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A Superconducting Bolometer for Terahertz Radiation Detection

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***Abstract* – In this work we present the progress on the realization of a superconducting microbolometer sensible to the THz radiation. The operation of this detector is based on an integrated antenna coupled to a suspended strip of superconducting material. The bolometer works anywhere in the temperature range 2-7 K which can be easily reached in helium bath cryostats or closed-cycle cryocoolers. We also report on two possible applications we are working on, one related to a system for homeland security and the other one to astrophysical observations.**

I. INTRODUCTION

In the last decade there has been an increasing interest in applications in terahertz sensing, spectroscopy and imaging that can be applicable in several fields such as astrophysics and atmospheric science, biomedical imaging, information and communication technology, non destructive evaluation, detection of concealed weapons, drugs, and explosives and so forth. The interest in applications in this region of the electromagnetic spectrum, which was characterized by a relative lack of convenient devices, has been triggered by the recent appearance of practical devices capable of both generating and detecting the radiation. The recent development of solid state sources such as Quantum Cascade Lasers (QCL) emitting in the THz region, for example, is giving a boost to the development of new applications as they improve their characteristics in terms of emitted power and operating temperature. There has been a large activity in recent years also concerning the development of the THz detectors. Here we present the performances of a superconducting bolometer with high sensitivity, ease to use and of an optimized readout electronics, called SHAB (Superconducting Hot-spot Air-bridge Bolometer)

II. THE BOLOMETER'S OPERATING PRINCIPLES

The Bolometer structure is based on a design first introduced by Luukanen and Pekola in 2003 [1]. It consists of a microscopic narrow Nb strip where, in order to improve its sensitivity, the thermal isolation is enhanced by removing the physical contact with the substrate, creating a free standing bridge structure. The application of a voltage bias to this superconducting structure causes the formation of a hot spot in the middle of the strip where the superconductor switches to the normal state. The suspended strip acts as a thermometer since the incoming radiation energy is dissipated in the hot spot region with a consequent modulation of its size. This results in a modulation of its resistance and, in turn, in a modulation of the current that flows as a result of the voltage bias. The recording of this current provides the measure of the radiation.

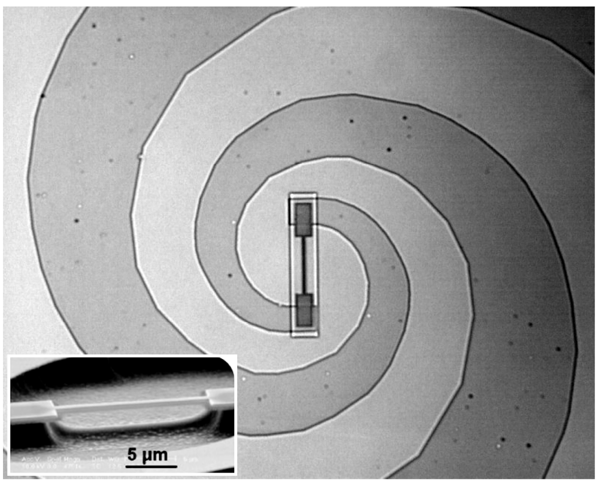

Fig. 1. Picture of the SHAB with the spiral antenna taken with an optical microscope. The inset is a SEM picture showing a detail of free standing bridge structure of the microbolometer

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The THz radiation is transferred to the bolometer bridge by means of a planar lithographic antenna electrically coupled. The antenna is shaped as a logarithmic spiral whose dimensions determine the relative bandwidth [2].

In figure 1 an optical microscope picture of the device is shown. The inset shows a SEM picture of the microbolometer bridge.

The suspended strip is 1 µm wide and 15 µm long. Its volume determinates the heat capacity C and, with the thermal conductance G, the time constant $\tau = C/G$ of the device. In previous measurements we have estimated a time constant value of about 200 ns which was according to what we what expected [3].

A hyperhemispherical silicon lens of 6 mm diameter is pressed on the back side of the chip containing the SHAB, in order to focus the incoming radiation to the planar antenna.

