AC-Biased Superconducting NbN Hot-Electron Bolometer for Frequency-Domain Multiplexing

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Abstract— We present the results of characterization of fast and sensitive superconducting antenna-coupled THz direct detector based on NbN hot-electron bolometer (HEB) with AC-bias. We discuss the possibility of implementation of the AC-bias for design the readout system from the multi-element arrays of HEBs using standard technique of frequency-domain multiplexing. We demonstrate experimentally that this approach does not lead to significant deterioration of the HEB sensitivity compared with the value obtained for the same detector with DC-bias. Results of a numerical calculations of the HEB responsivity at AC-bias are in a good agreement with the experiment.

INTRODUCTION

Multi-element arrays of superconducting bolometers are being developed for a number of astronomical observations in far-IR and mm range. The currently used detectors in such a systems have an ultimate sensitivity limited by photon noise that is achieved because of the millikelvin operating temperatures. Our NbN hot-electron bolometer (HEB) is one of the well-known devices operated at more convenient temperatures (about 10 K) [1]. It can be used as an element of such arrays for the far-IR (THz) range. However, integration of a large number of HEBs into array on a single chip presents a difficult problem in terms of design the readout system. The obvious solution of this problem is using of AC-bias for the detectors. This method allows an easy extension to multi-element arrays with the standard frequency-domain multiplexing (FDM) technique.

At the same time, THz frequency range is very attractive for a number of important practical applications, such as security systems and medicine. As one can see from real practice, developers all over the world prefer using of pulsed THz sources, which are reliable, more powerful, stable in operation and user-friendly with respect to the CW sources of THz radiation. For that reason, the practical THz systems should be equipped with sensitive and fast detectors. Both features are combined in a direct detector based on HEB.

AC CURRENT-BIAS

To establish proper operating conditions for the HEB direct detector, the bath temperature is raised by a heater from the liquid-helium temperature up to the value close to the critical temperature T_c. The HEB is then DC-biased to the operating point with the highest sensitivity. The same regime is used for TES. In a common SQUID readout system for TES, the negative electrothermal feedback is provided by using the voltage-bias, so any small change in the absorbed optical power is compensated by a change in the Joule power.

Alternatively, one can apply AC-bias to the HEB, in which case the Joule power oscillates between minimum and maximum at twice the bias frequency. This technique was previously discussed in [2] for devices with inverse time constant lower than the bias frequency. It was shown that the load curves taken with AC- and DC-bias were nearly identical, indicating that there was no degradation in the performance of the bolometer due to the AC-bias. This approach was also discussed without direct experimental demonstration in [4].

In this paper, we demonstrate operation of a superconducting THz detector based on the NbN HEB with an AC-bias at a frequency much lower than the detector inverse time constant. For the fast bolometer, this regime differs from the described above. In this case, the electron temperature of the bolometer changes between maximum and minimum value just like the bias current without any delay. Thus, not only the bias power oscillates between minimum and maximum value, but the resistance of the bolometer as well. We also discuss the possibility of implementation of the AC-bias for organizing the readout from the multi-element arrays of HEBs using FDM.

DEVICES AND SETUP

The main aim of our experimental study was characterization of responsivity and noise-equivalent power (NEP) of NbN HEB with AC-bias. We used an elliptical lens made of high-resistivity Si, without an antireflection coating. The HEB chip was glued to the flat surface of the lens made of the same material as the chip substrate. This structure was installed into the lens holder that was mounted onto the cold plate of the optical liquid-helium cryostat with a high-density polyethylene window and a cold Zitex-104 filters cutting off room-temperature background radiation.

In out measurements, we used a cryogenic low-noise amplifier with a gain of 24 dB across a bandwidth of 0.01-200 MHz. An AC-bias at 1 MHz was applied to the bolometer through a 1-kΩ resistor with the function generator. The input impedance of the amplifier was 50 Ω at the biasing frequency. For that reason, we did not use the bias-T in our

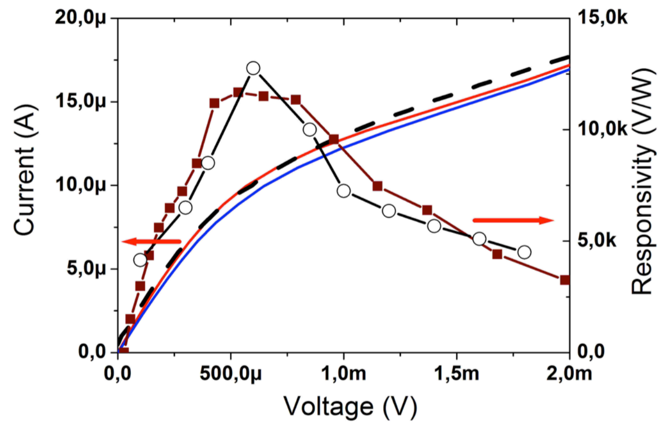

Fig. 1 Results of the experiment and the calculations. Blue and red curves show the calculated IV curves with the RF power and without it, correspondingly. Dash black curve shows the experimental IV curve. Wine and black curves show the calculated and measured HEB responsivity, correspondingly.

