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Multiphysics simulation of a superconducting bolometer working in a portable cryostat

Andrea Napolitano[1,2], Samuele Ferracin[1], Roberto Gerbaldo[1,2], Gianluca Ghigo[1,2], Laura Gozzelino[1,2], Daniele Torsello[1,2] and Francesco Laviano[1,2,*]
[1] Dipartimento di Scienza Applicata e Tecnologia, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2] INFN, Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

* Corresponding author's email: francesco.laviano@polito.it

Abstract. We present the characterization and the numerical simulation of a high-temperature superconducting bolometer based on an $YBa_2Cu_3O_{7-x}$ (YBCO) film, which is patterned in serpentine elements and selectively modified by means of micro-collimated high-energy heavy-ion irradiation. The local irradiation of YBCO yields to a controlled reduction of the critical temperature and of the critical current, but the resistance versus temperature slope is preserved near T_c. In this way, only the irradiated part of the YBCO films is used for detecting infrared radiation, while the pristine one serves for electro-thermal feedback. The bolometer has been engineered in a portable cryostat, which is equipped with an optical window for suitably filtering the spectrum of the incoming electromagnetic radiation. The optimization of the cryostat has been performed with modelling by finite element method of the whole apparatus, along with simulations of the bolometer response.

1. Introduction

Infrared spectroscopy and signal detection, especially in the THz domain, is a continuous growing field of study and both detectors and instrumentations are constantly improving and evolving towards practical applications [1]. Superconducting detectors are very useful for this scope because of their fast response, sensitivity and low consumption. High-temperature superconductors are promising for infrared detection both in the superconducting and in the normal state [2], and one can design transition edge bolometers that can be operated at LN2 temperature for detecting THz radiation [3,4].
The device here reported is a transition edge bolometer that is characterized by high responsivity, scalability and practicality due to a basic and rugged design. Because the working temperature is set above the LN2, we engineered a portable cryostat reducing the complexity and the cost of cooling apparatus. Moreover, our device is composed by two serpentine elements (hereafter named meanders): one meander is irradiated with high-energy heavy-ions in order to reduce the critical temperature (T_C) while preserving the resistance versus temperature slope, the other one is retained as grown in order to serve for electro-thermal feedback. The reduction of T_c is instrumental in detecting infrared radiation in THz regime, while maintaining the remaining part of the YBCO film in the superconducting state allows the reduction of the power consumption and response time.

In this study, we present the simulations of the whole system by finite element method (FEM), i.e., the superconducting bolometer and its housing in a LN2 cryostat, which is composed by the cold finger, thermal coupler, detector support with screws, resistive heater, external casing with optical window. The simulations were conducted both in stationary and in dynamic conditions, in order to gather information both on the detector housing and on the response of the bolometer by means of classical physical models. That will allow the optimization of the technical aspects of the design, in feedback with experiments. Moreover, implementation of physical models will be helpful to understand which physical phenomena are involved in the response of the YBCO detector when stimulated by the infrared radiation.

2. Description of the apparatus

2.1. Bolometer

YBCO films grown by thermal co-evaporation [5] on MgO substrates were acquired from THEVA GmbH. Their thickness is 250 nm, close to the value corresponding to the maximum critical current density [6]. The device is produced by patterning the YBCO film with standard optical lithography, with a double meander layout that is visible in Fig. 1, along with the measurement scheme. The meander strip has a width of 35 μm and a total length of 75 mm. One of the meanders is irradiated with 114 MeV Au^+ ions in order to reduce the T_C [7], with an almost rigid shift of the transition and of the normal resistivity curve (the superconducting state is reached at 84 K with a bias current of 1 μA). The resistance versus temperature characterization for both pristine and irradiated areas are presented in Fig. 2a, 2b. The maximum slope of the transition curve for the irradiated meander is as high as 7.6 kΩ/K (Fig. 2c), while the as-grown meander displays a maximum slope of 6.3 kΩ/K. From these measurements, the operating point of 85 K is chosen in order to bring the irradiated meander in the point of maximum slope and linearity of its resistance curve, while the unirradiated one remains in the superconducting state (also the other as-grown parts of the YBCO film are in the superconducting state and hence they do not contribute to power consumption and Johnson noise).

