

# Multi-chip-module-based micropyrometer with an IR metamaterials lens and bandpass optical filter

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## Abstract

This paper presents a complete microsystem micropyrometer, composed by the electronic system built in CMOS technology added by Multi-chip-module (MCM) techniques, the pyrometer subsystem and a low-loss optical lens and bandpass optical filters (1-4  $\mu\text{m}$ ) with inhomogeneous graded index metamaterials to simultaneously focus the light on the micropyrometer and for filtering in the desired range. The final goal is to obtain a miniaturised self-calibrated micropyrometer to detect the infrared radiation (IR) in the 1-4  $\mu\text{m}$  wavelength, for measure the temperature of objects without the need of contact. The structure of micropyrometer consists of a thermally insulated absorbing area and two thermopiles with the hot junctions placed in the absorbing area and the cold junctions on the silicon bulk, which acts as heat sink. The complete microsystem is fabricated in silicon planar technology and each thermopile has a different reference temperature, which is biased by a Peltier microstructure near the cold junction of the thermopile. The ground floor of all microsystem consists on a silicon die with a passivation membrane made of silicon nitride. The absorbing area consists on a black gold strip on the silicon nitride membrane, and it is obtained by anisotropic etching of the bulk silicon from the back of wafer.

## 1. Introduction

The measure of temperature is not always possible to do, by touching the bodies under test. Some of the reasons includes for example the siderurgy industry, where the highest temperatures (as is the case of the iron, whose melting point is around 1538° C) destroy the sensors. Another reason deals either with the impossibility or with unusefulness to directly touch the surface under measure, as it is the case of moving parts (for example, the rotors of electrical machines). Thus, the pyrometers revealed to be equipments of great utility, since they allow to measure the temperature of objects, without the need of physical contact. However, the commercially available pyrometers presents a serious limitation, e.g., the value to be measured depends on the emissivity of the surface of the object whose temperature will be measured. Moreover, this type of equipment is very expensive, thus it puts very difficulties when it is to be used in production lines that requires control of temperature, as it is the case of dyeing in the textile industry. The micropyrometer presented in this paper is based on a new method of contactless measuring the surface temperature and the emissivity of objects. This method uses two thermopiles with two different reference temperatures, which are biased by the Peltier devices, e.g., with the perfect and error-free knowledge of temperatures. Therefore, these two readings makes possible to measure the temperature of distant objects independently of its emissivity - e.g., from the equation (4), presented further.

## 2. Modelling

Considering a sensor at a temperature,  $T_{s1}$  [K], when this is exposed to a body at a certain temperature,  $T$  [K], the voltage,  $V_1$  [V], at its output is given by the Stefan's Law:

$$V_1 = K\sigma(T^4 - T_{s1}^4) [\text{V}] \quad (1)$$

where  $\sigma$  is the emissivity of the body,  $T_{s1}$  is the temperature in the sensor 1,  $T$  is the target temperature (e.g., the temperature to be determined), and  $K$  is a sensor constant. If a different temperature,  $T_{s2}$  [K], is present in another sensor 2, in a way that both sensors are distributed in order to equally receive the same amount of radiation, then the voltage,  $V_2$  [V], on this second sensor is also given by:

$$V_2 = K\sigma(T^4 - T_{s2}^4) [\text{V}] \quad (2)$$

The ratio of the voltages,  $V_1$  and  $V_2$ , will results in:

$$V_1/V_2 = (T^4 - T_{s1}^4)/(T^4 - T_{s2}^4) \quad (3)$$

After an arrangement of the previous equation, and given the two output voltages and the two temperatures in both sensors, the target temperature is easily known and given by:

$$T = \sqrt[4]{(V_1 T_{s2}^4 - V_2 T_{s1}^4) / (V_1 - V_2)} \text{ [K]} \quad (4)$$

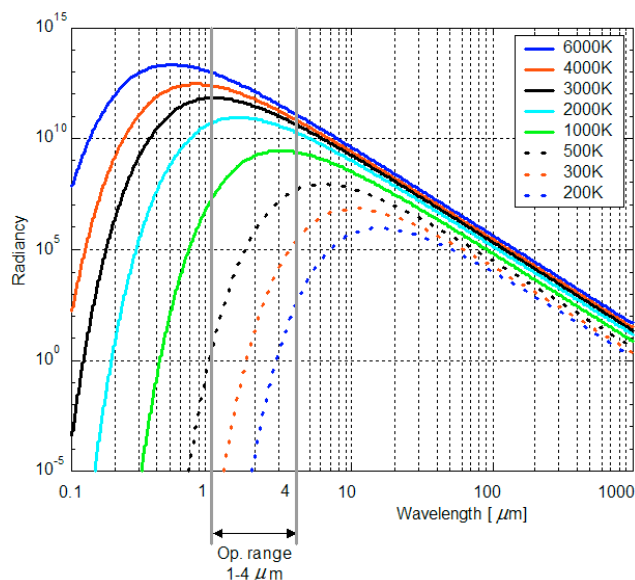


Fig. 1: Selected wavelength range, which was obtained from the Plank's Law.

The equation (4) is of major interest, because it's the proof of the concept behind the proposed micropyrometer, where it was referred that the known of the exact temperature references (provided by the Peltier devices) leads to a perfect knowledge of the target temperature,  $T$  [K]. Figure 1 was obtained from the Plank's Law, and shows that the radiance for a given wavelength is temperature dependent, thus the knowledge of this value also allow to know the exact value of the temperature (it must be noted that the figure didn't took in account the effect of the bandpass effect).

