Properties of Terahertz Superconducting Hot Electron Bolometer Mixers

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Abstract: A quasi-optical superconducting niobium nitride (NbN) hot electron bolometer (HEB) mixer has been fabricated and measured in the terahertz (THz) frequency range of 0.5~2.52 THz. A receiver noise temperature of 2000 K at 2.52 THz has been obtained for the mixer without corrections. Also, the effect of a Parylene C anti-reflection (AR) coating on the silicon (Si) lens has been studied.

Keywords: Hot electron bolometer (HEB) mixer, Terahertz, Noise temperature, Heterodyne detector

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I. Introduction

Developing highly sensitive terahertz (THz) receiver has become increasingly important for astronomical observation, remote sensing, and many other applications [1]. As the front end of a heterodyne receiver, at frequencies below 1 THz superconductor-insulator-superconductor (SIS) mixer shows excellent noise performances approaching the quantum limit [2], while above 1 THz superconducting hot electron bolometer (HEB) mixer seems a better choice in the sense that it has higher sensitivity and requires lower local oscillator power [3] than the SIS counterpart. Here, the fabrications and properties of NbN HEB mixers are reported. Also discussed are the correction of the receiver noise temperature, as well as the effect of the anti-reflection coating of the Si lens in the quasi-optical system.

II. Experimental and results

A superconducting HEB mixer mainly consists of an ultra-thin (a few nanometers) superconducting film, patterned to the shape of a short and narrow bridge and integrated with an antenna. Around its critical temperature (*Tc*), the film's resistance depends on the temperature sensitively. The superconducting NbN film is deposited epitaxially, by DC magnetron sputtering, on Si or MgO substrates in Ar+N2 gas mixture [4]. When the small bridge is irradiated by THz waves, the electrons inside will be heated up (so called hot electrons) and the energy will subsequently relax to the substrate through electron-phonon interaction. To design and characterize an HEB mixer, it is necessary to measure the parameters for the films in detail. An epitaxial NbN film 7 nm thick on MgO substrate is measured by a time-domain spectroscopy (TDS) system at frequency of 1.06 THz using a Backward Wave Oscillator (BWO) as the signal source [5]. The penetration depth λ is found to be about 330 nm, as compared to the value of λ =220 nm for thicker NbN films (several tens of nanometers).

As shown in Fig. 1, a complementary logarithmic-spiral antenna is integrated with the bolometer itself which is a NbN film (3.5-nm thick, 4 μm wide and 0.32 μm long) connecting across the antenna's inner terminals. The antenna should satisfy the conditions that the outer diameter (*D*) is larger than λ0max/4 and the inner diameter (*d*) is smaller than λ0min/20, where λ0max and λ0min are the maximum and minimum wavelengths in the free space for the antenna [6]. The superconducting NbN HEB bridge is fabricated by electron-beam (EB) lithography, while the gold antenna defined by photolithography on Si substrate. The *Tc* of NbN HEB bridge is about 10 K and Δ*Tc* is about 1.3 K. Its normal DC resistance at room temperature *R300* (82 Ω) is close to the impedance of the log-spiral antenna (about 75 Ω). If the RF impedance of the HEB mixer is approximately equal to its frequency-independent normal DC resistance at room temperature *R300*, the coupling between the superconducting HEB bridge and the log-spiral antenna might be rather good as well. But this is still an open question until now, although it has been used for the designs of the HEB bridge [3].