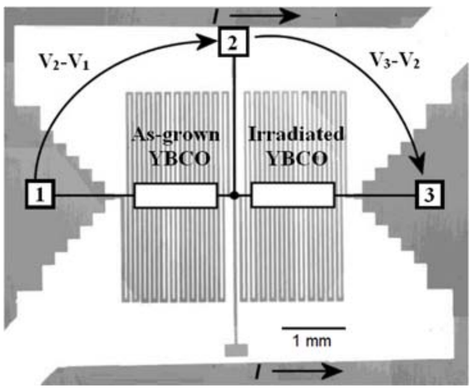


Figure 1. Photograph of the YBCO bolometer and electrical scheme for signal detection.

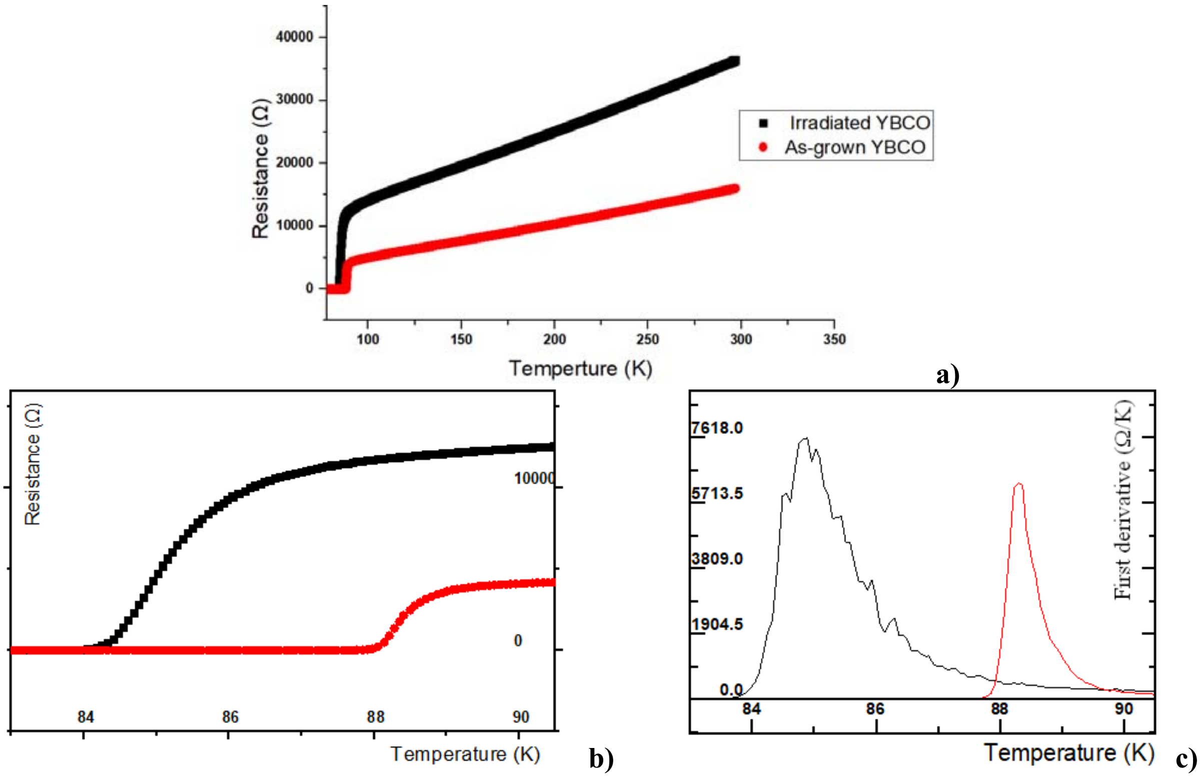


Figure 2. Resistance versus temperature characterization for both meanders of the YBCO bolometer (Fig. 2a). The resistances were simultaneously measured following the scheme of Fig. 1 with a bias current of 1 μA. Close-ups of the transition region (Fig. 2b) and corresponding derivatives (Fig. 2c).

