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Operation of a Wideband Terahertz Superconducting Bolometer Responding to Quantum Cascade Laser Pulses

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Abstract We make use of a niobium film to produce a micrometric vacuum-bridge superconducting bolometer responding to THz frequency. The bolometer works anywhere in the temperature range 2–7 K, which can be easily reached in helium bath cryostats or closed-cycle cryocoolers. In this work the bolometer is mounted on a pulse tube refrigerator and operated to measure the equivalent noise power (NEP) and the response to fast (μs) terahertz pulses. The NEP above 100 Hz equals that measured in a liquid helium cryostat showing that potential drawbacks related to the use of a pulse tube refrigerator (like mechanical and thermal oscillations, electromagnetic interference, noise) are irrelevant. At low frequency, instead, the pulse tube expansion-compression cycles originate lines at 1 Hz and harmonics in the noise spectrum. The bolometer was illuminated with THz single pulses coming either from a Quantum Cascade Laser operating at liquid nitrogen temperature or from a frequency-multiplied electronic oscillator. The response of the bolometer to the single pulses show that the device can track signals with a rise time as fast as about 450 ns.

Keywords Terahertz detectors · Superconducting bolometer · Quantum Cascade Laser

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1 Introduction

Ultrawideband operation is important for spectroscopy and imaging applications in both passive and active systems because it enables advanced features such as frequency-domain multiplexing in arrays, multispectral imaging for fingerprint recognition, and spectral encoding in general. Radiation in the THz range [1] is at the center of the interest for its non invasive imaging potential applicable from medical diagnostics to homeland security scanners. Ultrawideband (up to 100 MHz range) terahertz direct detectors are seldom available to detect short pulses or fast modulated signals like the one coming for instance from Quantum Cascade Lasers (QCL) emitters, so that, at present, high-cost and high-complexity ultrafast terahertz mixers, like hot electron bolometers, must be used in the non optimized direct detection mode. A superconducting microbolometer [2] with high sensitivity, ease of operation and optimized readout electronics at minimum front-end costs would solve the problem. We make use of a niobium film to produce a micrometric vacuum-bridge and decrease the thermal time constant to the sub-microsecond range, an approach first demonstrated by Luukanen and Pekola in 2003 [3]. The bolometer works anywhere in the temperature range 2–7 K, which can be easily reached in helium bath cryostats or closed-cycle cryocoolers [4]. Nowadays cryogen-free pulse tube refrigerators are commercially available, can operate continuously without requiring operator attention for years, and are simple to operate, on the other hand, they have some potential drawbacks, like mechanical and thermal oscillations and electromagnetic interference. To test these issues we chose a transMIT pulse tube cold head and we performed noise equivalent power measurements (NEP) of the device. The electronic bandwidth of the bolometer has been investigated by means of a QCL illuminator operating at liquid nitrogen temperature [5] and also using an electronic oscillator.

2 Bolometric Detector and Mounting

The operating principle of the superconducting hot spot air bridge bolometer (SHAB) is based on the so called hot spot model which has been proposed the first time by Skocpol, Beasley and Tinkham in 1974 [6]. Our antenna-coupled SHAB consist of a lithographic antenna electrically coupled to a temperature sensor, a free standing Nb strip 1 um wide and 15 um long [2]. The Nb strip acts both as resistive termination of the antenna as thermometer: by biasing the device with a constant voltage, a normal region, the hot spot, is formed in the middle of the bridge, due to the local increase of the temperature over the critical temperature Tc of the Nb film. THz power is dissipated mostly within the normal state region, and variations in the THz power affect the size of the normal state region of the bridge, which leads to a change of the quasi-static circulating current measured by a transimpedance amplifier (TIA) [2, 3]. Like a conventional bolometer our SHAB is well characterized by the intrinsic time constant $\tau = C/G$ that due to the reduced size of the bridge its extremely low. The hotspot model provides a time constant of the SHAB of 0.2 µs which gives in a rise time of 440 ns in response to a step excitation. This characteristic time constant, due to the electro-thermal feedback, is shorter than the intrinsic time constant. The fabrication process [2] of the bolometer is based on electron beam lithography. The EBL allowed us a great flexibility in changing design during the optimization of the fabrication process for the specific requirements. 49 chips (8 mm side) with five microbolometers per chip are fabricated in a batch. While the bolometers require cooling to cryogenic temperature, the complexity of the cooler is compensated by their high sensitivity, low manufacturing cost and frequency-agility. The nominal design bandwidth of our detector is 400 GHz–2 THz determined by the outer and the inner dimension of the logarithmic spiral antenna. Coupling of the terahertz radiation to the SHAB has been achieved by means of the integrated planar spiral antenna coupled through an hyper-hemispherical substrate lens. The SHAB has been mounted either on the cold plate of a liquid helium bath cryostat or in a pulse tube cooler, both equipped with an optical access; the 8 mm side chip is mounted in a copper holder, with back side pressed against the 6 mm diameter hyperhemispherical silicon lens. The silicon lens has a total thickness of 3.5 mm. For the hyper hemispherical silicon lens the distance between the focal point and the tip of the lens is $d_{hyper} = R(1 + \frac{1}{n})$ where R is the radius of the lens and n is the refractive index of the lens material which is 3.18 for high resistivity silicon over the broad THz spectral range. For silicon $d_{hyper} = 1.29R$. Considering the chip thickness of 0.37 mm one spiral antenna will be approximately located at the focus under f/0.6. The THz emission incident on the SHAB was filtered by a black high density polyethylene (HDPE) window at 300 K and then by two cold filters: a mylar window at 77 K and a fluorogold filter at 4.2 K with cutoff frequency around 6 THz. The detector is biased close to the voltage corresponding to the minimum current in the bridge where the best sensitivity is obtained.