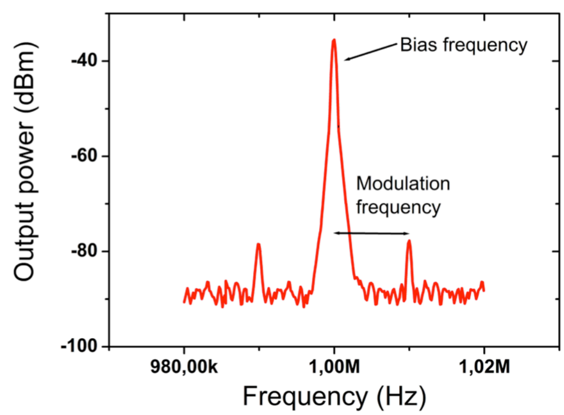

Fig. 2 Spectrum of the detector output power obtained from the output port of the low-noise amplifier. The bias frequency was 1 MHz. The input power was amplitude modulated with frequency of 10 kHz.

measurements. A gas discharge laser operating on a 2.5 THz H_2O line was used as a radiation source. The amplified signal from the bolometer was measured with the lock-in amplifier.

Results and Discussion

A basic principle of signal formation in the detector operated with the AC current bias differs from that in the case of DC-bias. The signal V_{out} that we measured was a difference between corresponding amplitudes of voltage oscillations from the bolometer with the applied RF power and without it. The power of the laser output was measured with a Golay cell. We calculated the input signal power P_{inc} using the measured transmission coefficient of the filters and the window. The input RF power was so adjusted that the detector was within its dynamic range. With these data we were able to calculate the optical responsivity of the entire receiver as $S_{Rx} = V_{out} / P_{inc}$. We measured S_{Rx} at different values of the amplitudes of the bias current along the optimal current-voltage curve at a bath temperature close to T_c. Then the input-signal power was attenuated until we were no longer able to detect any signal. We assumed that the remaining part of the lock-in amplifier readings was the noise level of the receiver.

Theoretical analysis of the described bias technique was based on the numerical solution of the well-known steady-state one-dimensional heat-balance equation applied to the HEB. The obtained results of our calculations, together with the measured values, are also shown in Fig. 1. Experimental results are shown with correction on the optical losses. The correction factor is about 5. This value is determined by the optical losses of the components of the experimental setup.

The noise level of the bolometer at the optimal operating point amplified with the cryogenic amplifier was measured to be about 0.4 $\mu V \cdot Hz^{-0.5}$, which is just about 2.3 higher than that for the same bolometer operated at DC-biased mode. We associate small degradation of the sensitivity with the instability of the employed function generator. So, as one can see, our mode of biasing the detector does not lead to significant degradation of its sensitivity.

The obtained results open the possibility of using an AC current-bias in conjunction with FDM [3] for constructing multi-element arrays of HEBs. Each element should be integrated with LC-filter with a specific resonance frequency. The inductance L_i of each LC-filter must be at least 24 μH for an operating resistance of about 60 Ω to obtain the bandwidth $\Delta f_i = R/(2\pi L_i)$ of 400 kHz. The resonance frequency of each LC-filter is selected by capacitors with values C_i chosen to keep the bias frequencies in the necessary range, using the relation $C_i = 1 / (4\pi^2 L_i f_i^2)$. For example, the necessary value of capacitance is equal to 10 pF for the bias frequency of 10 MHz. These inductors and capacitors can be easily manufactured using standard deposition technique.

The experimental demonstration of this idea at bias frequency of 1 MHz was performed using the amplitude modulation of the input power with the frequency of 10 kHz. The measured spectrum of the detector output power obtained from the output port of the LNA is shown in Fig. 2. As one can see, two sidebands located at the offset of the modulation frequency are clearly visible.

In summary, we have demonstrated successful application of the AC-bias to the HEB as a direct detector. This technique can be implemented for FDM for the multi-element arrays of HEBs. This work was supported in part by the Russian Foundation for Basic Research under Grant No. 16-32-00622 and the Russian Ministry of Education and Science under State Contract Nos. 14.B25.31.0007 and 11.2423.2017/PP.

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