2.2. Cryostat

The portable cryostat is a custom-wired dewar produced by Kadel® Engineering Corporation (Fig. 3 (a)). The YBCO bolometer is mounted on an aluminum disk, which is equipped with a Cernox® thermometer and with four SMD resistors constituting the heater (circuitry is made by a patterned copper film on Kapton®). The aluminum disk is screwed to the cold finger with a thermal coupler (Teflon® foil). The electrical contacts on the YBCO pads are soldered with indium alloy at temperature below 200 °C. The photograph of the mounted bolometer is presented in Fig. 3(b).

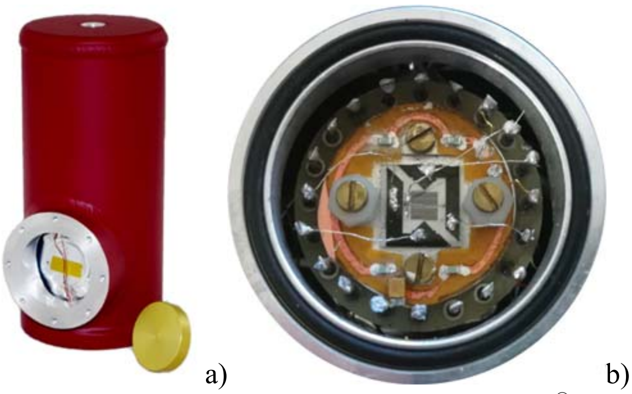


Figure 3. a) Photo of a standard LN2 portable cryostat made by Kadel® Engineering Corporation; b) Photo of the actual device mounted in the cryostat – The lateral size of the chip is 1 cm and the active part (double meander) is 3 mm wide, as shown in Fig.1.

3. FEM simulation

3.1. System design
The expanded view of the device housing is shown in Fig. 4. All the parts described in the previous section 2.2 are reproduced.

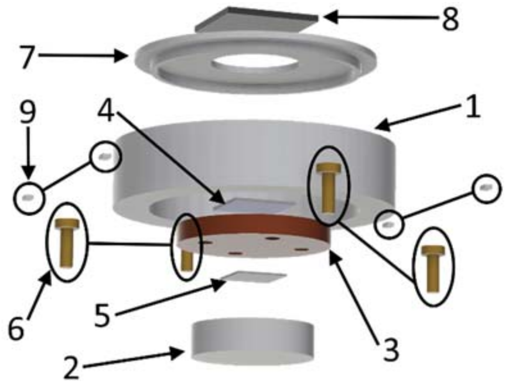
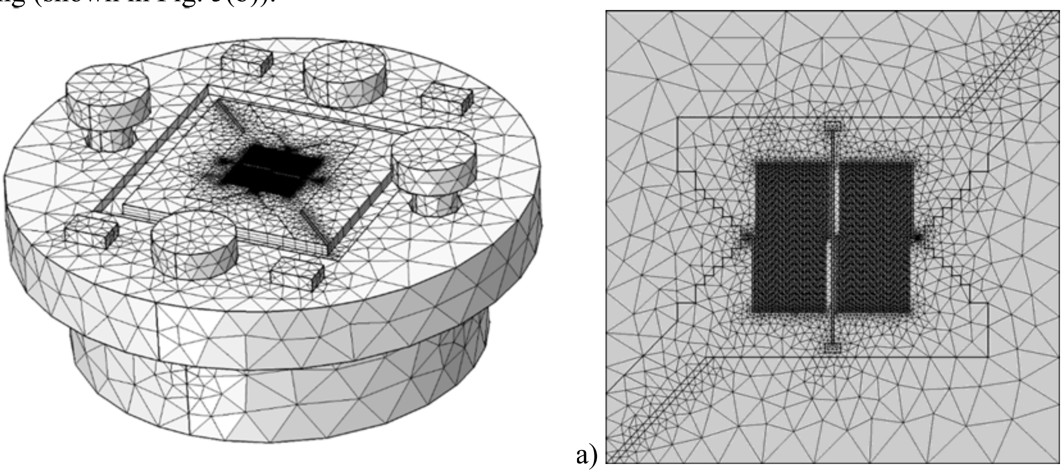


Figure 4. CAD exploded view of the whole detection system. Starting from the bottom, we included aluminum cold finger (2), PTFE thermal coupler (5), aluminum device support (3), MgO + YBCO bolometer (4), cryostat enclosure (1) and cover with high resistivity silicon optical window (7-8), screws (6) and SMD resistors (9).

