

# Integration of electronic system with electro-thermally cooled IR detector: thermal analysis

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**Abstract.** The paper presents thermal investigations of an idea of encapsulation in common, miniature package both preamplifier circuit and infrared photodetector cooled with the aid of four-stage thermoelectric module. Conducted numerical simulations show that the presence of electronics at printed circuit board with either ceramic or laminate substrate negligibly affects operation of thermoelectric cooler and hence, the operating conditions of the detector. Higher thermal loads are reported when placing wideband electronic system on the additional thermoelectric module. Even though, such solution reduces temperature difference between infrared sensor and the other part of electronics, additional cooler increases the amount of heat that must be dissipated from the package to the ambient.

## 1. Introduction

The history of infrared (IR) photon detectors reaches almost 100 years [1, 2], nowadays. In this class the semiconductor IR detectors should be pointed out as the one with rapid development. They offer selective wavelength dependence of the response per unit incident radiation power, high signal-to-noise performance and a very fast response. Even though, recently, more and more attention is given to near room temperature applications [2], higher performance parameters are available only when the photodetectors are cooled down to 200 K or even below. Temperature range of 240 K to 190 K can be assured by miniature thermoelectric coolers (TEC) [3]. Application of TEC allows creating system operating in room temperature from the point of view of end user [4], although IR detector is being cooled.

Further improvement in performance parameters of the detection modules demanded by modern optoelectronic applications can be obtained by integration of infrared sensors with wideband electronic systems. On the one hand, placing the preamplifier in the close proximity of the detecting structure allows increasing operational frequency and reducing the noises [1, 3]. On the other hand, in the case of electro-thermally cooled photodetectors, heat dissipating electronic system creates an additional heat load for the detector and its thermo-electric module (TEM). Higher thermal conditions result from convection mechanisms developing easier within bigger space of the package dedicated for the integrated solution (temperature at highest stage of TEM can be of 15 K higher due to convection and radiation [5]) and from the wire connection between the detector and the electronic board mounted in the locations with 100 K temperature difference [6]. Especially, the latter factor can be a serious problem



due to the fact that heat amount transported through electric short connections can easily exceed several mW and double or triple the heat losses of the IR detector. Hence, higher temperature at the highest stage of the TEM is obtained and it affects detector operation.

The paper presents thermal investigations of miniature package with mounted thermoelectric cooler for photodetector and preamplifying system at printed circuit board (PCB) located next to it. Different assembly configuration and different materials solution regarding PCB substrate have been examined together with additional TEM option. Moreover an influence of ambient temperature on the whole system operation is analysed and discussed.

## 2. Models of multi-stage thermoelectric coolers

To analyse thermal coupling of IR photodetector and preamplifying electronic circuit integrated in common miniature package, thermal model of multi-stage thermoelectric cooler (TEC) has been elaborated. Within the model, the thermo-electric behaviour has been replaced with thermal compact approach, already presented in [7] and by the authors in [5] for single and multi-stage solutions, respectively. The general idea here is to substitute the sets of semiconductor pellets with uniform domains with equivalent thermal conductivity and heat sources corresponding to heat absorption and dissipation due to Peltier and Joule heating effects. It simplifies using the model with computational fluid dynamics (CFD) code. These heat sources are defined as:

