Low Noise Receivers Using Niobium Nitride Hot Electron Bolometer Mixers from 0.76 to 3.1 THz

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Abstract: Low noise receivers using quasi-optical superconducting niobium nitride (NbN) hot electron bolometer (HEB) mixers have been designed, fabricated and measured in the terahertz (THz) frequency range for THz applications in astronomy and cosmology. The NbN HEB mixers consist of a planar complementary antenna and several nanometer (nm) thick NbN bridge connecting across the antenna's inner terminals on high-resistivity Si substrates. A double sideband (DSB) receiver noise temperature of 664 *K* at 0.76 *THz*, 920 *K* at 1.6 *THz*, 1630 *K* at 2.5 *THz* and 1710 *K* at 3.1 *THz* has been obtained without corrections and no anti-reflection (AR) coating on the surface of the lens.

Keywords: Hot Electron Bolometer (HEB) mixer, quasi-optical superconducting heterodyne detector, Terahertz (THz), receiver noise temperature

doi: 10.11906/TST.068-074.2009.06.08

1. Introduction

Developing the terahertz (THz) techniques becomes more and more important to the astronomy observations, remote sensing and many other expected applications [1]. Below 1.4 *THz*, Superconductor-Insulator-Superconductor (SIS) mixers showed the quantum-limited noise temperatures ($T_Q=hf/k_B$, where h is the Planck constant, k_B is the Boltzmann constant and f is the operating frequency) [2,3], while superconducting Hot Electron Bolometer (HEB) heterodyne mixers have a higher-sensitivity as well as a lower local oscillation (LO) power for the operating frequencies higher than 1.4 *THz* [4-7]. Therefore, it can be expected that the superconducting HEB mixers will be used widely in near future. Here, the fabrication and properties of the low noise NbN HEB mixers are reported at frequencies from 0.76 *THz* to 3.1 *THz*.

2. Experiments and Results

The main part of superconducting HEB mixers is an ultra-thin (about a few nanometers) superconducting film with extremely strong dependence of resistance upon temperature around its critical temperature (T_c). The superconducting NbN film was deposited by DC magnetron sputtering on the high-resistivity (> 5 $k\Omega cm$) Si substrates in Ar+N_2 gas mixture and substrate temperature keeping at room temperature (RT) [8]. Fig. 1 shows an atomic force microscopy (AFM) imaging of a 4.5 *nm* thick NbN film on Si substrate. The RMS value of about 0.42 *nm* is obtained in an area of 5 μm square, which means that the film is of high quality with smooth surface. And the excellent interlayer growth between the film and the substrate can be confirmed by the transmission electron microscopy (TEM) observations as shown in Fig. 2. T_c of about 9 K and the critical current density (J_c) of about 1.5×10^6 A/cm^2 at 4.2 *K* have been obtained for such ultra-thin films. When the small bridge made by the ultra-thin superconducting film is irradiated with a THz photon, the electrons inside will be heated up (so called hot electrons) and the energy will subsequently relax to substrate through the electron-phonon interaction [4].

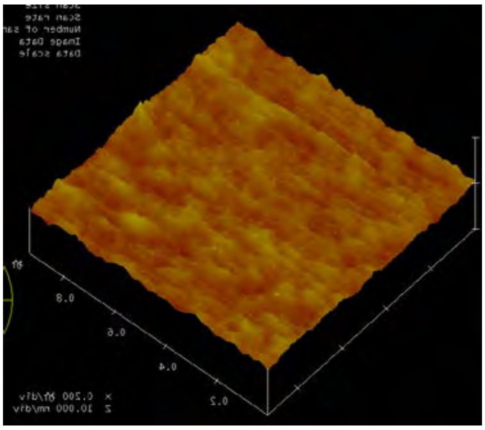

Fig. 1 AFM imaging of a 4.5 *nm* thick NbN film on Si substrate.

