Development of an All-NbN Waveguide SIS Mixer for 0.5 THz

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***Abstract* –With a gap frequency double that of Nb-based ones (~0.7THz), NbN SIS tunnel junctions are of particular interest for the development of heterodyne mixers at frequencies beyond 1 THz. To demonstrate the potential of NbN SIS tunnel junctions for astronomical applications, we developed a 0.5 THz all-NbN waveguide SIS mixer to observe the CO (J=4–3) emission at 0.46 THz with the POST submillimeter-wave telescope. In this paper, we mainly describe the mixer design, NbN junction fabrication and mixer performance. In particular, the mixer performance is compared with that of a 0.5-THz Nb SIS mixer previously installed on the same telescope. Some testing observation results are also presented.**

I. INTRODUCTION

Heterodyne mixers based on SIS tunnel junctions have been widely used for astronomical and atmospheric observations at millimeter and submillimeter wavelengths [1]. In fact, SIS mixers with Nb-based SIS tunnel junctions have achieved noise temperatures as low as three times the quantum limit below 0.7 THz, which is the gap frequency of Nb SIS tunnel junctions [2]. At frequencies higher than 0.7 THz, however, the transmission loss in Nb thin-film superconducting microstrip lines increases significantly due to the breaking of cooper pairs, thereby deteriorating the performance of Nb SIS mixers to some extent. With the increasing requirements of astronomical research in the submillimeter band (0.3-3 THz) [3], ones have been attempting to develop SIS mixers based on SIS tunnel junctions of a larger energy gap.

NbN SIS tunnel junctions [4], which have a gap frequency of about 1.4 THz [5], are a good candidate for the development of SIS mixers at frequencies higher than 0.7 THz. To demonstrate the potential of NbN SIS tunnel junctions for astronomical detection at submillimeter wavelengths, we developed a 0.5 THz waveguide-type NbN SIS mixer for the Portable Submillimeter Telescope (POST) [6,7], which aims at observing spectral lines over the 0.5 THz atmospheric window. The POST has a diameter of 30 cm and is currently situated at a site at an altitude of 3200 m (Delingha, China).

This paper mainly introduces the design, fabrication, and characterization of the 0.5-THz waveguide NbN SIS mixer. Its performance is also compared with that of a 0.5-THz Nb SIS mixer that was previously installed on the same telescope. Some preliminary observation results with the 0.5-THz waveguide NbN SIS mixer are exhibited.

II. MIXER DESIGN

Fig. 1 shows a cross-sectional view of the 0.5-THz waveguide NbN SIS mixer. As indicated in Fig. 1, the SIS mixer chip, based on the MgO substrate (with a dielectric constant of 9.6), is 102-µm wide and 51-µm thick and is inserted in a slot measuring 119 µm × 119 µm. A full-height waveguide measuring 510 µm × 255 µm was chosen for this design. It should be pointed out that there was no backshort cavity introduced in this design to ease the mechanical fabrication of the waveguide mixer block. The conventional bow-tie waveguide probe (refer to Fig. 1), located at the

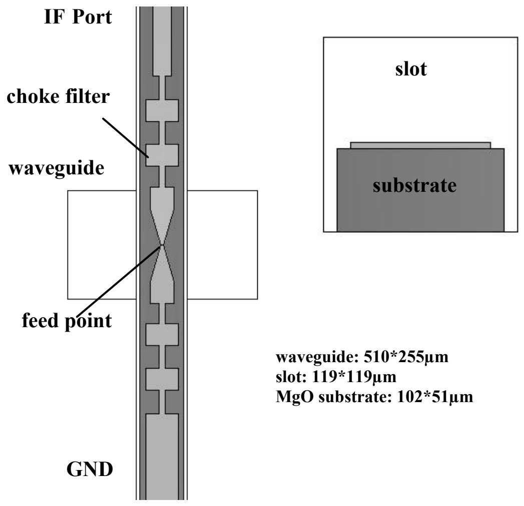
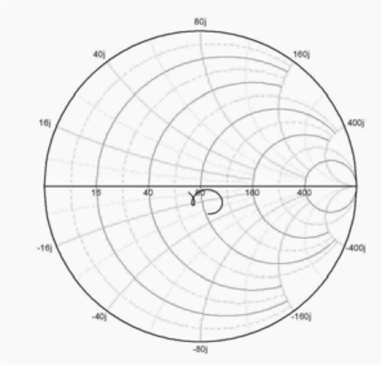
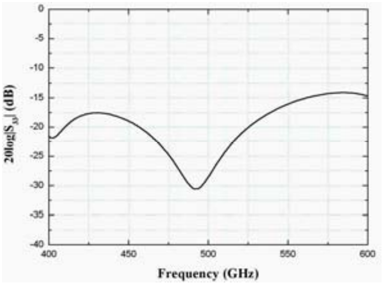


Fig. 1. Cross-sectional view of the 0.5-THz waveguide NbN SIS mixer.