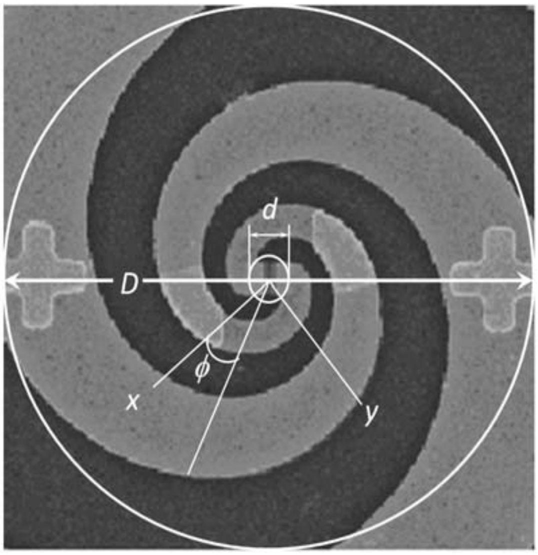

Fig. 1 Microphoto of the quasi-optical NbN HEB mixer

The noise temperature of the quasi-optical NbN HEB mixer is measured using the Y-factor method in the frequency range of 0.5-2.52 THz. The measurement setup is similar to that described in our previous paper [7]. In the experiments, for frequencies *f*=0.76, 1.62 and 2.52 THz, the LO source is provided by an optically pumped far-infrared gas laser (FIRL100 made by Edinburgh Instruments Ltd.), while for *f*=0.5 and 0.85 THz the LO source is a Gunn oscillator with multipliers and a BWO, respectively. Using a Si hyper-hemispherical lens with a diameter of 12 mm and no anti-reflection (AR) coating, the radiation is focused onto the HEB mixer via the log-spiral antenna integrated with it. It should be pointed out that in order to have sufficient LO power pumping at each frequency, the thicknesses of the Mylar films used for the beam splitter (at an angle of 45 degrees with the incidence direction) and the window on the vacuum chamber (normal to the incidence direction) are carefully selected to optimize the transmission. Table 1 summarizes the thicknesses of the films and the corresponding transmission efficiencies, which are calculated by the circular polarization characteristic of the log-spiral antenna.

f (THz)	LO source	Window	Beam splitter	*Trx,m* (K)
2.52	CH3OH @FIRL100	0.98 @ 36μm	0.73 @15μm	2000
1.62	CH2F2 @FIRL100	0.79 @ 36μm	0.81 @15μm	2000
0.85	BWO	0.93 @ 15μm	0.93 @15μm	1100
0.76	HCOOH @ FIRL100	0.78 @ 36μm	0.99 @6μm	1200
0.5	Gunn	0.97 @ 15μm	0.98 @12μm	800

Table 1 Results of the receiver noise temperatures at *f* = 0.5 THz to 2.52 THz.

The HEB mixer is firstly measured at 2.52 THz. The unpumped and optimally pumped current-voltage (*I-V*) curves of an NbN HEB mixer working at 4.2 K are shown in Fig. 2, together with the receiver noise temperature (*Trx,m*) measured as a function of the dc bias voltage along the optimally pumped *I-V* curve. The lowest *Trx,m* (measured at 1.4 mV and 55 μA, with no correction) reaches as low as 2000 K at 2.52 THz, as shown in the Fig. 2. The *Trx,m* increases considerably while the dc bias is shifted away from the optimum bias point. We then measure the *Trx,m* at lower frequencies ranging from 0.5 to 1.62 THz. All the results are summarized in Table 1. As the beam splitter and window both have different transmission efficiencies at the testing frequencies, it is necessary to correct their noise contributions. Furthermore, the impedance mismatching between the HEB mixer and log-spiral antenna should be taken into account for the corrections

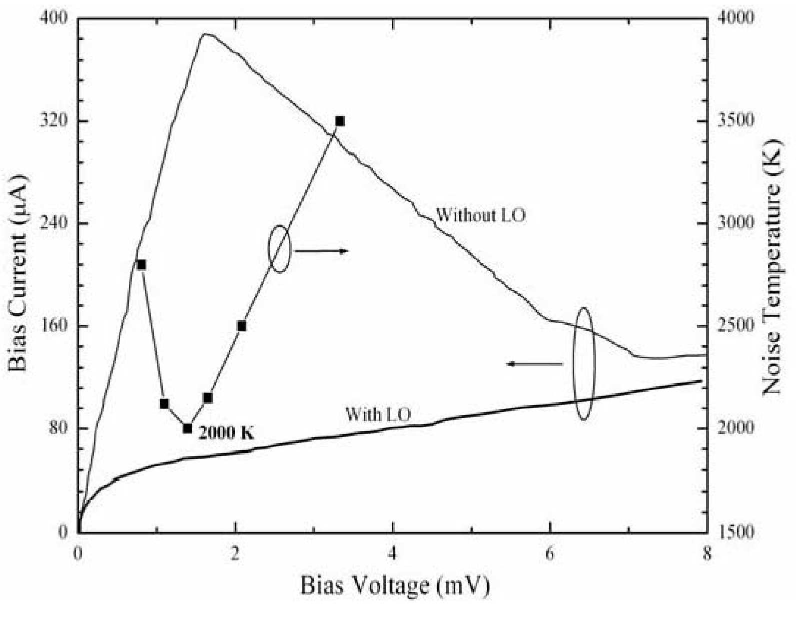

Fig. 2 *I-V* curves with different LO powers and noise temperature of the receiver as a function of bias voltage along the optimal pumping *I-V* curve. 36-μm and 15-μm thick Mylar films are used as the window and beam splitter.

to get the corrected mixer noise temperatures (*Trx,c*). The corrected *Trx,c* is about 500 K [8] for the frequencies ranging from 0.5 to 2.52 THz and is frequency independent as expected for the mixers with *Trx,c* of several times larger than the quantum limited noise temperature. It should be noted that the dominate correction is the impedance mismatching at the higher frequencies, where the coupling loss due to the non-uniform distribution of the RF current is quite larger compared with that at the lower frequencies [8].