The fabrication process [4] of the bolometer is based on the electron beam lithography (EBL). The EBL allows us a great flexibility in changing the design during the optimization of the fabrication process and in adapting the constructive parameters for a specific application. When the SHAB is voltage biased and cooled to 4.2 K, its *I(V)* characteristics follow the Hot-Spot model [1], where the curve presents a minimum when the volume of the hot spot equals about half of whole strip volume. In figure 2 a typical characteristic of our SHAB, voltage biased and cooled to 4.2 K is shown. A best-fit of the hot-spot model parameters allows to evaluate the thermal conductance (*G)* value. The bolometer electrical responsivity, i.e. the current response to a given electrical power, $S_I = dI/dP_{in}$ is inversely proportional to the voltage bias.

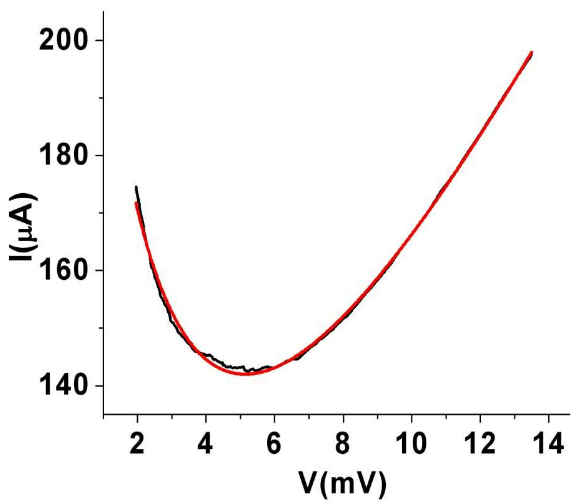

Fig. 2. Typical I(V) characteristics of the SHAB (black) with a corresponding fit curve obtained according to the Hot-Spot model (red)

III. READOUT OF THE BOLOMETER

The readout of the bolometer is performed by means of a transimpedance amplifier (TIA) which provides both the voltage bias of the bolometer and the measurement of the current flowing in the bolometer [5]. The electrical schematic principle of the TIA connected to the SHAB is shown in figure 3. The feedback resistor R_f is cooled close to the SHAB in order to minimize its contribution to the noise and to avoid the contribution of the cryogenic wires that, with their resistance, would spoil the voltage bias. The best sensitivity, with an electrical noise equivalent power NEP ≈10 fW/Hz½ over a frequency band from 100 Hz to 10 KHz, has been obtained biasing the SHAB close to the minimum in the *I(V)* characteristics; this represents a trade-off between the need of a large dynamic resistance Z (to minimize the contribution of the amplifier to the overall noise), and a large responsivity of the device.

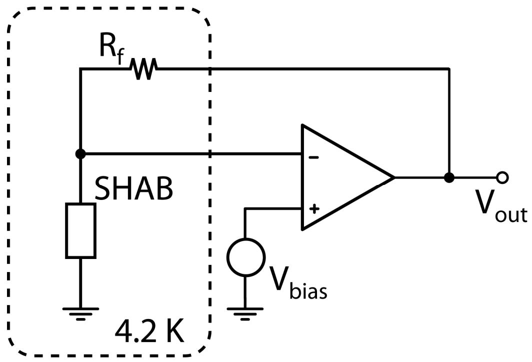

Fig. 3. Electrical schematic principle of the TIA connected to the SHAB

IV. BOLOMETER APPLICATIONS

Among the fields where the bolometer can be used, we are now investigating two possible applications related to a spectral signature system for homeland security and to astrophysics.

A. Spectral signature system

Since many materials among ERCs (Explosive and related compounds) and drugs present unique spectral "fingerprints" in the terahertz range, the development of systems, capable to perform a spectral analysis in this range of frequencies, is of great importance in homeland security applications [6].