(a)



(b)

Fig. 2. (a) Simulated embedding impedance plotted on a Smith chart and (b) simulated return loss (referring to 80 Ω at the feed point) as a function of frequency.

waveguide center, was adopted to couple the RF and LO signal from waveguide to the SIS junction circuit.

The RF embedding impedance of the 0.5 THz waveguide NbN SIS mixer was simulated in the frequency of 0.4-0.6 THz with the aid of HFSS. Fig. 2 plots the simulated embedding impedance seen at the feed point (refer to Fig. 1) for an optimized waveguide probe structure. It can be clearly seen that the embedding impedance is pretty close to 80 Ω in the frequency range of 0.4–0.6 THz and the relative bandwidth is about 35% for the return loss less than -13dB.

Based on the calculated embedding impedance shown in Fig. 2 and Tucker's quantum mixing theory [8], we designed the twin-junction tuning circuit (refer to Fig. 3), which has a tuning inductance inserted in between the parallel connected twin junctions [9,10] to tune out their geometric capacitances. The junction critical current density (J_c) was taken as 15kA/cm^2 and the junction size was 1µm in diameter, corresponding to a $\omega R_n C_j$ product of 7.3 at 0.5 THz and a normal state resistance (R_n) of 29.5Ω for individual junctions. An impedance transformer was placed between the feed point and the twin SIS tunnel junctions to have good impedance matching between them. Note that the junction tuning circuit and impedance transformer are both made of a thin film superconducting microstrip line composed of NbN (200 nm)/MgO (200 nm)/NbN (350 nm) three layers.

III. JUNCTION FABRICATION

For the fabrication of all-NbN SIS tunnel junctions, firstly, we deposited the NbN/AlN/NbN tri-layer on an MgO substrate measuring 20 mm × 20 mm × 0.3 mm. The base and counter NbN layer were both 200-nm thick. The NbN films were prepared without additional substrate heating by reactive dc magnetron sputtering in a gas mixture of Ar and N_2. A low total pressure (~2 mTorr) and high power density were used to promote the growth of the NbN films. The AlN barrier was deposited by dc sputtering in pure N_2 gas with a low power density to have good control over its thickness. Secondly, the waveguide probe and choke filter were patterned by conventional photolithography and etched by reactive ion etching (RIE) with CF_4 and Ar gases. Thirdly, the SIS tunnel junctions were defined and a 200-nm thick MgO layer was deposited by RF sputtering to insulate the base and wiring electrode. Finally, a 350-nm thick wiring NbN layer was deposited and patterned after the lift-off of the photoresist, Fig. 3 shows the photograph of a fabricated 0.5 THz NbN SIS junction chip.

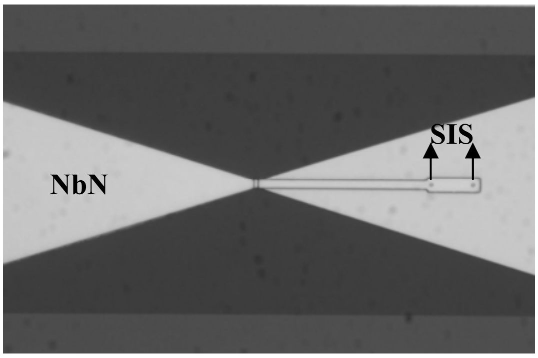


Fig. 3. Photograph of a 0.5 THz NbN SIS junction chip (part).

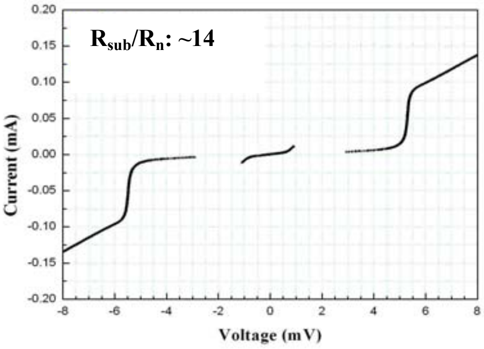


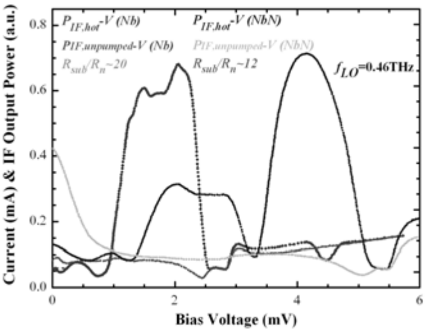
Fig. 4. Measured dc I-V curve of a 0.5 THz NbN SIS junction.

A typical DC I-V curve (measured at 4.2 K) of fabricated 0.5-THz NbN SIS tunnel junctions is shown in Fig. 4. Obviously, the gap voltage is about 5.4 mV. And the sub-gap current is fairly small, giving a quality factor (i.e., R_{sub}(4 mV)/R_n) of about 14. In addition, a resonance step can be clearly observed at about 1mV, which indeed corresponds to a Josephson frequency of around 0.5THz.

