Thermal Characterization of an LTCC Module for Miniature Atomic Clock Packaging

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Abstract

This paper presents the thermal characterization of an LTCC module dedicated for the packaging of a miniature atomic clock. An LTCC device of dimensions of 15 × 22 mm^2 has been designed for the packaging of the elements of a miniature atomic clock. This module acts as a carrier for the components of the clock as well as temperature controller; this is particularly attractive since each component of the atomic clock requires precise and well defined working temperatures. For the thermal characterization of the designed module, various thermal simulations have been performed, by finite-element modelling using the software ANSYS; in each simulation a different experimental heating configuration was hypothesized, in order to determine the power required for achieving the desired temperature in the ideal case (module in perfect vacuum with no losses rather than conduction towards the external "cold" zone, through two small bridges) , and also for estimating the thermal losses that convection introduces into the system. The simulations were then experimentally validated: the configurations previously hypothesized and simulated, were experimentally realized; the experimental results were consistent with the simulations. The best experimental configuration was found, in which the heating performance was fairly close to the ideal one. The results show that LTCC is a very attractive technology for atomic clock packaging also in terms of dissipated power, if the system is efficiently insulated.

Keywords: LTCC, atomic clock, thermal simulation

1 Introduction

Atomic clocks [1-3] are devices able to measure time and frequency with a very high precision (accuracy of 10^{-9} seconds per year), and for this reason they are the base of communication networks and global positioning system (GPS) [4]. For such applications, from one side there is the need to reduce both size and power consumption of atomic clocks, in order to allow the spread of portable, eventually battery-powered devices [5,6,7]; from the other side the demand for high precision standards is also increasing more and more, with the massive diffusion of secure communications and precise navigation systems. In this context, the goal of this research is to fabricate a miniature, low power Rb atomic clock. The miniaturization level aimed is not the one achieved by MEMS technology: the designed device will be in the 10 cm^3 volume and 100 mW power range; the importance of this research is to conceive batch and reliable processes, which will allow a big reduction of the cost production of the devices. This paper presents an innovative packaging approach for miniature atomic clocks, using the LTCC [8] technology. The elements of atomic clocks need to be efficiently connected to each other, and some of them need a precise, stable and reliable temperature control: in particular, the light source needs a well-defined working temperature for emitting light at the right frequency, and also the mini-cell, in order to keep the frequency emitted by the Rb atoms fixed. The use of LTCC technology is particularly attractive for this application because of the possibility it offers to integrate temperature control and measurement, as well as other active elements (i.e. magnetic sensors) all in one packaging module [9,10]. This paper presents an LTCC module realized for carrying, temperature-stabilizing and interconnecting the elements of an atomic clock. The component of the clock will be attached onto one packaging module, and the different modules will be aligned onto a PCB support for building up the final system. Thermal simulations have been realized for simulating the behavior of the heating plate and estimating the minimum value of power required for achieving the desired working temperature (hypothesized, in the case of mini-cell, at 70°C), and the amount of loss that convection introduce into the system. The simulations were then experimentally validated.

2 The Designed LTCC Module

The designed LTCC module is equipped with a heating AgPd serpentine on the top layer, and a PTC resistor for temperature measurement on the bottom layer. It has an adjustable thickness of 400 μm, overall dimensions of 15 × 22 mm2; there is an aperture at the centre for letting the light passing through of dimensiosn 5 × 5 mm2 and the total heated area is 15 × 12 mm2. The heated area is insulated by the external "cold" area, were the electrical connections are placed: the two zones only communicate through two small external bridges, in the low-loss configuration. Other configurations are possible for this module, which introduce more conduction loss but make the module less fragile and able to carry heavier weight in case needed. The module is in fact equipped with 4 optional small bridges and another central bridge, bigger than the others (Fig.1b, red arrows). These bridges can be easily cut down in case a low-loss configuration is wished. Moreover, it is possible to change the temperature distribution along the heated area: the current flow in the bottom part of the heated area is in fact regulated by an SMD resistor, soldered on dedicated pads (fig.1a, red rectangle). This is useful for the mini-cell, for keeping the alkali metal away from the window. Photos of the designed device are shown in Fig.1 and Table 1:

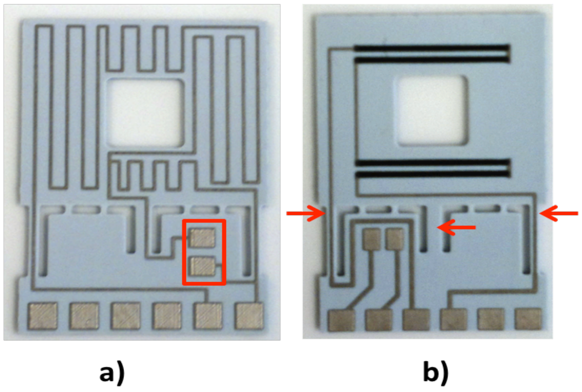

Fig.1: LTCC heater/carrier modules. a) top of the module, heating conductive serpentine for local temperature control, and SMD pads for regulating heat flow on the bottom part of the LTCC (red rectangle); b) PTC resistor for temperature measurement, external plus optional bridges (red arrows)

The detailed dimensions of the designed device are shown in Table 1.

Table 1: Detailed dimensions of the LTCC module

	Length [mm]	Height [mm]
Overal dimensions	15	22
Heated area	15	12
Aperture for light	5	5
External bridges	1	3.2
Optional 4 small bridges	0.5	0.7
Optional central bridge	1	3.2

Thermal Simulations Performed and Discussion

The software ANSYS was used for performing different finite-element simulations of the heating plate, and the value of power required for achieving 70°C was monitored. The simulations were performed on the module hypothesizing different configurations: firstly, the configuration was with the module equipped with all the optional bridges, then, the configuration with the central bridge and the external bridges was simulated, and finally it was simulated the configuration with only the external bridges. The temperature distribution along the heated area was observed in the different cases and then compared with the configuration in which the bottom part of the heating serpentine is short-circuited (mounting a 0 Ω SMD resistor on the dedicated pads of Fig.1a). All these simulations were performed hypothesizing no losses other than conduction in the LTCC bridges (complete vacuum, no radiation). Finally, the effect of convection on the heating and the losses that it introduces was also estimated, simulated and experimentally validated. The first configuration simulated was the module in its original layout, with the five thermal bridges intact that introduce a considerable conductivity loss. The outside zone ("cold" zone) was hypothesized being at 20°C. A fine mesh was used in this case, in order to carefully observe what happens at the bridge edge. Fig.2 shows a screenshot of the meshed device during the simulation: it is possible to clearly see that the bridges are finely meshed in order to estimate in the most accurate way the temperature distribution along these areas:

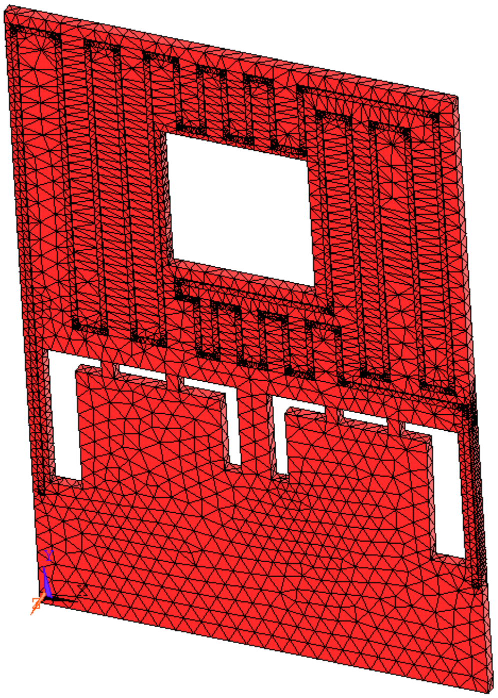

Fig.2:The results of the smart meshing of the LTCC device in its original configuration

The finite-element simulation shows a non-homogeneous distribution of the temperature, as expected. In this case, almost all the bottom part of the heated area results 10 to 15°C colder than the top part. This happens because the bridges introduce a considerable conduction loss between the heated zone and the zone of the electrical pads, hypothesized at 20°C. In this case, for achieving a temperature of 70°C (typical working temperature of the mini-cell), 4.6 V and 13.6 mA of current were necessary, which corresponds to a total power of 62.56 mW. The results of this simulation are shown in Fig.3:

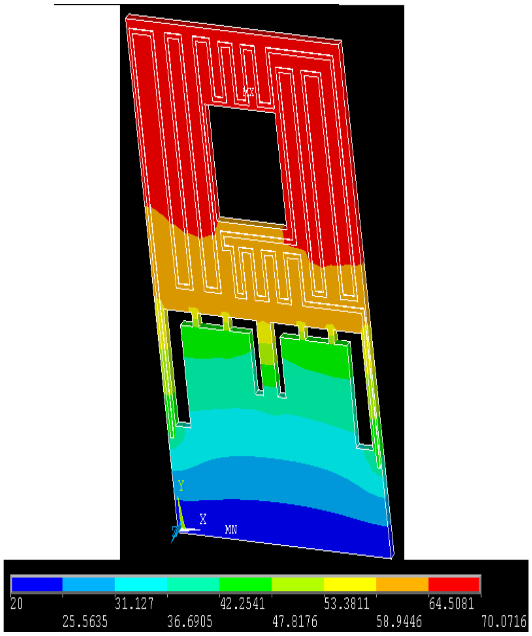

Fig.3: Results of finite-element simulation of the LTCC module in its original configuration

The next step was to simulate the LTCC module without the 4 intermediate small bridges, so when it is equipped only with the two external bridges and the central bridge. It is possible to see in this case that the temperature distribution is more homogeneous respect to the first case, and only the zones close to the bridges results colder than the top part of the heated area. The temperature difference is within the range of 10°C. In this case, 3.7 V and 10.9 mA of current were necessary to achieve the temperature of 70°C, so a total power of 40.33 mW. The power required for achieving the same temperature decreased of the order of 20% respect to the first case. This was expected because of course the conduction loss is decreased respect to the first case, due to the elimination of the 4 intermediate bridges which created a thermal short-circuit between the heated area and the cold zone. The result of this simulation is shown in Fig. 4:

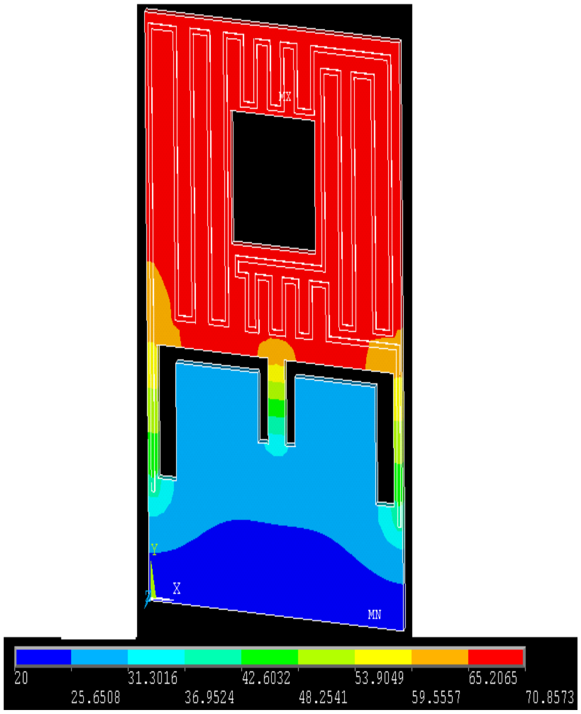

Fig.4: Result of the thermal simulation of the LTCC device equipped with te external and the central bridges only

The next step was to simulate the LTCC device in its low-loss configuration: in this configuration, also the central bridge is cut down, and the module is equipped only with the two external bridges, mandatory for letting the current flow from the pads through the serpentine. The module in this configuration is more fragile, but still it can withstand without problems the weight of a mini-cell for a miniature atomic clock. On the other hand, it offers better performances in terms of heating. In this case, the temperature distribution along the heated area is homogeneous: colder zones are observed only in the bottom corners, the small areas close to the external bridges. In this configuration, 3.25 V and 9.6 mA were necessary to achieve the temperature of 70°C, that is a total power of 31.2 mW. The power required for achieving the same temperature decreased of around 50% respect to the first case (LTCC with all the bridges). The result of this simulation is shown in Fig.5:

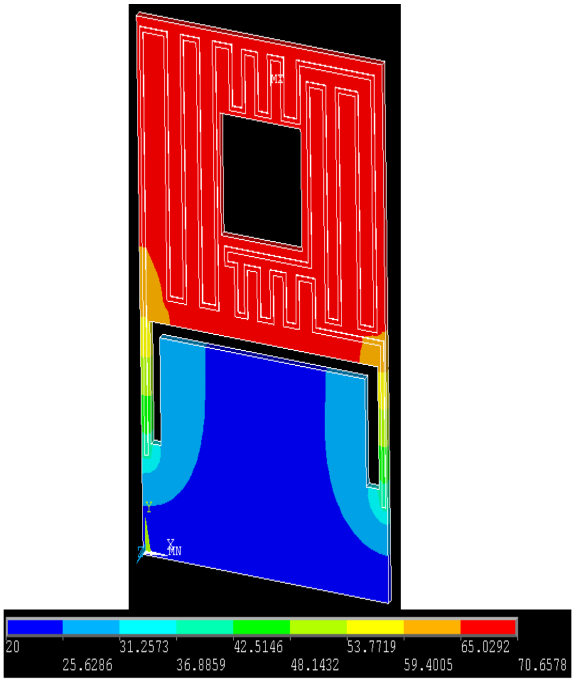

Fig.5: Result of the thermal simulation of the LTCC module in its low-loss configuration

As previously explained, this module allows the alteration of the temperature distribution along the heated area by an SMD resistor that regulates the current flow on the bottom of the heated area. It is desirable to have a colder zone in case the LTCC acts as carrier/temperature controller for the mini-cell, for keeping the alkali metal away from the window. Another finite element simulation was performed hypothesizing that the value of the SMD resistor that regulate the flow of current into the bottom part of the serpentine is equal to 0Ω: this means that there is no current flowing on the bottom part of the serpentine, so the temperature gradient along the heated area is maximum. The result of this simulation is shown in Fig.6. As it is possible to see, the temperature difference achieved between the bottom and the top of the heated area is again in the range of 10°C. In this case the power required for achieving the temperature of 70°C is 43.3 mW(3.7V, 11.7 mA): this means that in this case, with the bottom part of the serpentine short-circuited and the four optional small bridges cut we got more or less the same temperature gradient of the first case, when the LTCC was in its original configuration, but for achieving the same temperature we need around 20% less power.

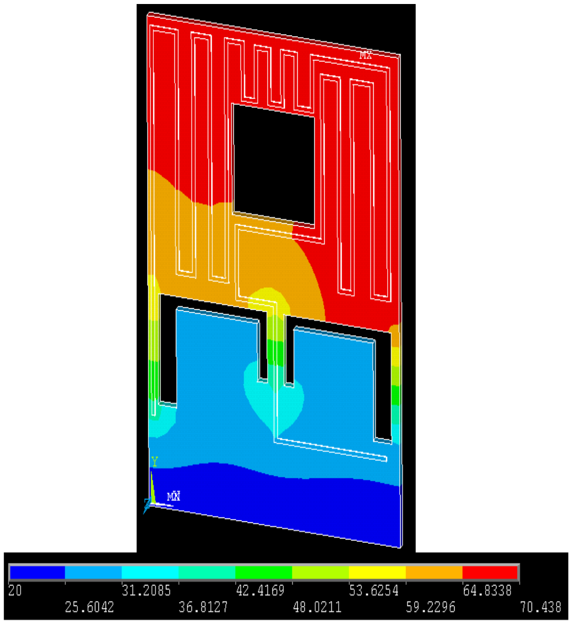

Fig.6: Result of the thermal simulation of the LTCC with the bottom part of the heating serpentine short-circuited

