Effects of Thermal Losses on the Heating of a Multifunctional LTCC Module for Atomic Clock Packaging

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Abstract

An innovative multifunctional LTCC module has been designed for miniature atomic clock packaging. Efficient packaging and interconnection of the atomic clock packaging is a critical issue and a precise temperature control is required for some components, such as mini-cell and light source. The great advantage of using LTCC technology for this application is that it allows the integration of different functions, such as heaters and PTCs resistors for temperature measurement and control, and optionally other active elements.

In this research, a platform for measuring the thermal conductivity of materials has been developed in order to perform precise thermal studies on the packaging. The relationship between achieved temperature and power dissipated for the heating of the LTCC module has been calculated in different experimental configurations, in order to determine the effects of conduction and convection on the heating and estimate the thermal losses that they introduce into the system.

Introduction

The atomic clock is a device able to measure the time in the most accurate way [1,2,3] (accuracy of 10^{-9} seconds per day), and is the time base of global-positioning systems (GPS) [4] and of other devices such as telecommunication networks and data processing. Reducing both size and power consumption of atomic clocks is an active field of research, as this will allow the diffusion and spread of communications and navigation portable systems [5]. This research aims to design a miniature low power atomic clock in the 10 cm^3 volume and 200 mW power range and to determine industrial, reliable and repeatable processes for producing this device. In this light, packaging of the fundamental elements of the device (at least the light source, reference cell and detector) plays a critical role [6]. The active elements of the atomic clock must be connected to each other, efficiently packaged and some of them require precise temperature control: the reference cell at typically to 70°C and the light source (mini-plasma lamp or laser diode). In this research, we realized the packaging of the elements of the miniature atomic clock using LTCC [8] (Low Temperature Co-fired Ceramics) [7] technology. LTCC technology is an ideal platform for this application because of its ease of structuration and 3D integration for packaging and microsystems [8,9], and especially for the possibility to integrate suspended heaters for local temperature control, together with active elements such as sensors, beside purely electrical connections. This paper presents an LTCC module dedicated for atomic clock packaging;. Each component of the clock can be easily attached onto one module, and the different modules can be aligned onto a PCB support in order to build up the final system (Fig.1).

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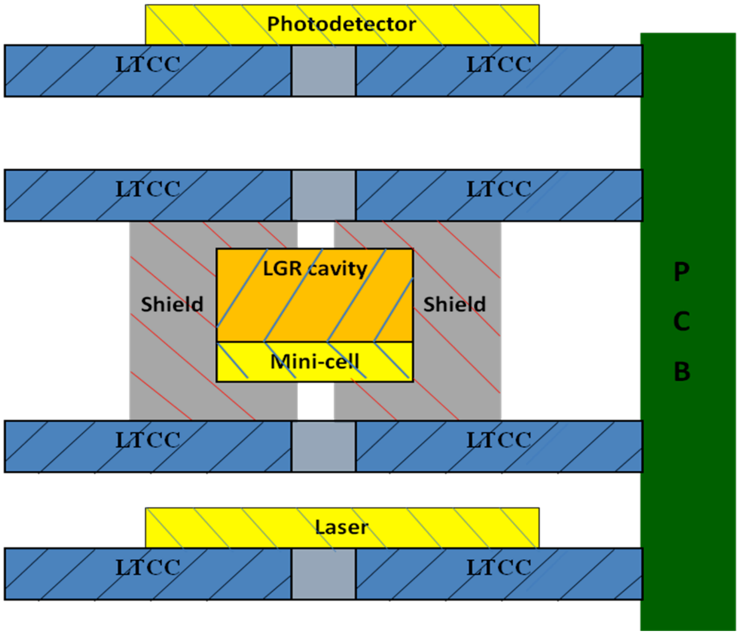

Fig.1: Schematic of the atomic designed clock (LGR = Low Gap Resonator; PCB = Carrer Printed Circuit Board for the overall device)