We are developing a THz spectral signature system based on a multicolour QCL emitter and a SHAB receiver. The source consists of a linear array of 4 QCLs [7] emitting in a frequency range from 2 to 5 THz. The sample under test can be placed along the optical path and the radiation transmitted or reflected by the sample is detected by the SHAB. From the relative differences in

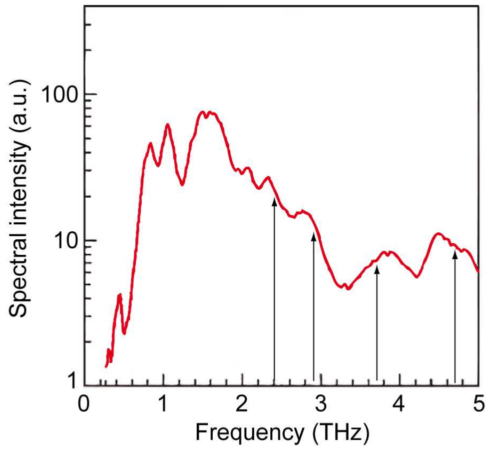

Fig. 4. Frequency response to a blackbody source of the conventional SHAB. Frequency emissions of QCL array is represented by arrows

the absorption peaks at the various frequencies of the QCLs, we can gather information about the substance under test. A better discriminative capacity can be obtained by increasing the number of QCLs. The frequency response of the SHAB has been estimated by using a Fourier-transform infrared (FT-IR) spectrometer [8]. The result is shown in figure 4 where the respective frequency emissions of the QCLs are reported.

According to calculations based on a simple log-spiral antenna model with internal diameter of 15 µm [2], the response bandwidth shows a high frequency cutoff around 2 THz. Despite this, the SHAB shows a certain level of sensitivity up to the higher frequency of the QCLs.

We have tested the response of the SHAB to single pulses (4 µs duration) generated by the QCLs. The results are shown in figure 5.

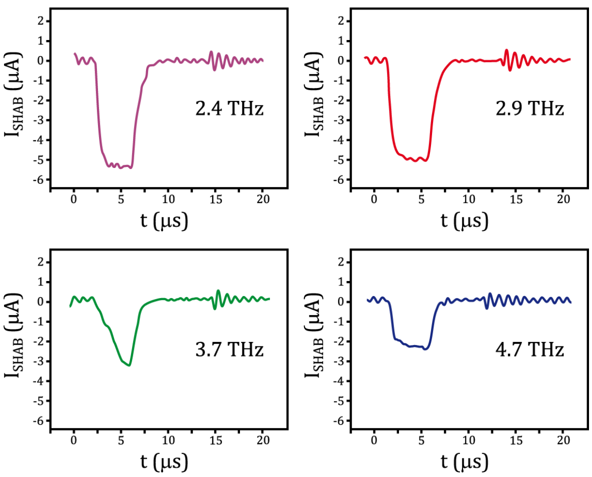

Fig. 5. SHAB response to single pulses generated by 4 QCLs working at different frequencies.

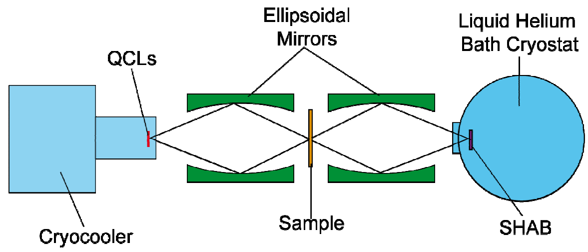

Fig. 6. Experimental setup used to measure the transmittance of different materials (chalk, sugar and aspirin)

A preliminary test to verify the system's ability to recognize materials has been carried out.

We have measured the transmittance of three different materials (chalk, aspirin and sugar). In figure 6 the experimental setup is shown.

The radiation generated by the four QCLs is focused to the material under test by a first ellipsoidal mirror and to the SHAB by a second one. The QCLs are hosted in a cryocooler which keeps them to their operating temperature of about 13 K, while the SHAB is housed in a liquid helium bath cryostat working at about 4.2 K. In order to avoid an excessive attenuation of the radiation, the sample has been prepared by mixing the specific material in the proportion of 10% with HDPE (High Density Polyethilene) powder, which has low losses in the THz range. The results are shown in figure 7, where the transmittance of the materials for the four QCL frequencies is shown. The measurements have been performed twice for each sample in order to check the reproducibility.