Convection Study and Discussion

All the simulations presented until now were done hypothesizing the module in perfect vacuum (no convection, no radiation). It is interesting to simulate also the effect of convection, and estimate the loss that it introduces into the system. In order to simulate the convection effect, the convection film coefficient h must be calculated, because the heat flux is proportional to this coefficient. The first step to do is to calculate the Rayleigh number, that, in case of free convection near a vertical wall is equal to:

$$Ra_x = \frac{g\beta\Delta T x^3}{\nu\alpha} \qquad 1.$$

In Equation 1, Ra_x is the Rayleigh number at the position x, g is the acceleration due to gravity, β is the thermal expansion coefficient, T_s is the temperature of the wall (LTCC), ΔT is the temperature difference between the air and the wall (LTCC),x is the characteristic length (in this case, the distance from the leading edge), ν is the kinematic viscosity and α is the thermal diffusivity of the fluid. The calculation of the Rayleigh number gives Ra_x=2006311. Since $Ra < 10^9$, it is the case of laminar flow. Knowing that the Prandtl number of the fluid (the air) is fixed because it only depends on the properties of the fluiud and equal to 0.7, the next step is to calculate the Nusselt number, that in case of laminar flow, free convection on a vertical wall can be calculated by the empirical correlation of Churcill and Chru:

$$Nu = 0.68 + \frac{0.67Ra^{1/4}}{[1+\left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}]^{4/9}} \qquad 2.$$

The calculation of the Nusselt number gives Nu=20. Finally, we are now able to calculate the h coefficient:

$$h = \frac{k}{L}Nu \qquad 3.$$

The calculation of the h coefficient gives h=22.7, which is a fair value in case of free convection with air as fluid. Knowing this coefficient and hypothesizing the air bulk temperature equal to 22°C, it was possible to make another finite-element simulation for estimating the loss introduced by convection into the system. The result of this simulation is shown in Fig. 7. The external “cold” part in this case is at homogeneous temperature, precisely the temperature of the outside air, since the convection effect is dominant to the conduction with the hot zone. For achieving the temperature of 70°C, in this case, a total power of 784 mW was necessary (16V, 49 mA), so an increase of the power dissipated of about 2000% respect to the analog case in vacuum. From this important consideration it is evident that, in order to reduce the power for the heating, an efficient thermal insulation of the packaging is required. In case of atomic clock, the perfect vacuum cannot be achieved, but a configuration with an efficient insulating material surrounding the packaging, in order to reduce the effects of convection is required.

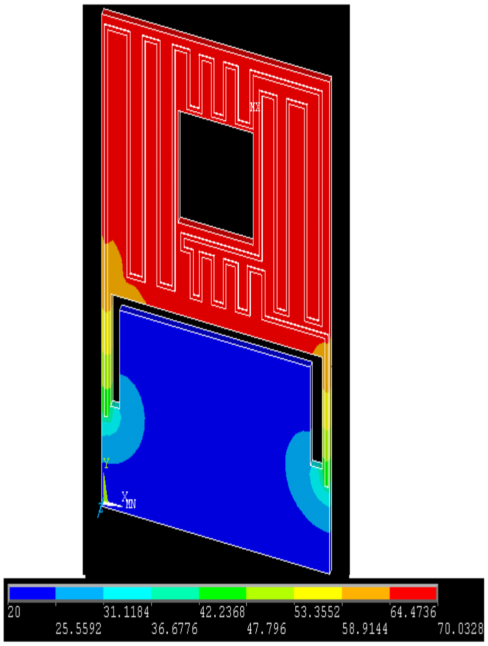

Fig.7: Result of thermal simulation when the module is in contact with air (convection loss)

Experimental Results

Different experimental configurations were tried in order to get a heating performance as close as possible to the ideal one, obtained through the simulations. The configuration which offered the best heating performance was when the LTCC (in its low-loss configuration, without any optional bridge) was put in between two layers of insulating foam. Each layer had a thickness of 1 cm. The conduction loss from the hot zone to the insulating foam is very weak because of the low thermal conductivity of the foam (k=0.04 W/mK). Moreover, the foam strongly reduced the convection loss, even if a small amount of convection was still present, due to the air that passes through the small holes of the foam. This Configuration will be called Conf.A. Fig.8 shows a schematic of Conf.A. In order to further reduce the convection loss, this configuration was repeated in low-pressure atmosphere ($p= 1.6\cdot 10^{-1}$ mbar), and a further decrease of the heating power was observed in this case. This second configuration tested, with low-pressure atmosphere, will be called Conf.B. Fig.9 shows the relationship Power dissipated-Temperature achieved by these two heating configurations.

