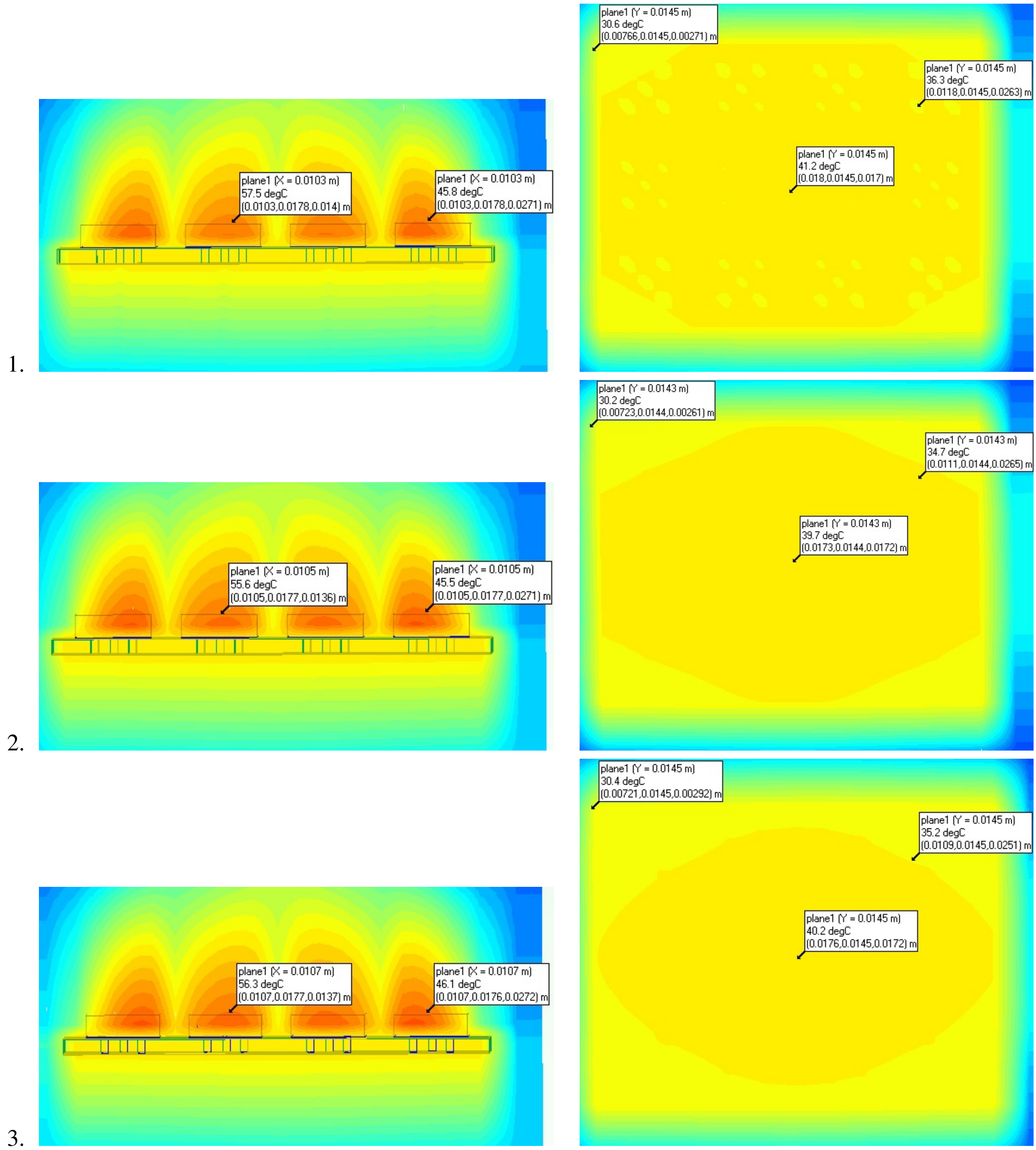