For temperatures between 300 K and 2000 K, the maximum sensitivity on the receiver, taken from the Plank's Law imposes that the micropyrometer must operate in the 1-4  $\mu\text{m}$  range, e.g., for frequencies ranging from 300 THz to 75 THz.

### 3. IR metamaterial lens and optical bandpass filters

#### A. Motivation

Optical filters for infrared in dielectric materials need a multilayer stack of two different materials with very different refractive indexes (for example, silicon dioxide,  $\text{SiO}_2$ , and titanium dioxide,  $\text{TiO}_2$ ) with more than a set of ten layers (minimum for the range that we are interested). Also, the thickness of each layer (accuracy with two decimal places in nanometers) is difficult to obtain by sputtering deposition. Therefore, an infrared metamaterials lens and bandpass optical filter it is a remarkable solution for this type of micropyrometer devices. Off course the loss in transmission is higher but it compensates in fabrication.

#### B. Design

It has been recently realised that metamaterials (artificial electromagnetic materials with engineered properties) can be designed to control electromagnetic fields in rather general ways. The concept of transformation optics, which is based on finding artificial materials that create the desired configuration of electromagnetic fields, has been developed by several research teams [1]. Thus, this pushed the efforts in the last years, towards the realisation of negative index materials (NIMs) at optical frequencies. This has included numerical studies of infrared magnetic metamaterials and NIMs and experimental demonstrations of THz, mid-infrared and near-infrared magnetic metamaterials as well as near-infrared NIMs. The NIM structure incorporates a negative electric permittivity,  $\epsilon$ , resulting from an array of thin metal wires parallel to the direction of electric field and a negative magnetic permeability ( $\mu$ ) resulting from a pair of finite-width metal stripes separated by a dielectric layer along the direction of the incident magnetic field. The values of  $\epsilon$  and  $\mu$ , at a fixed wavelength of the incident light, can be independently controlled by manipulating the width of the metal wires, shifting the resonance frequency of the structure and so changing the value of the refractive index  $n=(\epsilon\mu)^{1/2}$  while keeping small variations in the impedance  $(\mu/\epsilon)^{1/2}$  and hence in the transmission [2,3]. To meet the optical requirements in the optical band (1-4  $\mu\text{m}$  range), a four-layered Au/dielectric/Au/glass-substrate with squared cavities of 1  $\mu\text{m}$  side (see Figure 2) must be fabricated and assembled using

multi-chip-module (MCM) techniques above the micropyrometer (Figure 3) [4]. The dielectric material can be silicon oxide or silicon nitride.

#### 4. Design of micropyrometer

Figure 3 shows an artwork of the proposed micropyrometer. The materials for the Peltier converters and the Seebeck elements are antimony and bismuth tellurides [5]. For each pyrometer an optical lens with bandpass characteristics must be designed to simultaneously focus the radiation and for filtering the spectrum, let passing the IR radiation in the 1-4  $\mu\text{m}$  range.

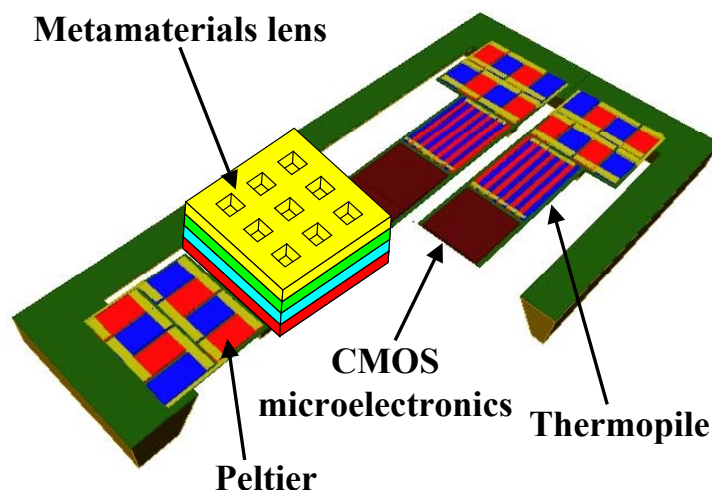
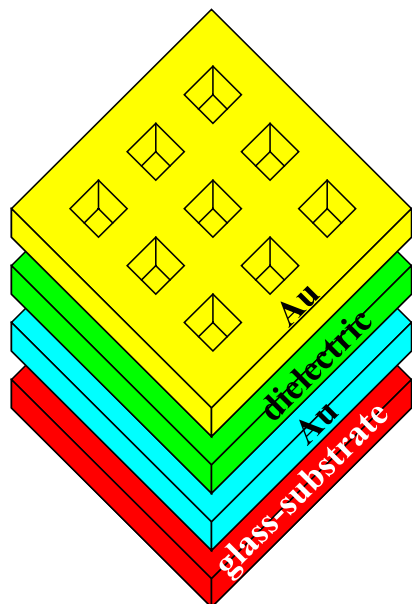


Fig. 2: The metamaterials multilayer stack.

Fig. 3: An artwork of the complete microsystem with a lens and optical filter made in metamaterials to simultaneously focus the radiation and for filtering in the desired infrared range.

#### 5. Conclusion

This paper presents a new concept for a miniaturised self-calibrated pyrometer microsystem assembled with interface electronics to detect and to quantify the amount of infrared radiation in the 1-4  $\mu\text{m}$  wavelength range in order to measure the temperature of an object without the need of physical contact. The target application of this micropyrometer, is to measure temperature in production lines that requires its control in real-time, as is the case of a textile dyeing. The ultimate innovation deals with the design and fabrication of a low-loss lens and optical filter in metamaterials for IR radiation in the 1-4  $\mu\text{m}$  range.

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