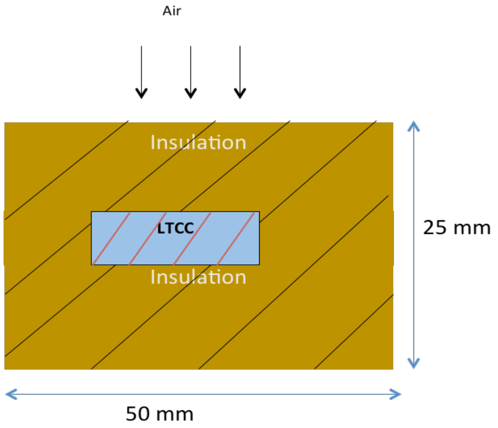

Fig.8: Schematic of the best heating configuration obtained

Finally, it is interesting to compare the best performance obtained (Conf. B, in low-pressure atmosphere) with the ideal one, obtained with the finite-element simulations. The ideal case is when the module is in perfect vacuum and there are no losses other than the conduction through the small external bridges. Fig.10 shows this comparison

Discussion

The last comparison in Fig.10 shows that theoretically there is still room for further improving the heating performance, probably by further reducing the pressure. However, this experimental configuration cannot be used for atomic clock packaging, because of the difficulty that implies the fact of creating low-pressure zones inside the device. The best experimental heating configuration tested that can be used in the packaging of an atomic clock is Conf.A (Fig. 8). This configuration offers a heating performance which is good (70°C were achieved with 70 mW of power) enough for the miniaturization/power required for this research. It has been proved, so, that LTCC technology is a very elegant solution for the packaging of an atomic clock, because it offers the possibility to integrate various functions in one unique module; LTCC is also a low-cost solution, because cost production of LTCC is very low, and it is possible to make a batch series production, drastically decreasing the manufacturing cost. Finally, LTCC is also an acceptable platform in terms of power required for the heating, if the packaging is efficiently insulated.

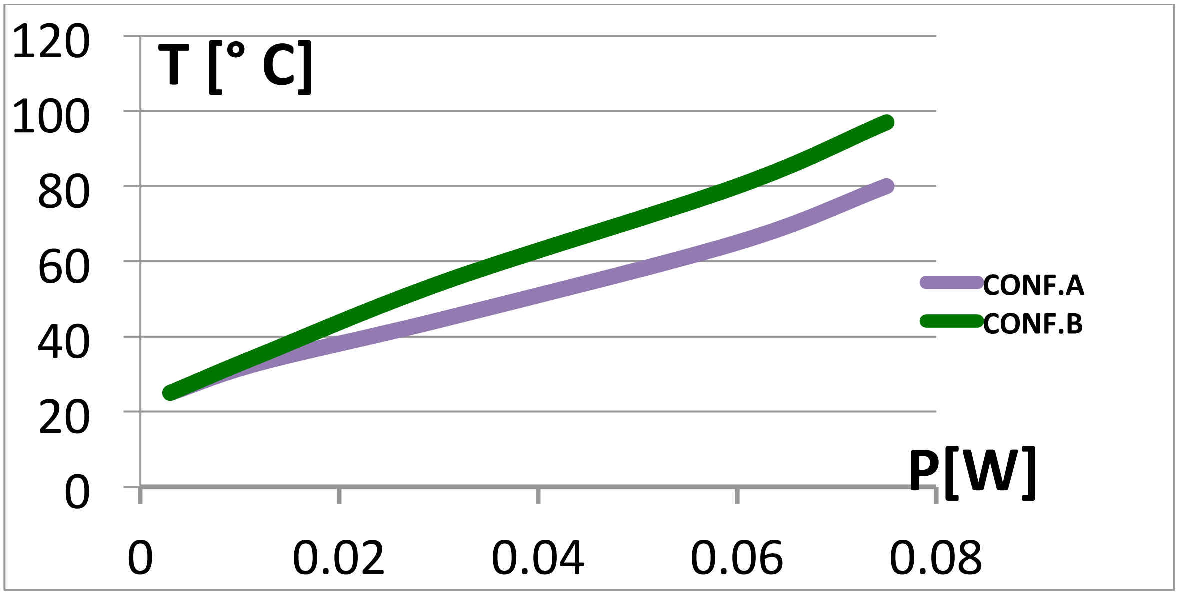

Fig.9: Comparison of the heating performance: the same experimental configuration, repeated in low-pressure atmosphere, shows an increasing of the performance, due to a decrease of the convection loss.