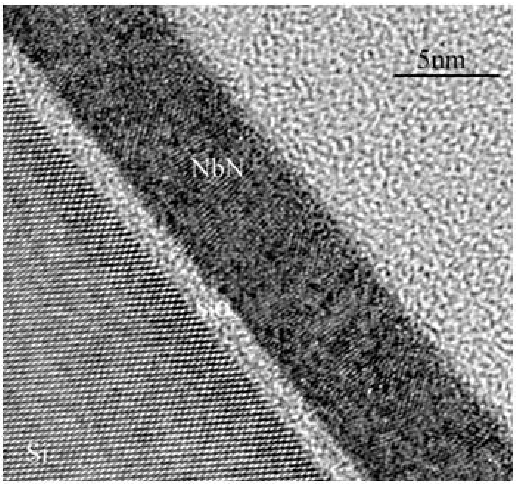

Fig. 2 TEM imaging of NbN ultra thin film on Si substrate. A SiO_2 intermediate layer of about 1.5 *nm* is formed.

The NbN HEB mixer consists of a complementary logarithmic-spiral antenna and a 3.5 *nm* thick NbN film connecting across the antenna's inner terminals. The outer diameter (*D*) of the antenna should be larger than $\lambda_{0max}/4$ and inner diameter (*d*) be smaller than $\lambda_{0\min}/20$, where $\lambda_{0\max}$ and $\lambda_{0\min}$ are the maximum and minimum wavelength in the free space [9]. During the fabrication, NbN thin film is first deposited. It is then covered by photoresist. Two square openings are positioned on the photoresist through which an additional NbN layer about 10 *nm* thick is deposited. Finally gold is deposited. The two square openings, with a preset distance between each other, are used to help maintain the desirable length of the bridge while the additional NbN is used as a buffer so that the superconductivity of the bridge underneath will not be seriously degraded by the gold contact [7]. The superconducting NbN HEB bridge (refer to Fig. 3, measuring about 4 μm wide and about 0.4 μm long) was fabricated by electron-beam (EB) lithography, while the gold antenna defined by photolithography on Si substrate. The T_c of NbN HEB mixer is about 8 *K* and ΔT_c is about 1.3 *K*. Its normal resistance at room temperature R_{300} (around 150 Ω) is 2 times higher than the calculated impedance of the log-spiral antenna (about 75 Ω). In general, the RF impedance of the HEB mixer is approximately equal to R_{300}, which is frequency independent. If this is the case, the measured quasi-optical HEB mixer might have imperfective coupling between the superconducting HEB mixer and the log-spiral antenna. Therefore, there is room for further improvements for our receivers.

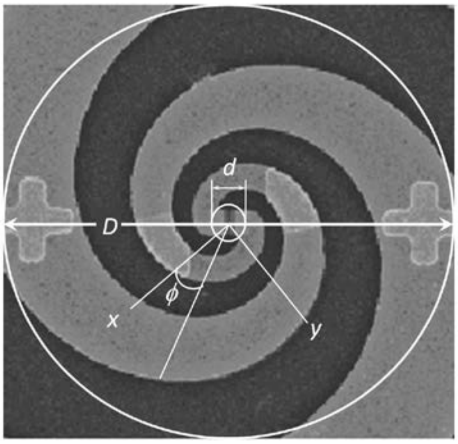

Fig. 3 Microphoto of the quasi-optical NbN HEB mixer.

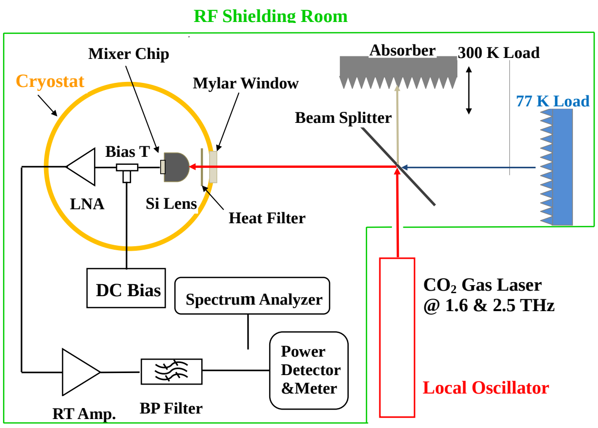

Fig. 4 Schematics of the measurement system.