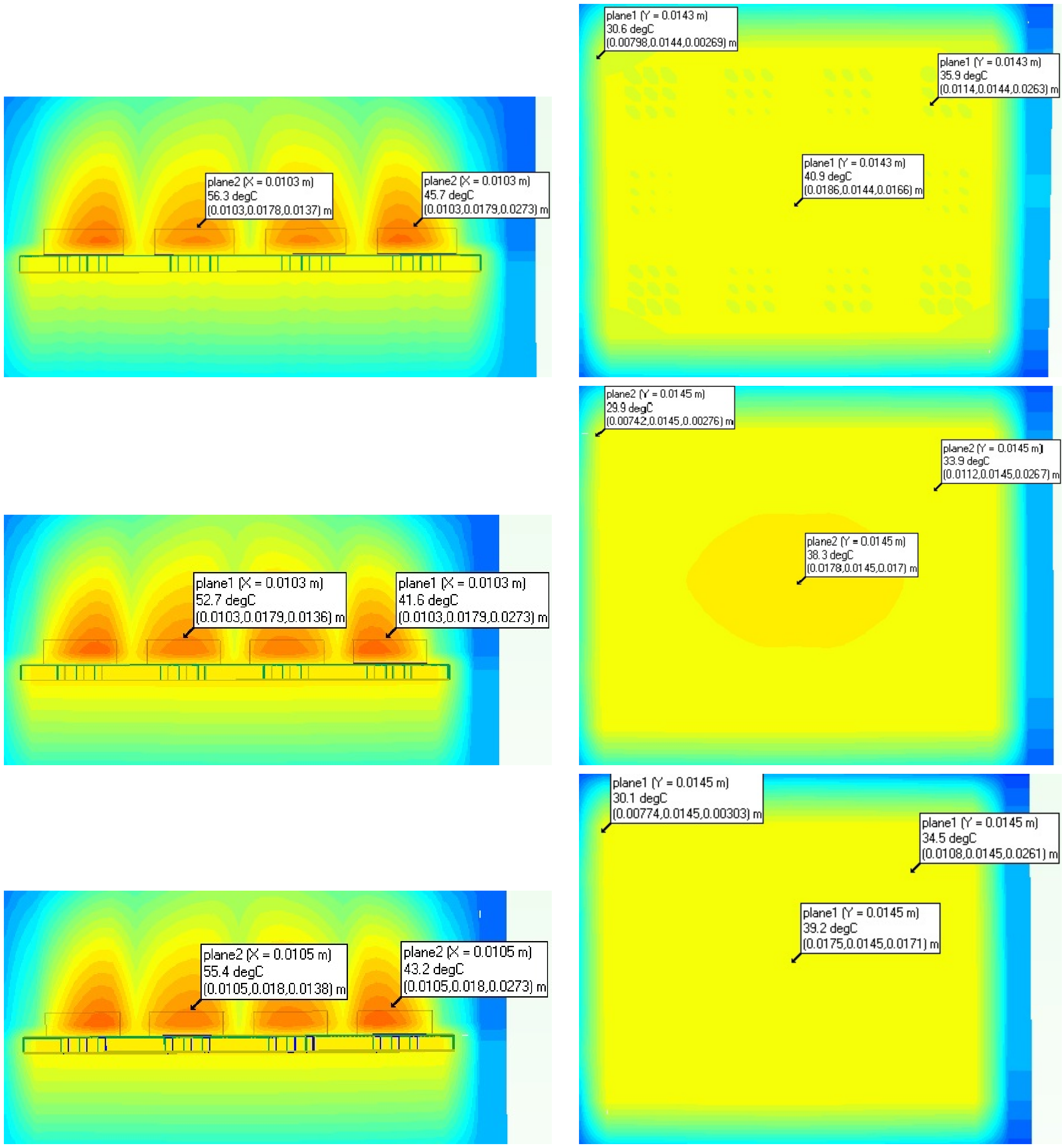