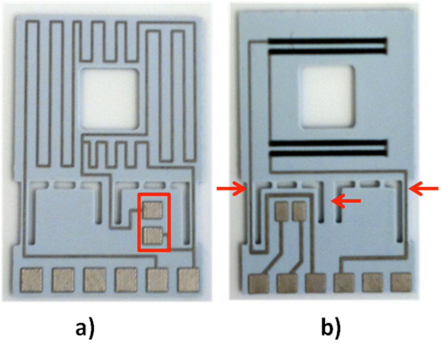

Fig.2: LTCC heater/carrier modules. a) top of the module, heating conductive serpentine for local temperature control, and SMD pads for regulating heat flow on the bottom part of the LTCC (in the red rectangle); b) PTC resistor for temperature measurement.

The heated area is insulated by the SMD pads ("cold" zone): the two zones only communicate through two external small bridges and an optional central bridge (red arrows)

The designed device (Fig. 2) has an adjustable thickness of 500 μm and it is equipped at the centre with an aperture for the light passing through, a heating conductive serpentine for local temperature control and a PTC [10] (Positive Temperature Coefficient) thermistor for temperature measurement. It is possible to slightly alter the temperature distribution along the module by creating colder and warmer zones: the heat flow in the bottom part of the module may be altered by an SMD resistor that is soldered on dedicated pads (Fig. 2a). This is useful in the case of an alkali metal cell, in order to insure the liquid droplet stays at a definite position, away from the window. The detailed dimensions of the designed module are summarized in Table 1:

Table 1: Detailed dimensions of the LTCC module designed for atomic clock packaging:

	Length [mm]	Height [mm]
Overall dimensions	15	22
Heated area	15	12
Aperture for the light	5	5
Dimension of the external bridges	0.6	5
Optional centre bridge	1	3.2

For this LTCC module, the electrical power dissipated for achieving different values of temperature has been monitored; different experimental configurations were tried, in order to determine how much conduction and convection influence the heating performance in terms of power dissipated [11, 12]. Configurations in which conduction and convection losses were minimised and/or maximised have been tested, and the results were compared in graphics.

Thermal conductivity measurement system

For thermal characterization of the packaging and estimation of the thermal losses due to conduction, we developed a system able to measure the thermal conductivity of large-cell foam.

The platform developed for thermal conductivity measurement is described in Fig. 3.

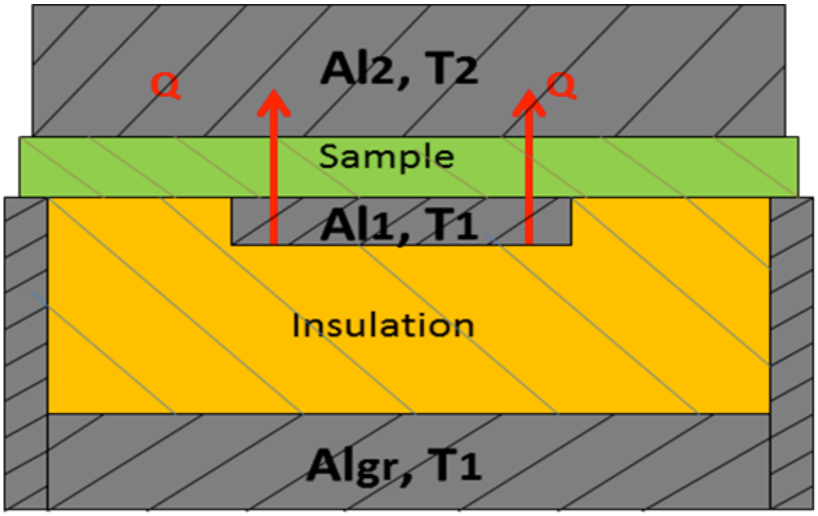

Fig.3: Platform for measuring thermal conductivity of materials

The developed platform consists of two heated aluminium blocks (Al_1 and Al_2), with the sample placed in between. Both aluminium blocks are thermally regulated to set temperatures (T_1 and T_2). The system is designed so that the only thermal flux Q (Fig. 3) possible from the inner block is to the top block. For this purpose, there is a "guard envelope" (Al_{gr}) all around Al_1, kept at the same temperature T_1 as Al_1, yet physically separated from it by insulating foam. Since Al_{gr} and Al_1 are kept at the same temperature and thermally insulated from each other, no parasitic heat flow occurs between them, ensuring the heating power on Al_1 truly corresponds to the thermal flux Q. Therefore, knowing Q and temperatures T_1 and T_2, the thermal conductivity k is calculated using Fourier's law:

$$Q \approx -\frac{k(T_1 - T_2) * S}{\mathrm{h}} \qquad (1)$$

In equation (1), Q is the heating power given to Al_1, k the thermal conductivity of the sample, S the cross sectional area of the sample and h the thickness of the sample.

With respect to other methods for measuring the conductivity [13,14], this offers the following advantages:

1) It allows the use of insulating material basically “as is”, with no need to adjust size.
2) It is not sensitive to coarse-structure materials such as large-cell foams.

Experimental results

Various experimental configurations have been tested, in which both convection and conduction were minimized or maximized. The power required for achieving certain values of temperature, in different experimental situations, has been monitored and compared, in order to estimate the thermal losses for convection and conduction during the heating of the LTCC module. The most important configurations that have been tested are summarized in fig. 4, and the results in fig.5:

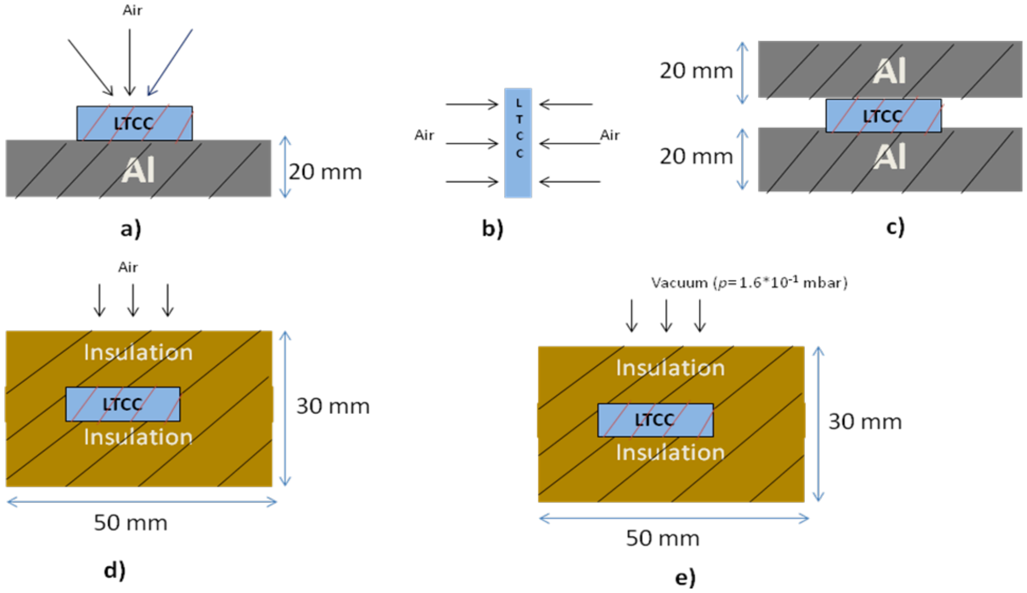

Fig.4: Experimental configuration tested

The most relevant experimental configurations tested, illustrated in fig. 4, are:

a) The module is heated when in contact with an Al block (thickness 20 mm) on bottom (conduction loss) and with air on top (convection loss);
b) The module is held vertically and heated in open still air (free convection loss is maximized);
c) The module is heated when in contact with an Al block (thickness 20 mm) on top and bottom (conduction loss is maximized);
d) The losses are minimized by putting the module in contact with s thermally insulating foam (k=0.044 W/m/K at 300 K, measured using our platform) around all its parts;
e) The losses are further minimized by putting the module, in contact with the same insulation foam, in vacuum (p= $1.6*10^{-1}$ mbar).