IV. Mixer Performance

The noise performance of the 0.5 THz waveguide SIS mixer was characterized by the conventional Y-factor method. It should be pointed out that due to the time limit (for the installation of the 0.5 THz NbN SIS mixer on the POST telescope for the winter season of 2007), the SIS junction device was indeed not optimized. In spite of that, preliminary measurement showed an uncorrected noise temperature as low as 150 K (about six times the quantum limit), including a RF noise contribution (resulting mainly from the measurement setup) of approximately 100 K.

To further investigate the characteristics of NbN SIS mixers, we compared the IF-output-power response and the temperature dependence of noise performance of the 0.5 THz waveguide NbN SIS mixer with respective ones of a 0.5 THz Nb SIS mixer previously installed on the POST telescope. Note that for both SIS mixers, we used a small permanent magnet to suppress the Josephson effect. The results are displayed in Figs. 5a-5b. It can be clearly seen from Fig. 5a that the 0.5 THz NbN SIS mixer has an IF-output-power response (on the first photon step) completely immune from the Josephson effect and the photon-assisted tunneling effect originated from the negative branch of the junction's I-V curve. Obviously, larger gap voltage accounts for this improvement. Fig. 5b shows the temperature dependence of noise performance measured for the two 0.5 THz SIS mixers.



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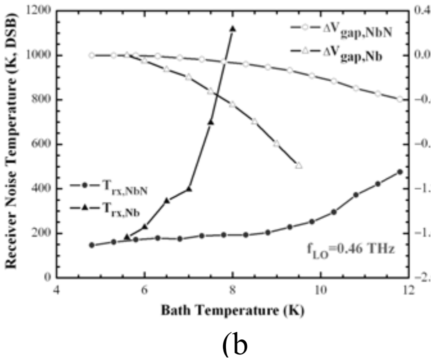

(b

Fig. 5. Comparison of the performance of a 0.5 THz NbN SIS mixer and a 0.5 THz Nb SIS mixer, with (a) the IF-output-power response and (b) the temperature dependence.

While the noise performance of the 0.5 THz Nb SIS mixer starts to deteriorate considerably from about 6 K, that of the 0.5-THz NbN SIS mixer is almost constant up to a bath temperature of 8 K and is still reasonably good to 10 K, which is already beyond the critical temperature of Nb SIS tunnel junctions. The results shown in Fig. 5 indicate that with higher critical temperature (or higher energy gap), NbN SIS mixers have less stringent requirements for cooling and magnetic field, which are very beneficial to real applications.

V. Astronomical Observation

The 0.5 THz NbN SIS mixer was installed on the POST telescope, which is aimed at observing spectral lines over the 0.5-THz atmospheric window for the purpose of large-scale surveys along the galactic plane. The POST has a diameter of 30 cm and is currently located at a site at an altitude of 3200 m (Delingha, China). Using the 0.5 THz NbN SIS mixer, on Dec. 31, 2007 we detected spectral line emission from CO (J = 4–3) at 0.46 THz toward Orion A. The zenith atmospheric opacity during the observation was around 2.0 (~13.5% transmission) at the observation frequency. The observed spectrum with an integration time of 6.2 min is shown in Fig. 6. The root-mean-square noise temperature is approximately 0.79 K. This is the first astronomical observation ever made with NbN superconducting tunnel junctions.

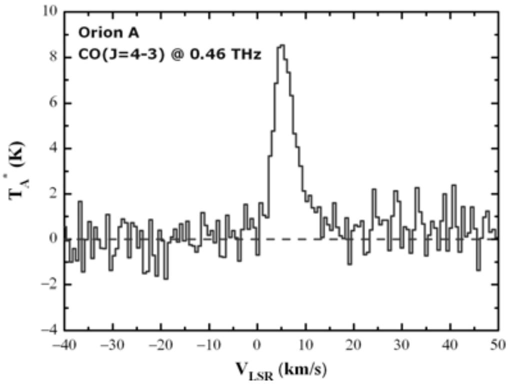

Fig. 6. CO spectrum observed with the 0.5 THz NbN SIS mixer.

VI. Summary

We have successfully developed a low noise 0.5 THz wavguide all-NbN SIS mixer. The lowest receiver noise temperature (uncorrected) is below 150 K, approaching six times the quantum limit. In addition to high sensitivity, the 0.5 THz NbN SIS mixer has shown higher stability and less stringent requirements for cooling than a Nb SIS mixer in the same frequency band.

The 0.5 THz NbN SIS mixer has been installed on a sub-millimeter telescope (POST, with a diameter of 30 cm). The CO (J=4–3) spectrum emission has been detected toward Orion A. It is the first astronomical observation ever made with an NbN SIS mixer.

It can be concluded that NbN SIS mixers are potentially useful beyond 1 THz and even have some merits at low frequencies. They may play important role in THz astronomical and atmospheric research, especially for space-borne observations.

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