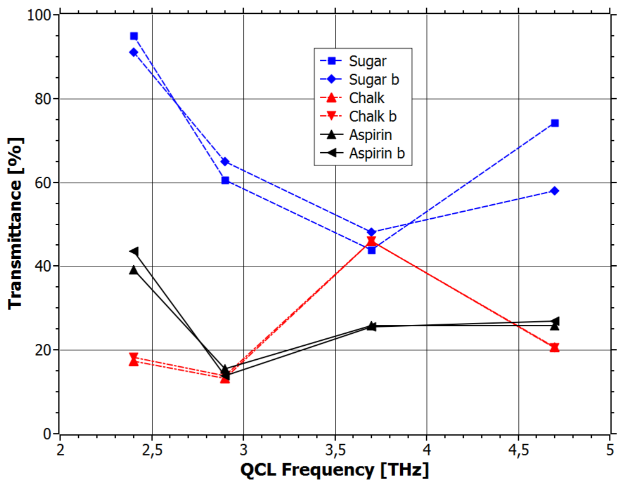

Fig. 7. Transmittance of chalk, sugar and aspirin. Each measurement was repeated twice in order to check the reproducibility

In these preliminary measurements we have experienced a low frequency noise, perhaps due to the fact that part of the optical path was in air and, since the terahertz radiation is strongly absorbed by the water vapour, the measurements could have been affected by the moisture variation.

We are now working on the optimization of the whole system especially on what regards the optical setup; in particular, we are optimizing the optical coupling and we are studying a possible setup in which the whole optical path is enclosed in vacuum or in a controlled atmosphere space.

B. Astrophysical application

Millimetre and submillimetre observations are of great interest in many different astronomical fields, since they can yield a new view upon the Universe we live in. As a result, a great effort has been done in order to develop sensors with an increasing sensitivity such as semiconductor bolometers, or the superconductors detectors of the new generation like the Transition Edge Sensors (TES) [9, 10] or the Kinetic Inductance Detectors (KID) [11]. In any case, to achieve a very good sensitivity, it is necessary to operate them at ultra-low temperatures (300 mK or below). Achieving and maintaining such temperatures is challenging. On the other hand, ground based observations are affected by the absorption of the incoming radiation by the ambient atmospheric water vapour and the variations of this absorption causes a noise in the measured signals. This means that it is not useful to push the sensitivity of the detector beyond a certain limit for ground-based observations. That's why for the ground-based telescope COCHISE [12], we are planning to use a SHAB that even if not so extremely high sensitive (compared to that of TESs or KIDs), has the advantage of operating at higher temperatures, greatly simplifying the cryogenic set-up.

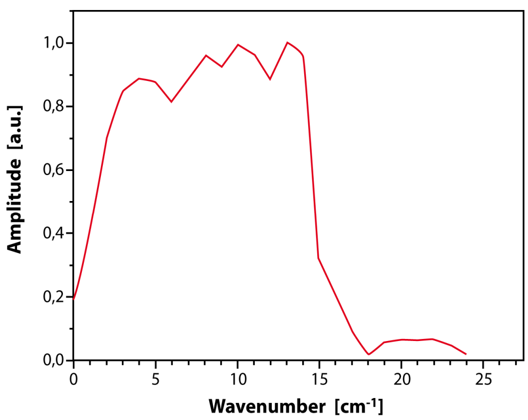

Fig. 8. Frequency response of the dedicated SHAB, obtained with a Lamellar Grating

In the observations with the COCHISE telescope, we are interested in the frequency range around the peak of the Cosmic Microwave Background (CMB), that means millimetre wavelengths. For this reason a SHAB with a redesigned planar spiral antenna has been fabricated to meet the necessary bandwidth for these measurements. Preliminary tests have been performed by means of a Lamellar Grating in order to measure the bandwidth of this dedicated SHAB. In figure 8 the measurement of the resulting bandwidth is reported, showing the shift towards the millimetre band.

Work is ongoing for the optimization of the optical coupling of the radiation with the SHAB.

V. CONCLUSIONS

We have reported on a superconducting bolometer coupled by an integrated planar antenna to THz radiation. The characteristics of the bolometer are a high sensitivity, ease of operation and optimized readout electronics. Furthermore the bolometer operates in the temperature range 2-7 K, which can be easily reached in helium bath cryostats or closed-cycle cryocoolers. We have also reported on two possible applications we are working on, one related to a system for homeland security and the other one to astrophysical observations

VI. ACKNOWLEDGMENTS

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