Fig. 8. Simulations with 5 thermal vias filled with different material: 1) filled with air; 2) filled with Cu; 3) filled with SnAgCu.

close, while the temperature of the model with thermal vias, filled with air remains significantly higher in the whole structure.

The results of the simulations for the 9 thermal vias configuration are shown in Fig. 9

No. **Thermal simulation by Flotherm of the whole structure of the LED matrix** **Temperature distribution on the underside of the circuit board**



1.

2.

3.

Fig. 9. Simulations with 9 thermal vias filled with different material: 1) filled with air; 2) filled with Cu; 3) filled with SnAgCu.

Table 4 summarizes the temperature results for simulations with 4, 5 and 9 thermal vias. In the table, T_d is the temperature of the LED, near the center of the structure, and T_{pcb} is the temperature at the center of the underside of the circuit board.

A graphical representation of the temperature profiles for the various via configurations and filling materials are presented in Fig. 10 and Fig. 11.

Table 4. Temperatures, generated by the thermal simulations with various thermal via configurations and different filling material

Thermal vias configuration	**Thermal vias filled with air**		**Thermal vias filled with Cu**		**Thermal vias filled with SnAgCu**	
	T_d (°C)	T_{pcb} (°C)	T_d (°C)	T_{pcb} (°C)	T_d (°C)	T_{pcb} (°C)
4	59.5	41.7	57.5	40	58.6	40.9
5	57.5	41.2	55.6	39.7	56.3	40.2
9	56.3	40.9	52.7	38.3	55.4	39.2

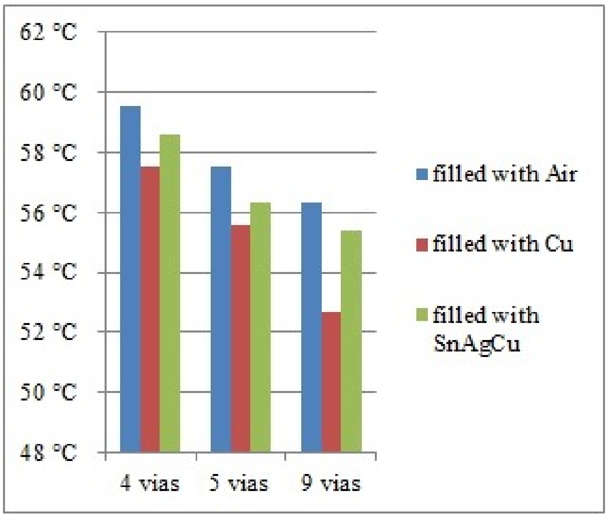


Fig. 10. Temperature of the LED close to the center of the circuit board.

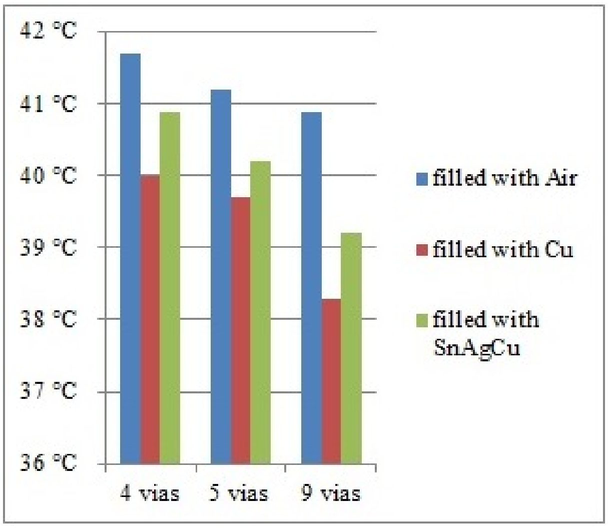


Fig. 11. Temperature at the center of the circuit board.