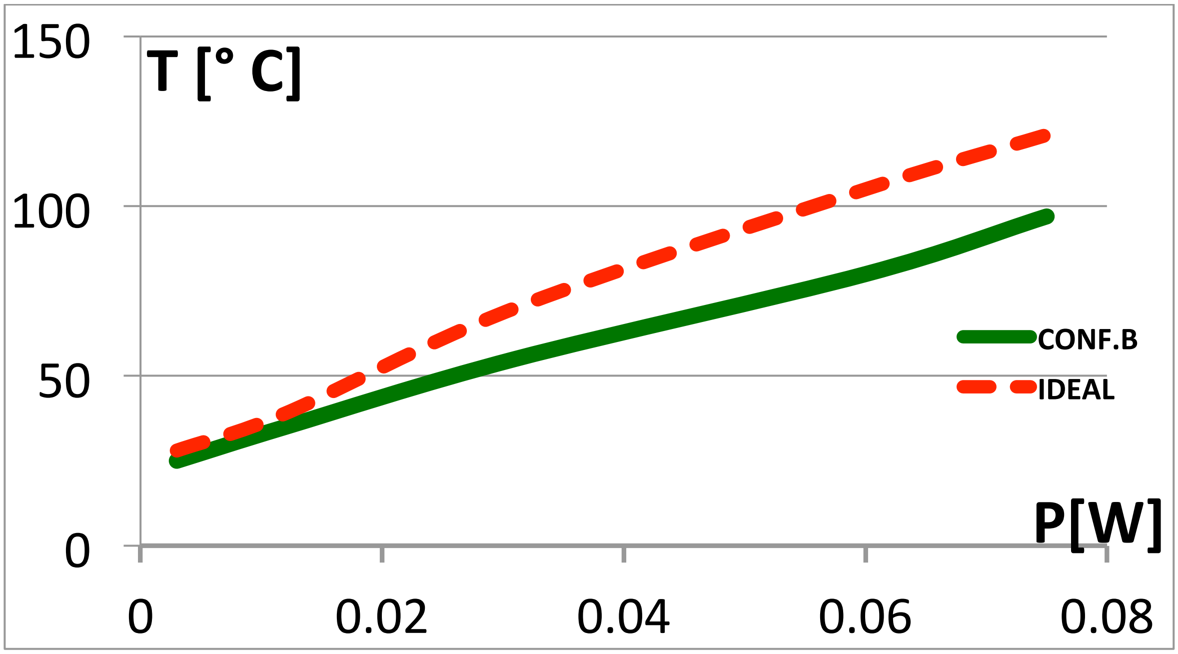

Fig.10: Comparison between the best heating experimental configuration (Conf.B) and the ideal case, calculated with thermal simulations.

Conclusions

This paper presented a complete thermal analysis of an LTCC module for atomic clock packaging. Finite-element thermal simulations were performed in order to find out the minimum amount of power required for heating the packaging up to 70°C (typical working temperature of reference mini-cell of the clock). The designed module gives the possibility to change the temperature distribution along its heated area by short-circuiting a part of the heating serpentine: this configuration was also simulated, showing that it is possible to create a zone of ca. 10°C colder along the heated area, without introducing further losses. The effect of convection on the heating was also simulated, highlighting that it introduces a big loss into the system, Therefore if low-power application is required for the heating, it is important to efficiently insulate the system in order to reduce the convection loss. A good experimental heating configuration was tested and the heating performance in this case was close to the ideal case. This research shows that LTCC technology, if properly insulated, represents a very elegant and efficient solution for the packaging of atomic clocks.

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