The double sideband (DSB) receiver noise temperature (T_N) of the quasi-optical NbN HEB mixer was measured by the Y-factor method at the frequencies (*f*) from 0.76 *THz* to 3.1 *THz*, where the equivalent temperatures of the blackbody load at 300 and 77 *K* have been used according to the Callen-Welton definition [10]. The loads are placed about 30 *cm* from the cryostat. The measurement system is shown in Fig. 4. In this experiment, an optically pumped far-infrared gas laser (FIRL100, with output power of about several *mW* now and linear polarization), made by Edinburgh Instruments Ltd., was used as the LO source. It is deployed outside of an RF shielding room due to its big size and all other equipment is set inside of the RF shielding room, so that the RF noise can be reduced effectively in our lab. As a result, the distance between output of the laser and input of the cryostat is little far from each other (about 70 *cm*), which will decrease the power of THz signals quite large in air and about 2% output power of the laser can reach to the window of the cryostat at 2.5 *THz* and with the 30% humidity of air, experimentally. Using a Si hyper-hemispherical lens with the diameter of 12 *mm* and no anti-reflection (AR) coating on its surface, the radiation is focused onto the HEB mixer via the antenna integrated with it as shown in Figs. 3 and 4. A cryogenic low noise amplifier (LNA) with noise temperature of 12 *K* and gain of about 30 *dB* at frequency range of 1.3-1.7 *GHz* and operation temperature of about 15 *K* together with two other general RT amplifiers are used to amplify the intermediate frequency (IF) signal of the mixers. No additional isolator is applied between the mixer and the LNA, but a bias tee is employed there. An IF filter with center frequency of 1.5 *GHz* and bandwidth of 100 *MHz* is used between the IF amplifier and microwave power meter or detector. It should be pointed out that in order to have sufficient LO power pumping from 0.76 *THz* to 3.1 *THz*, the strength of the window should be considered, and the beam splitter (at an angle of 45 degrees with the incidence direction) and vacuum window (normal to the incidence direction) should be selected with different thickness of Mylar films. Here, 36 μm and 15 μm thick Mylar films are used as the window and beam splitter, respectively. In this case, optical loss of about 0.05 *dB* for window and 1.2 *dB* for beam splitter can be calculated at 2.5 *THz*. However, the loss of about 1.8 *dB* for 36 μm window film was measured experimentally at 2.5 *THz*, due to its warped surface by the vacuum of the cryostat and its absorption caused by the quality of the films. This additional loss will degrade the measured T_N about 60 *K* at 2.5 *THz* theoretically. We need to characterize all of the used optical parts experimentally to get a calibrated T_N and DSB conversion loss of the mixer in near future.

First, the T_N was measured at 0.76 *THz*. The unpumped (No RF) and pumped (RF) current-voltage (*I-V*) curves of an NbN HEB mixer working at 4.2 *K* are shown in Fig. 5 (a), together with the DSB receiver noise temperature (T_N) measured as a function of the dc bias voltage along the optimally pumped (with LO) *I-V* curve. The contact resistance of about 10 Ω is shown in the *I-V* curve, which is measured by a two probe method. The lowest T_N (measured around 1 *mV*, without any corrections) reaches as low as 667 *K* at 0.76 *THz*. It is about 17.5 times of T_Q. Also, the T_N at frequency of 1.6 *THz* has been measured. The lowest T_N reaches of 920 *K* at this frequency and is about 11.5 times of T_Q. At 1.6 *THz*, the total optical losses are calculated to be about 5 *dB*, which including 1.8 *dB* for the beam splitter and window, 2.3 *dB* for lens reflection, lens absorption and lens antenna, and 0.9 *dB* for the air path between the load and the cryostat. Using the isothermal method [11], the absorbed LO power of about 130 *nW* is estimated. This LO power is about 50 times lower than the measured one, where a Golay Cell detector is placed at the position of cryostat window and same laser power for lowest T_N is irradiated via the beam splitter. The main reason about this difference is due to the misalignment for our optical system, which will be improved using controllable stage to move the cryostat. The T_N increases considerably while the dc bias is shifted away from the optimum bias point. We then measured the T_N at frequency of 2.5 *THz* and 3.1 *THz* as shown in Fig. 5 (b) and (c). The lowest T_N reaches as low as 1630 *K* at 2.5 *THz* and 1710 *K* at 3.1 *THz*. It is about 13 time of T_Q at 2.5 *THz* and 11 time of T_Q at 3.1 *THz*. The frequency dependence of the T_N may be explained by the impedance mismatching between the antenna and the mixer [12].