3 Results

Commercial cryocoolers are available from several manufacturers. The coolers are typically based on either the Gifford-McMahon or the so called Pulse-Tube heat cycles. We have chosen to use a pulse tube cryocooler, which has no moving parts at low temperatures, no need for a liquid-helium bath cryostat and low mechanical vibration resulting in a longer life compared to other coolers. The transMIT pulse tube cold head that was used, provides a cooling power higher than 10 W and 50 K for the first stage and 0.6 W and 4.2 K for the second stage. These numbers are obtained when the cold head is combined with the SUMITOMO CNA612 compressor. The bolometer is mounted on the cold plate of the pulse tube and needs about two hours to reach the operating temperatures, which are respectively 40 K and 2.7 K for the two stages with the minimum heat load. We measured the SHAB current fluctuations in the frequency domain by means of a spectrum analyzer connected at the output of the transimpedance amplifier. In order to investigate the time response of the bolometer we used both a electronic oscillator and a QCL illuminator operating at liquid nitrogen temperature [5]. For this purpose, an improved transimpedance amplifier, faster than the one used earlier [7], was used in these measurements. We tested the TIA separately in order to ensure that we were not limited in bandwidth by the readout and the value obtained was about 1.8 MHz. The NEP measurements have been performed biasing the device at different points of the current-voltage characteristics in

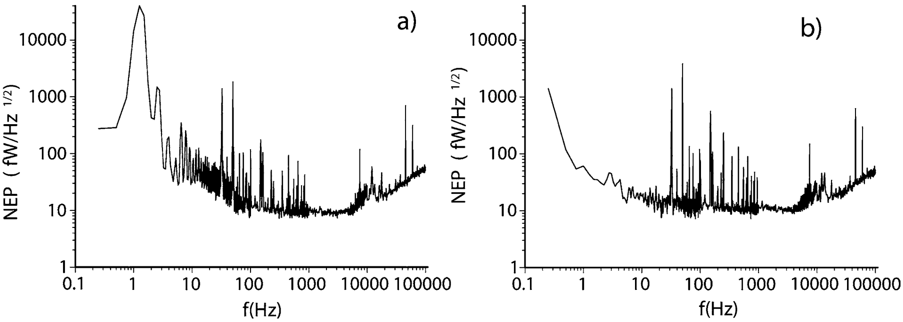

Fig. 1 Noise Spectra of the bolometer obtained in a pulse tube cryocooler. (**a**) Spectrum while the compressor is on (**b**). Spectrum obtained while the compressor is off. The 1 Hz peak and the higher harmonics are not visible anymore

order to find the best compromise between high responsivity and good match with the optimal noise resistance of the amplifier.

Figure 1a shows the NEP spectrum obtained by using the pulse tube cooler. Temperature variation induced by the operation cycle due to expansion/compression of the helium gas is around 30 mK and it shows up in the spectrum as a 1 Hz peak and higher harmonics. Figure 1b shows the spectrum obtained while the compressor has been switched off for a short period where the 1 Hz peak and higher harmonics are not visible any more.