3.2. Finite element model
For FEM simulation, we used COMSOL Multiphysics® software with modules: Structural mechanics, Heat transfer, and AC/DC. For each material, heat capacities were computed using Debye's low temperature formula and PTFE thermal conductivity was estimated using a logarithmic expansion. The measured YBCO resistivity data were directly loaded. Physical models included in simulations are “Heat transfer with surface to surface radiation”, “Electric shell currents”, and “Electric currents”. A PID controller has been developed in order to stabilize the temperature by means of the SMD resistors. The active feedback has been defined by the Global ODEs and DAEs modules. The mesh used for the system is free tetrahedral (shown in Fig. 5(a)), except for the meanders that needed a free triangular meshing (shown in Fig. 5(b)).



a) b)

Figure 5. a) Mesh of the internal components (enclosure, cover and optical window have been hidden for clarity); b) mesh of the bolometer; the meanders have finer triangular meshing.

3.3. Temperature stabilization

The stabilization of the temperature at the chosen working point (85 K) is obtained by means of the PID controller and the heater in about 90 s with the chosen parameters. The temperature distributions, before and after the action of the active control, are shown in Fig. 6.

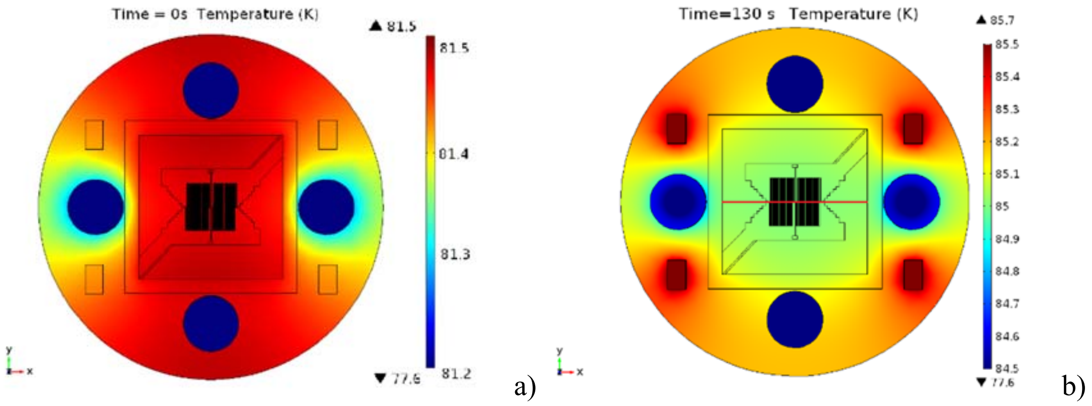


Figure 6. a) Temperature distribution without active control (note that only two screws are in contact with the detector support in order to minimize the heat transfer toward the cold finger); b) temperature distribution after stabilization with active control. The resistors are clearly the heat sources and the screws are the major heat sinks. The red line corresponds to the temperature profile shown in Fig. 7.

Before turning on the current in the resistors, the average detector temperature is above 81 K because of thermal radiation from the casing at ambient temperature (cold finger is set to T = 77.6 K). After stabilization at 85 K (reference point at the center of the device), the temperature profile across the two meanders, at the mid line of the bolometer geometry, is rather constant as visible in Fig. 7 (total variation of 16 mK, corresponding to a 2% resistance difference of the meander between center and border). This is a good result since variation across the meander is even lower – around 8 mK corresponding to 1% of resistance difference – and it will give an error in the measurement comparable with the one introduced by the sensibility of the equipment.