$$Q_{absorb,i} = 2 \cdot N_i \cdot T_{ji\_C} \cdot \alpha \cdot I \quad (1)$$

$$Q_{diss,i} = 2 \cdot N_i \cdot T_{ji\_H} \cdot \alpha \cdot I \quad (2)$$

$$Q_{J,i} = 2 \cdot N_i \cdot I^2 \cdot R_{eq} \quad (3)$$

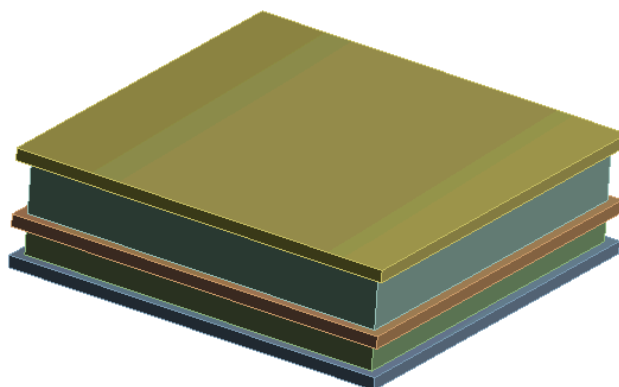
where:  $Q_{absorb,i}$  and  $Q_{diss,i}$  denotes heat rates absorbed and dissipated at the junctions of TEM  $i$ th-stage,  $T_{ji\_C}$  and  $T_{ji\_H}$  – temperature at the cold and hot junction of TEM  $i$ th-stage,  $N_i$  – number of thermocouples at  $i$ th-stage,  $I$  – Peltier current,  $R_{eq}$  – equivalent resistance of semiconductor pellet and parts of copper connections.

As exemplary structures, two TECs of RMT Ltd. Company have been chosen [8]: 2MX04-046-0510t and 4MD04-116-10. First of them is a two-stage stage solution selected for electronic circuit; while the second one is a four-stage TEC dedicated for photodetector mounting. Performance parameters of both thermoelectric modules are gathered in table 1. As an example, figure 1 shows modelled geometry of the two-stage TEC 2MX04 046-0510t, which contains 15 and 31 thermocouples at the first and the second stage, respectively. For both stages the width and depth of the equivalent thermal domain are the same; even though, the number of pellets differs.

**Table 1.** Performance parameters of chosen thermoelectric coolers at 300 K in vacuum [8].

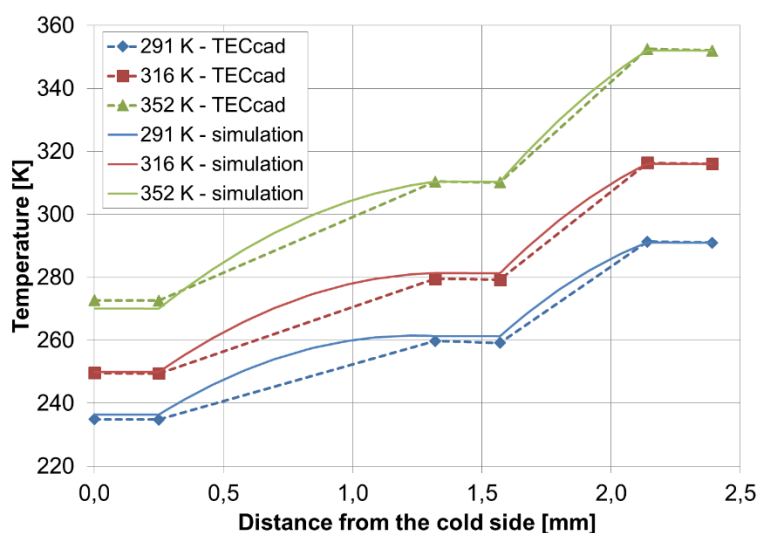
Margin	2MX04-046-0510t	4MD04-116-10
$\Delta T_{max}$ [K]	91	127
$Q_{max}$ [W]	1.59	0.30
$I_{max}$ [A]	1.1	0.5
$U_{max}$ [V]	3.9	8.4
N [-]	15/31	4/11/31/70

where N is a number of thermocouples at each stage.



**Figure 1.** Model outline of 2MX04-046-0510t thermoelectric cooler.

The elaborated model has been verified by comparing the results of simulations with the data supported by TEC producer, which are available in TECcad software [9] in the form of temperature values at particular junctions of the cooler. Figure 2 presents curves obtained for Peltier current of 0.7 A and three different values of temperature at the hot side. The data from the manufacturer are plotted with the aid of markers that for better visibility are connected with the aid of dotted lines. In CFD 3D simulations, the line, along which the data have been analysed, is the TEC's axis of symmetry. Good agreement between the numerical and experimental data taken from TECcad software confirms correctness of the elaborated model.



