Superconducting Detectors for Terahertz Imaging

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***Abstract*—Superconducting niobium nitride (NbN) hot electron bolometer (HEB) detectors consist of a complementary logarithmic-spiral antenna made of gold and an NbN film (bridge) connecting across the antenna's inner terminals have been fabricated and characterized. For its performance as a heterodyne mixer, the system DSB noise temperature of about 500 K and the intermediate frequency (IF) gain bandwidth (GBW) of about 4 GHz have been obtained at 4.2 K and 0.65 THz. For its performance as a direct detector, a microwave-driven scheme has been tried.**

I. INTRODUCTION

THE developments of terahertz (THz) imaging for person-borne concealed weapons at security-check points and non- destructive inspection of defects in materials have burgeoned over the last decade, due to its high spatial resolution comparing with the microwave and atmospheric/obscurant penetration comparing with the optics. To demonstrate such advantages, 0.65 THz maybe a quite suitable frequency point, be at enough high frequency for high spatial resolution and can penetrate the atmosphere for quite long distance. However, there are not so many sensitive, fast and convenient detectors working at 0.65 THz. Superconducting tunnel junction (STJ) detectors and transition-edge sensors (TES) have enough sensitivity, but should be working at much lower temperatures, which makes the system more complicate. Superconducting hot electron bolometer (HEB) mixers are very sensitive at 4.2 K and the frequencies higher than 1 THz. We have fabricated the niobium nitride (NbN) HEB mixers with the system double sideband (DSB) noise temperature lower than 10 times of the quantum limit: hf/k_B (where h is the Planck constant, k_B is the Boltzmann constant and f is the operating frequency) at the frequencies higher than 1 THz [1]. Here, we will report the performances of the NbN HEB detectors at 0.65 THz.

II. FABRICATIONS AND RESULTS

A. Device

The HEB detector consists of a superconducting bridge made from an ultra-thin NbN film and a logarithmic-spiral planar antenna with frequency independent impedance. The NbN bridge 2 μm in width, 0.2 μm in length and about 4 nm in thickness is connected to the planar antenna to efficiently couple the THz signal. The antenna is designed to work at 0.4-4 THz. The ultra-thin superconducting NbN film is deposited by DC magnetron sputtering on high-resistivity silicon (Si) substrate in Ar+N_2 gas mixture while keeping the substrate at room temperature (RT). A root-mean-square roughness of approximately 0.42 nm is obtained for a 4 nm thick film over an area of 25 μm^2. The critical current density of about 1.5×10^6 A/cm^2 at 4.2 K and critical temperature of about 9 K are obtained. After depositing the ultra-thin film, it is covered with photoresist, and two square openings are positioned on the photoresist by electron beam lithography (EBL) which determines the length of the bridge. In order to prevent degradation of the superconductivity of the bridge, an additional NbN film of 10 nm thickness is deposited on the opened NbN ultra-thin film as a buffer. Then a 50 nm thick gold film is deposited and the bridge's width is defined by photolithography and reactive ion etching (RIE). At the end a complementary logarithmic-spiral antenna made of gold is connected to the two poles. The details of the fabrication process are reported in [1-3]

B. Experimental setup

We use a quasi-optical setup to couple THz signal from the source to the HEB. The HEB chip is glued to the center of the back of a hyper-hemispherical lens made of high-resistivity Si. The lens without anti-reflection (AR) coating is used. The lens is fixed in an oxygen free copper fixture which is thermally sunk to the 4.2 K cold plate of a liquid helium cryostat. We use a microwave synthesizer with its multipliers at 0.65 THz as the local oscillation (LO) sources. A mylar film with a thickness of 15 μm is used for the beam splitter (BS) and the mylar film with a thickness of 36 μm is used for the cryostat window. Two black polyethylene films with thickness of about 0.1 mm and one G-110 Zitex, which is a porous polytetrafluoroethylene (PTFE) film, are used in the THz input hole at 77 K thermal shielding frame as infrared (IR) filters. To reduce the environment noise, all the equipments except the computer are placed in an RF shielding room. The cryostat is put on an optical table with anti-vibration structures.