When comparing the results of Fig. 10 and 11 it can be seen that by increasing the number of vias the LEDs and the circuit board temperatures are reduced in each of the examined cases. The temperature difference of the LEDs near the center in the configurations with 4 and 9 thermal vias, filled with air is $\Delta T_{d_{air}} = T_{d_{4vias\_air}} - T_{d_{9vias\_air}} = 59.5 - 56.3 = 3.2°C$. In the configurations with 4 and 9 thermal vias, filled with copper the difference is $\Delta T_{d_{Cu}} = T_{d_{4vias\_Cu}} - T_{d_{9vias\_Cu}} = 57.5 - 52.7 = 4.8°C$. Lower temperature decrease of the LEDs is observed in the case of vias filled with paste SnAgCu paste, respectively $\Delta T_{d_{SnAgCu}} = T_{d_{4vias\_SnAgCu}} - T_{d_{9vias\_SnAgCu}} = 58.6 - 55.4 = 3.2°C$.

The temperature differences on the bottom side of the PCB are much smaller, for example in configurations with 4 and 5 thermal vias, filled with air it is $\Delta T_{pcb_{air}} = T_{pcb_{4vias\_air}} - T_{pcb_{5vias\_air}} = 41.7 - 41.2 = 0.5°C$, between those with 4 and 9 vias it is $\Delta T_{pcb_{air}} = T_{pcb_{4vias\_air}} - T_{pcb_{9vias\_air}} = 41.7 - 40.9 = 0.8°C$. In the other cases with 4 and 5 vias, filled with copper the difference is $T_{pcb_{4vias\_Cu}} - T_{pcb_{5vias\_Cu}} = 41.7 - 41.2 = 0.5°C$, and between 4 and 9 vias the difference is $T_{pcb_{4vias\_Cu}} - T_{pcb_{9vias\_Cu}} = 41.7 - 40 = 1.7°C$. The results for vias, filled with SnAgCu paste are similar.

SUMMARY OF THE OBTAINED RESULTS

From the obtained results it can be concluded that by increasing in the number of thermal vias the heat transfer in the test structure in each examined case is significantly improved. By increasing the number of thermal vias, the thermal conductivity of the circuit board is increased, which significantly improves the heat transfer. While increasing the number of vias it is very important to take into account the temperature changes and the temperature gradients, in order to find the optimal solution for the specific needs.

Simulations show that when the thermal vias are filled with a material, having a high thermal conductivity, the heat is transferred substantially more efficient trough the circuit board because of the lower thermal resistance. Thermal vias, filled copper provide the lowest thermal resistance and thus dissipate the heat better. They are suitable for high-power LED applications. Thermal vias, filled with SnAgCu are cheaper than copper and, although having a smaller thermal conductivity convey heat well and are suitable for low-power LED applications. Thermal vias, filled with air improve heat transfer, but to a smaller extent. They have a large thermal resistance and heat cannot be channeled well from the source through the PCB to be dissipated in the surrounding area.

In conclusion from the obtained results we can say that the proposed method for improving the heat transfer of the reference LED structure leads to a considerable temperature decrease in the structure, especially in the case with 9 copper filled thermal vias. The reduced temperature of the LED matrix reduces the thermal stress and increases the reliability.

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ИНОВАТИВНО ИЗСЛЕДВАНЕ НА ТОПЛООБМЕНА В СВЕТОДИОДНИ МОДУЛИ ЧРЕЗ ТОПЛИННИ СИМУЛАЦИИ

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(Резюме)

В настоящата работа е направен критичен анализ на топлообменните процеси в светодиоден модул чрез 3D CFD топлинно моделиране. Създаден е топлинен 3D модел на светодиодна матрица и е изследвана неговата топлинна ефектиност. От направените топлинни симулации са намерени топлинните напрежения в структурата и са предложени подходи за оптимизация на конструкцията и повишаване на надеждността. За тази цел са създавани цифрови модели на конструкции на печатната платка с различни конфигурации топлинни отвори. Направен е анализ на FR4 печатна платка с 4, 5 и 9 топлинни отвора и е изследвано въздействието на различни запълващи материали – въздух, мед и SnAgCu, за да се изяснят комплексните взаимовръзки на топлоотвеждането в структурата.