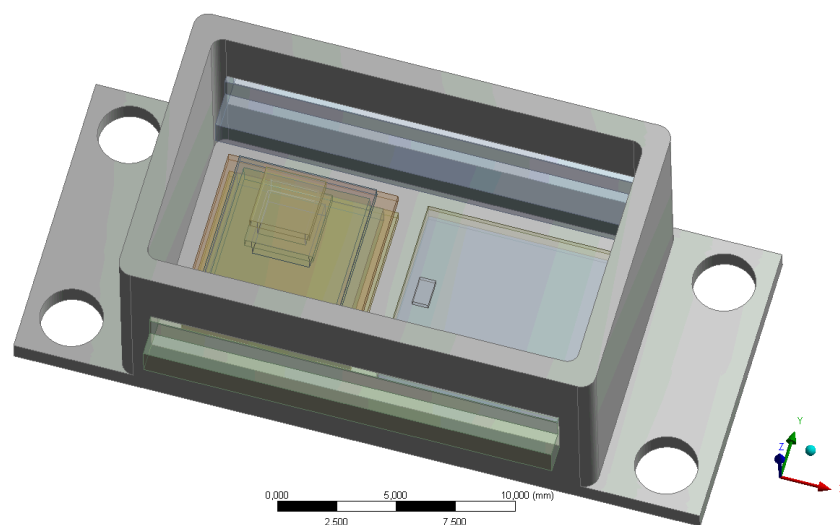
**Figure 2.** Comparison of temperature distribution within axis of 2MX04-046-0510t thermoelectric cooler with data from TECcad software [9].

### 3. Model of miniature package with integrated electronic circuit

Next, the elaborated model of four-stage TE cooler dedicated for IR detector has been integrated with electronic circuit within miniature FlatPack. A preamplifying system in a form of silicon die of the dimensions 0.7 x 1.2 x 0.25 mm is placed at printed circuit board (PCB) and located next to the photodetector TEC. Different solutions regarding PCB (assembly configurations) has been investigated:

- DCB (Direct Copper Bonding) – two side copper clad AlN ceramics where thicknesses of AlN and copper layers equal 0.63 mm and 0.3 mm respectively;
- Elevated DCB – the DCB board as above mounted at the copper dais, so the total thickness equals to 6.9 mm – the photodetector's TEC height;
- I-Tera – two side copper clad I-Tera laminate where thicknesses of isolator and copper layers equal 0.2 mm and 0.012 mm respectively;
- Additional TEM – additional two-stage TE cooler with AlN ceramics covered with copper conducting mosaic.

Geometry of an exemplary modelled structure is shown in figure 3.



**Figure 3.** Miniature package with thermoelectric cooler dedicated for photodetector and PCB with preamplifier.

Simulations have been conducted with the aid of ANSYS CFX software for the following assumptions and boundary conditions:

- ambient temperature varies in the range 10 to 70°C;
- heat sink of thermal resistance 2 K/W is mounted at the bottom surface of the package;
- all other surfaces exchange heat with surrounding due to the convection with heat transfer coefficient of 10 W/m<sup>2</sup>K;
- the package is filled with xenon gas;
- parameters of solid state materials used in modelled structure are gathered in table 2;
- gravity acceleration is directed opposite to the x-axis (the worst situation [5]);
- model of photodetector's TEC is elaborated for heat load at the highest stage of 10 mW and Peltier current of 0.45 A [5, 6];
- model of additional TEC is elaborated for heat load of 300 mW and Peltier current of 0.7 A;
- heat losses in preamplifier equals to 300 mW.