The results of the tests are summarized in Fig. 5 (graphic $P - T$):

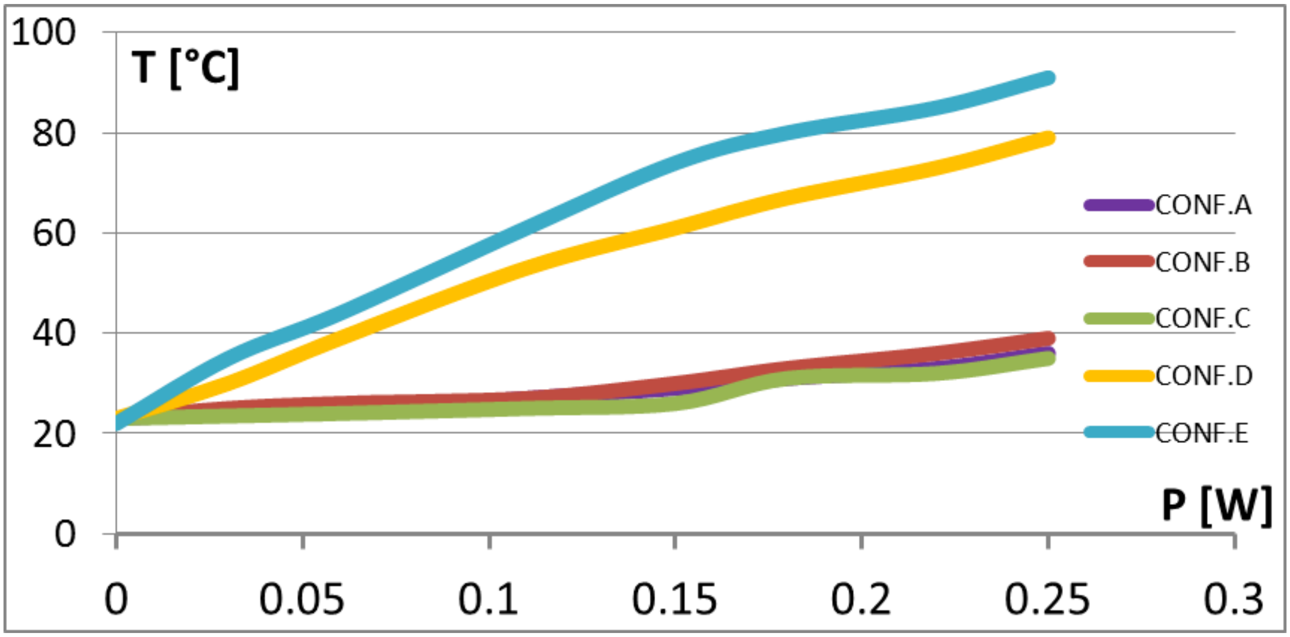

Fig.5: Experimental results of the heating of the module

Discussions

The results show that both convection and conduction may introduce important thermal losses, of similar magnitude: in fact, the heating performance is very poor in conf. A (conduction and convection losses are present in an equal measure), conf. B (convection is preponderant to conduction) and conf. C (conduction is preponderant to convection). However, by thermally insulating the package (conf. D), we were able to get much better performance: using the same heating power, the temperature of the LTCC module increased in the order of 100%. The heating performance further increased in low-pressure atmosphere ($p= 1.6 \cdot 10^{-1}$ mbar).

It is interesting to compare the last result, which is not ideal due to conductivity of the foam material and relatively low vacuum (mean free path ≈ 0.4 mm), to an “ideal” case with no losses other than conduction in the LTCC bridges (complete vacuum, no radiation). The temperature for this ideal case has been calculated, taking into account only conduction through the small external bridges, with the hypothesis that the cold zone is kept at 25°C (Fig.6) and assuming a thermal conductivity of 3 W/MK for the LTCC [15]. This is compared to our best experimental result (for conf.E, fig.4) in Fig. 7, and shows there is still room for improvement, especially at high temperatures.