1) Heterodyne detection

We use an adjustable DC voltage source to bias the HEB. The bias voltage and current can be collected to the computer by a digital multimeter. The intermediate frequency (IF) signal from the HEB is connected to a DC block, let to pass through an isolator, and then amplified by a cryogenic low noise amplifier (LNA) and an RT amplifier. The Y-factor method is used to measure the noise temperature (T_N) of the mixer.

2) Direct detection

A setup same with one used in the microwave stabilization experiment [1] is used for the direct detection measurement. The microwave signal is injected via a cold bias-tee and a 20 dB cold attenuator, then a cold circulator to the HEB. Also, the temperature of the HEB can be adjusted. There is no DC low noise amplifier inside the cryostat, but an RF LNA same with the mixer measurement is used to amplify the output signal from the HEB.

C. Results

1) Heterodyne detection

We use an improved Y-factor method to obtain the noise temperature (T_N). The improved method can eliminate the effect of direct detection of the HEB. The details of the discussion of the method are reported in [1-3]. In brief, we measure the IF output power, P_{Hot} and P_{Cold}, corresponding to the hot and cold loads, at the same DC bias point to get $Y = P_{\text{Hot}}/P_{\text{Cold}}$. The uncorrected T_N can be calculated by following expression:

$$T_{N,rec} = \frac{T_{Hot} - YT_{Cold}}{Y-1},$$

T_N at LO frequencies of 0.65 THz is shown in Fig. 1. The lowest T_N of about 500 K has been obtained. Also, the IF gain bandwidth (GBW) of about 4 GHz has been measured.

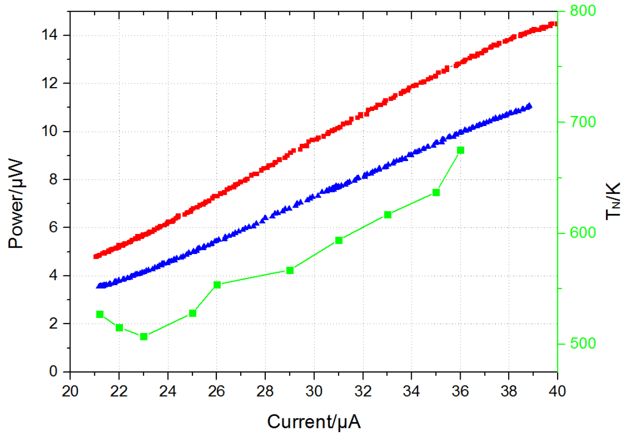

Fig. 1 Bias current dependences of the output powers (red one for the hot load and blue one for the cold load) and the noise temperature (green one) for an HEB mixer at 4.2 K and 0.65 THz. The bias voltage is optimized at 1.25 mV.

2) Direct detection

The responses of the HEB detectors to the microwave and THz signals with difference frequencies from 0.1 GHz to 2.5 THz have been measured in details. The results show that the small microwave signal with frequencies lower than IF GBW can be used to partially suppress the critical current and result in the *I-V* curve without any hysteresis. So we can bias the HEB stably to get the direct response to the THz irradiations.

Also, the hot and cold loads have been used to measure the optical noise equivalent power (*NEP*) of the detectors. The *NEP* at the optimized bias point of about 7×10^{-12} W/Hz$^{0.5}$ has been obtained. This value is quite good for the fast imaging applications and can been expected to be improved by the optimizations of the devices and measurements.

III. SUMMARY

HEB detectors working at 0.65 THz have been fabricated and characterized for the THz imaging. For the mixer, the system DSB T_N of about 500 K and the IF GBW of about 4 GHz have been obtained. For the direct detector, the *NEP* of about 7×10^{-12} W/Hz$^{0.5}$ has been obtained at 4.2 K and 0.65 THz.

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