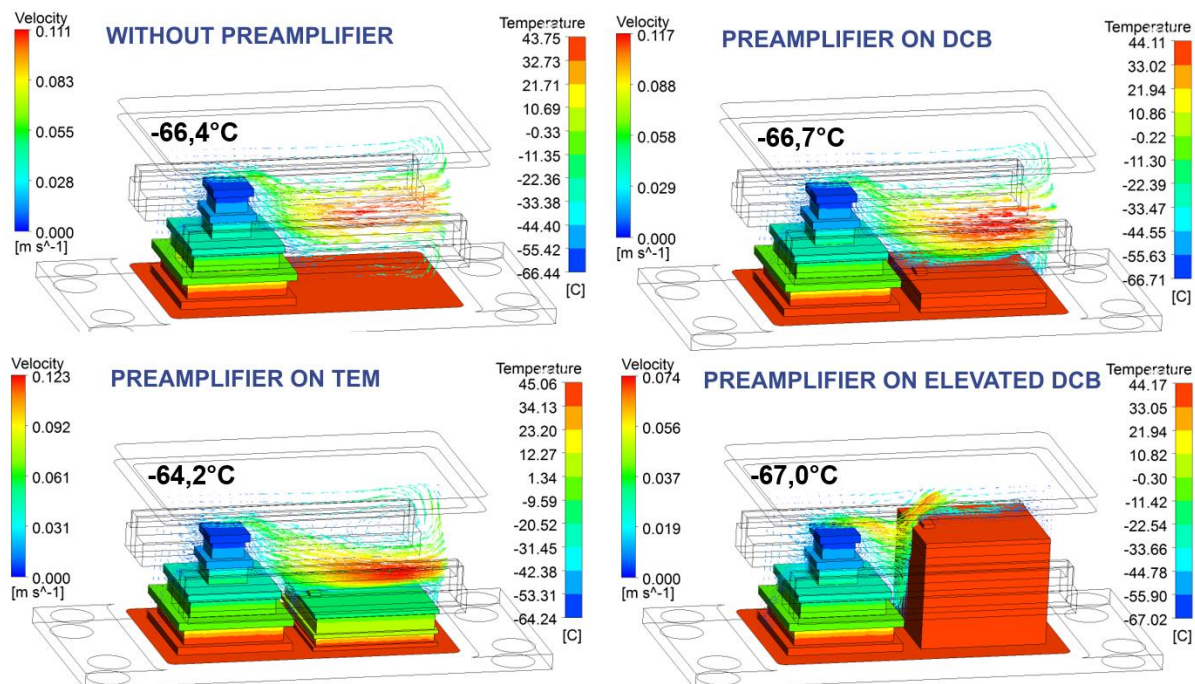
Exemplary temperature distributions at the internal surfaces (TEC and PCB), and velocity fields within the cross-sections of the modelled structures for three assembly configurations compared to situation without electronic circuit are presented in figure 4. The minimum temperature at the highest stage of the cooler is also marked in the figure. It can be noticed that the presence of the electronic circuit on any type of PCB almost does not affect the temperature distribution at the highest stage of TEC. Nevertheless, elevated DCB configuration influences velocity field within the package and slightly suppresses convection. The poorest conditions are achieved while using additional TEM for preamplifier

circuit due to higher heat load at the bottom of the package that affects operation of the detector's four-stage TEC. It should be emphasised that in this situation heat sink with lower thermal resistance is required to keep the temperature at the package at the same value as it was in configurations without additional TEM.

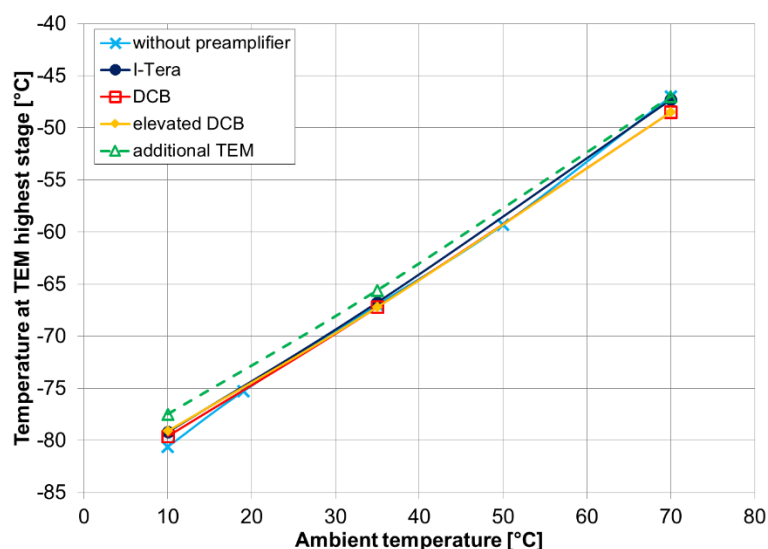
**Table 2.** Parameters of solid state materials used in modelled structure.