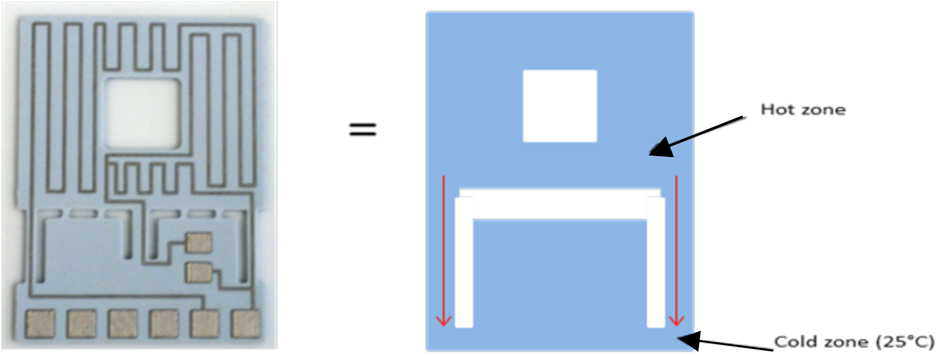

Fig.6: In the ideal situation, the only thermal loss is by conduction from the hot zone to the cold zone through the small LTCC bridges (red arrows)

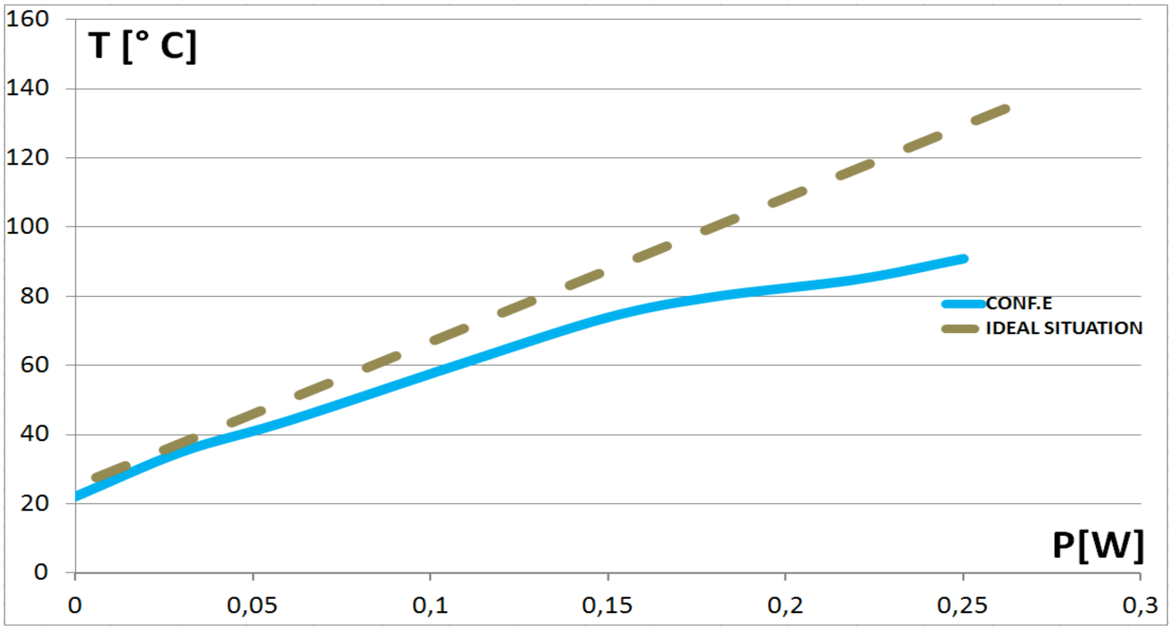

Fig.7: Comparison between the ideal situation and our best heating performance

Conclusion

In this work, thermal losses of LTCC multifunctional heaters/carriers for miniature atomic clock elements were characterized for different configurations. Air convection may lead to undesirably large losses. Therefore, polymer foams were investigated and applied as insulating materials, yielding a considerable increase of thermal resistance. Further improvements can still be achieved using hermetic vacuum packaging, if extra minimization of the atomic clock power requirements is necessary.

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