The spectra show that we have obtained an electrical noise equivalent power of 10 fW/Hz$^{1/2}$ in the frequency region from 100 Hz to 10 kHz which equals the best results that we have previously obtained in a liquid helium cryostat [8] and we can conclude that the operation in pulse tube cooler does not degrade the performance of the bolometer. In order to investigate the electronic bandwidth of the bolometer we used both an electronic oscillator and a QCL illuminator.

The SHAB is illuminated by a train of pulses of the radiation generated by the frequency-multiplied tunable electronic oscillator in the range 0.15–0.75 THz (by Virginia Diodes Inc.) with a nominal rise time of about 1 us, emitted in free-space by a horn antenna, collected and refocused onto the detector lens by a pair of 90° off-axis parabolic mirrors. The emitted power is independently measured by a calorimeter to account for variation of the emitted power with frequency. The oscillator output is amplitude-modulated (AM) at selected frequencies between 30 Hz and 1 MHz by a master oscillator, which also works as reference for the lock-in amplifier.

Figure 2 shows the bolometer response to the incident train of pulses. The resulting rise time of the SHAB turned out to be about 850 ns, which represents an upper limit to the SHAB rise time due to the intrinsic limit of the source.

In order to better estimate the SHAB rise time we used microsecond single pulses coming from a QCL. The QCL source operates in a double metal waveguide configuration, is emitting in the range 2.2–2.4 THz and is driven by a homemade current pulse generator. It was mounted on the cold finger of a separate cryostat and the beam was directed into the window of the bolometer cryostat. We illuminated the SHAB with pulses of $\Delta t = 2$ μs with a repetition rate of 1 kHz.

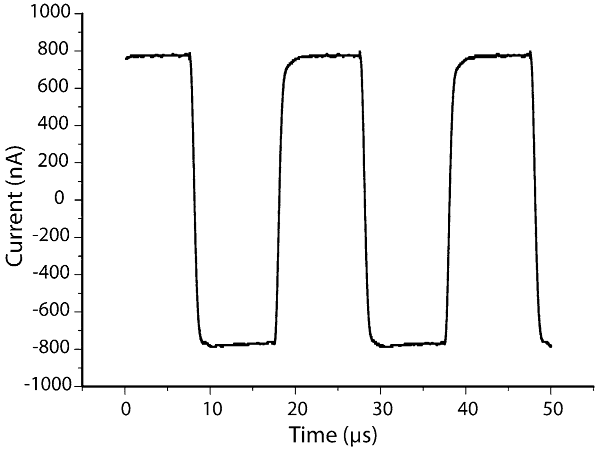

Fig. 2 Bolometer response to incident train pulses coming from a electronic oscillator

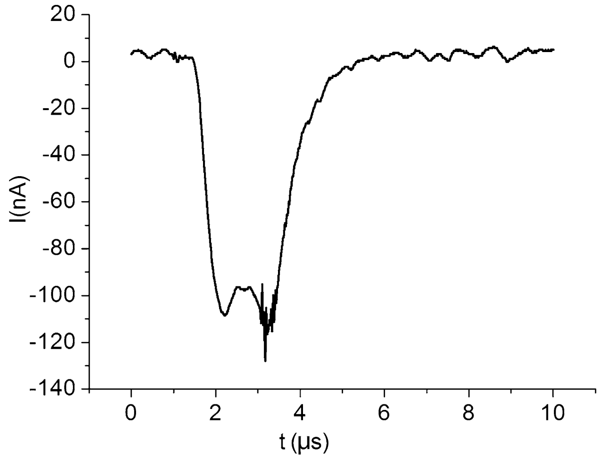

Fig. 3 SHAB response to a single QCL pulse

Figure 3 shows the SHAB response to a single QCL pulse. In this time scale the power emitted by the QCL is not stable as shown in the figure. For this reason we have only a rough estimate of the rise time of about 450 ns which is anyway in good agreement with what expected.

4 Conclusions and Perspectives

We tested the SHAB in a pulse tube cooler and measured 10 fW/Hz$^{1/2}$ of Noise Equivalent Power confirming the results obtained when operated in a liquid helium cryostat showing that potential drawbacks related to the use of a pulse tube refrigerator are irrelevant. Moreover in the same run of measurements we estimated the time constant of the bolometer by illuminating the SHAB with fast pulses emitted by an electronic oscillator source and a Quantum Cascade Laser emitter. We found a bolometer time constant value of about 200 ns in agreement with what we expected to find from the theory.

In order to improve the speed of the bolometer we are designing and fabricating a new batch of devices with a shorter air bridge to get a smaller heat capacity.

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