Material	Thermal conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m <sup>3</sup> ]	Emissivity [-]
tungsten/copper	190	163	16330	0.05
copper	401	380	8920	0.05
bismuth telluride	1,4	188	7850	0.36
silicon	150	710	2330	0.60
AlN ceramics	170	920	3300	0.90
I-Tera laminate	0.32	950	1850	0.90

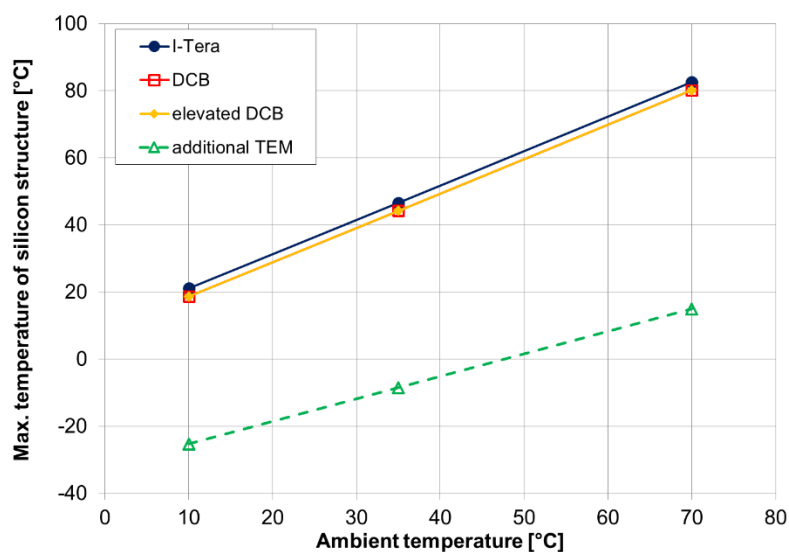
The influence of the ambient temperature on thermal conditions within the area of detector location and maximum temperature of preamplifying silicon structure is presented in figure 5 and 6, respectively. We can see that both temperature at the highest stage of TE cooler, as well as temperature of electronic element increase with increase of ambient temperature. Curves in figure 5 confirms that from the point of view of thermal load on detector's TEC, all investigated configurations are comparable, despite of additional TEM case. Temperature of electronic element differs significantly only in the case of mounting preamplifier on the additional cooler. In the case of PCB with much bigger thermal resistance (9.77 K/W for laminate based solution and 0.08 K/W for ceramic based solution) like I-Tera laminate solution in comparison to DCB board, temperature of semiconductor element is only 2.5°C higher.



**Figure 4.** Influence of different assembly configuration on temperature and velocity fields in the modelled package.



**Figure 5.** Temperature at TEM highest stage versus ambient temperature for different assembly configurations.



**Figure 6.** Temperature of silicon structure versus ambient temperature for different assembly configurations.

#### 4. Conclusions

Encapsulation in common miniature package of both preamplifier circuit and IR photodetector is a beneficial solution due to high performance parameters that can be obtained. Unfortunately, thermal coupling between these two electronic parts exists. Heat can be transported through gaseous medium filling the package, through the constructional elements of the package and through the solid connection between the detector and the wideband electronic system. In the paper, the latter factor has been assumed to be constant, but two first heat transport paths have been investigated. Results of conducted simulations have proven that the electronic system placed next to the thermoelectrically cooled detector has only slight influence on the TEC operation. Comparable thermal operating conditions for IR semiconductor structure can be assured when using PCB with either ceramics or laminate substrate for electronic system. Furthermore, the reduction of free convection within the package can be assured by elevated PCB solution. Assembling electronic circuit on additional TEC, even though reduces the temperature

difference between the detector and the remaining electronic part, generates additional heat loads and hence influences the operation of the detector cooler. Further investigation regarding thermal coupling through solid connections is demanded.

## 5. References

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