In addition, the Si hyper-hemispherical lens for focusing the RF and LO signals to the above HEB mixer has no AR coating, which might account for approximately 30% loss according to the calculations. In an attempt to solve this problem, Parylene C has been chosen for the AR coating, as it is a thermoplastic polymer thermally stable and chemically inert, with good adhesion properties and low water absorption [9]. Also, it can be deposited from the gas phase at room temperature with sufficient thickness up to several hundreds of micrometers, which is necessary for lower frequencies in THz region. To further investigate its usefulness as coating at THz region, Parylene C films with different thicknesses are deposited on 1 mm thick high-resistivity (> 5 kΩ cm) Si substrates and tested by using a THz time domain spectroscopy (TDS) system [10]. By comparing the measured transmittances of such samples with calculated ones, at room temperature the refractive index *n* is found to be 1.65 and absorption coefficient α to be 2 cm^{-1}. These values indicate that Parylene C film is suitable for the AR coating on Si optics, although it is not an optimal one (*n* =1.85). Subsequently, Parylene C films with quarter wavelength thicknesses at respective frequencies have been deposited on the surfaces of the Si hyper-hemispherical lenses to investigate the effect of the AR coating on the receiver noise temperature. Fig. 3 shows the measured results using the coated lens (a) as well as the uncoated lens (b). The thickness of the coated film is 18.5 µm, which is equal to the quarter wavelength thickness at *f*=2.52 THz. The receiver noise temperature of 3500 K is obtained as shown in Fig. 3 (a) for the coated lens, which means that about 22% improvement has been achieved by comparing with the result in Fig. 3 (b), where the receiver noise temperature of about 4500 K is obtained. Similar results have been obtained at lower frequencies down to 0.76 THz with the thickness of the coated film of 54 µm. These results demonstrate that Parylene C is a useful coating material at THz range.

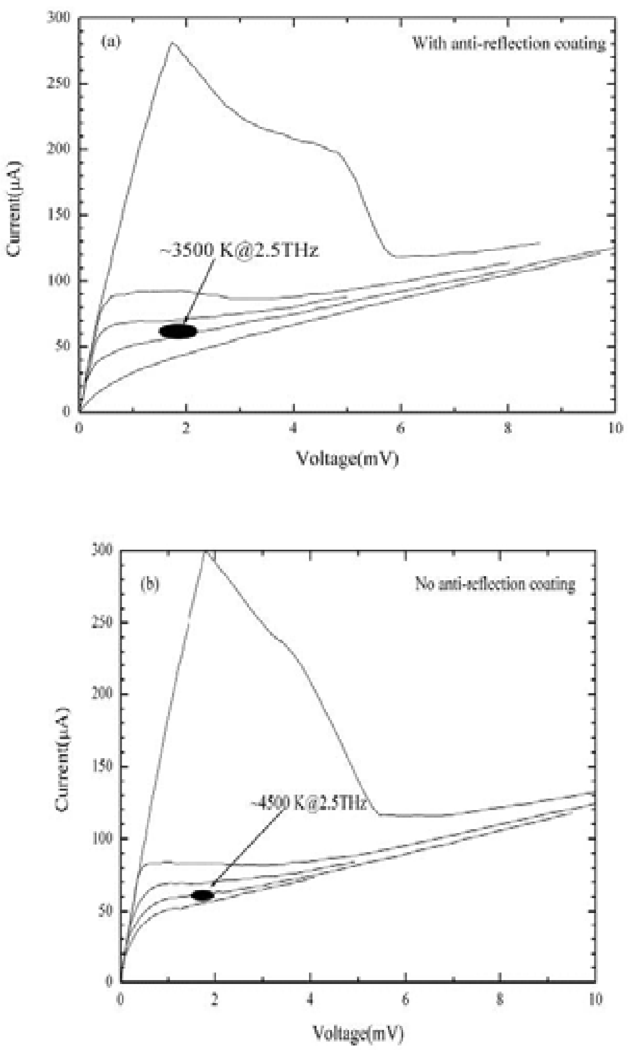

Fig. 3 I-V curves with different LO powers and noise temperatures of the receiver as a function of bias voltage for an NbN HEB mixer (a) with AR coating; (b0 without AR coating on the Si lens. 36-µm and 15-µm thick Mylar films are used as the window and beam splitter

III. Conclusions

The noise temperatures of a quasi-optical superconducting NbN HEB mixer have been investigated from 0.5 to 2.52 THz. The lowest receiver noise temperature measured at 2.52 THz is 2000 K with no corrections, and reduces to about 500 K after correcting the noise contributions of the beam splitter, window and mismatching between the HEB mixer and log-spiral antenna. Also, the improvements of the receiver noise temperature by the AR coating have been demonstrated at THz range.

Acknowledgments

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