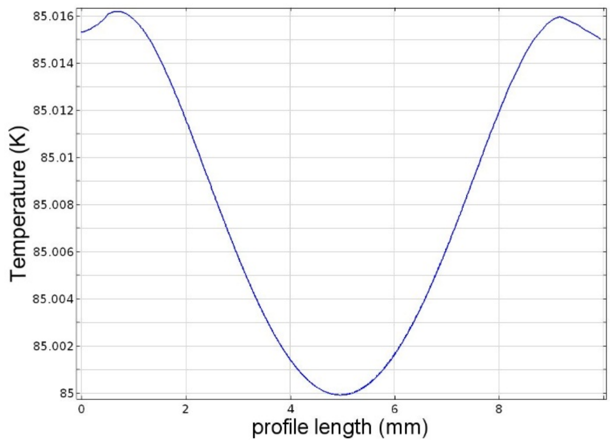


Figure 7. Temperature profile across the two meanders along the mid line of the bolometer geometry. Because the reference point for active control is the central point of the bolometer, its temperature is exactly 85 K.

3.4. Bolometric response

The dynamic behaviour of the device was simulated by time dependent pulses from a thermal source outside the cryostat. Here we present the data corresponding to a black body set at T = 900 K with a total power of 1 W. The pulse shown in Fig. 8 has a duration of 1 μs, which should be shorter than the minimum decay time associated with the thermal diffusion through the bolometer. In fact, taking the heat capacity of the irradiated meander divided by the thermal conductivity of the MgO substrate [3], we obtain a time constant of about 4 μs. The voltage closely follows the temperature of the bolometer with a slow decaying due to the thermal diffusion through the device support (previous measurements have shown a decay time of 0.5 ms [8]). The voltage curve is well fitted with a double exponential formula whose shorter time constant is below 20 μs, which is consistent with theoretical evaluation previously performed in [3].

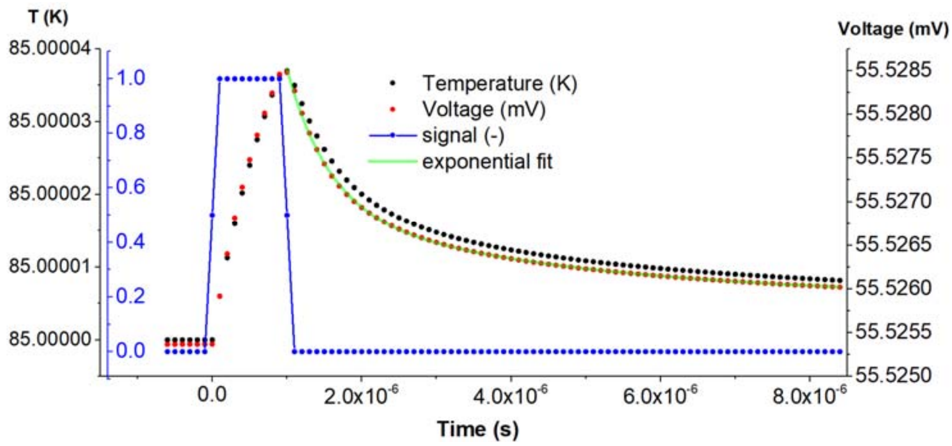


Figure 8. Simulation of the bolometer response with a heat pulse of 1 μs (blue line in the plot).

4. Conclusions

Modelling of superconducting detectors can be very useful for optimization of the sensor housing, of the cooling system and of the temperature control, along with understanding the physics underlying the detector operation. A complete FEM simulation of a superconducting infrared bolometer detector, constituted by an YBCO meander that is modified by high-energy heavy-ion irradiation, of the components for actual mounting the sensor in a portable cryostat and of the cryostat environment was performed with COMSOL Multiphysics® software. The agreement between experimental data and theoretical estimations is satisfactory and allowed us to identify that the temperature distribution (estimated by the simulations) displays a rather large difference between the center and the border of the detector, after the stabilization at the working temperature point. As a consequence, further improvements of the sensor housing and of the temperature control systems are being studied in order to achieve better thermal stability and uniformity.

Acknowledgements

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