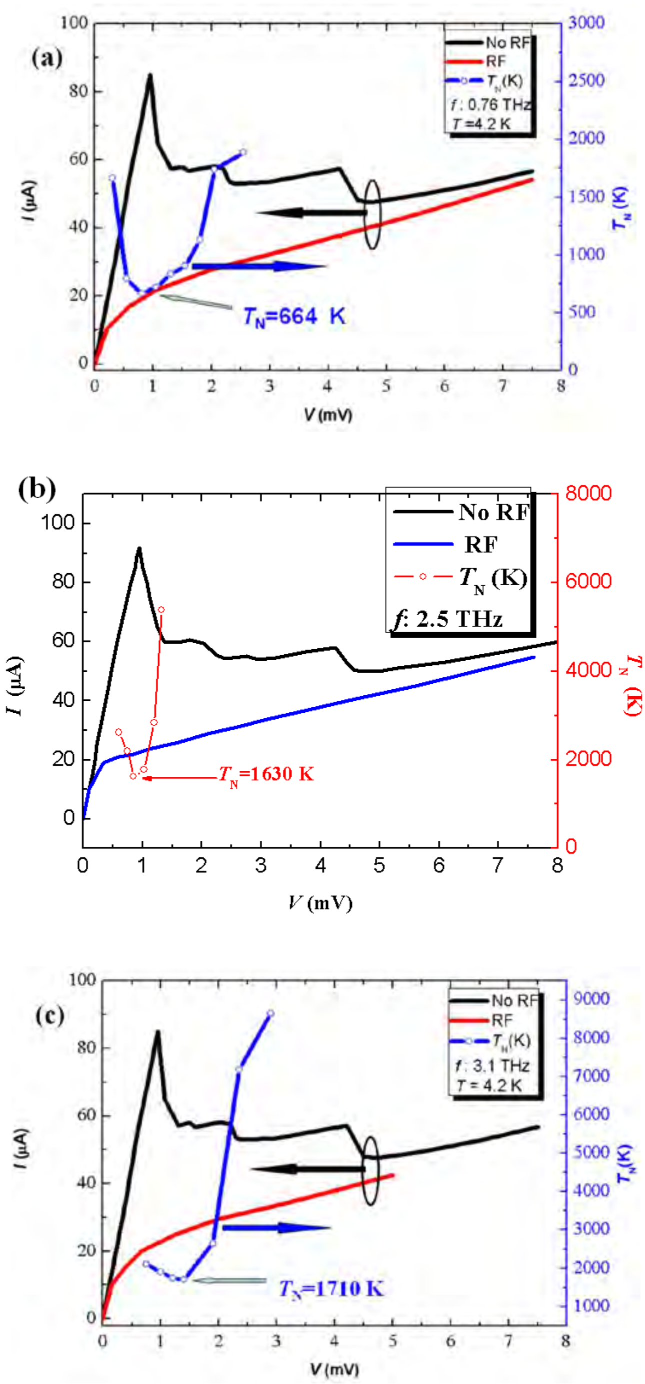

Fig. 5 *I-V* curves with optimized LO power and DSB noise temperature of the receiver as a function of bias voltage. 36μm and 15μm thick Mylar films are used as the window and beam splitter, respectively. The results are measured at frequencies of (a) 0.76 *THz*; (b) 2.5 *THz* and (c) 3.1 *THz*.

3. Conclusions

The DSB receiver noise temperatures of the quasi-optical superconducting NbN HEB mixers have been investigated at frequencies from 0.76 *THz* to 3.1 *THz*. The lowest DSB receiver noise temperature measured at 3.1 *THz* is 1710 *K* without any corrections. It is about 11 time of T_Q.

Acknowledgement

The work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 10778602, 60721063, 60571007, and the National Basic Research Program of China (973 Program) under Grant 2006CB601006, 2007CB310404.

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