Development of a 0.85 THz Nb-AlN-NbN Superconductor-Insulator-Superconductor Mixer

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***Abstract*–China is planning to build a 5-m THz telescope named DATE5 at Dome A in Antarctica. The telescope will operate in 0.85 THz and 1.5 THz frequency bands. A waveguide superconductor-insulator-superconductor (SIS) mixer is developed for the 0.85 THz frequency band by utilizing parallel-connected tunnel junctions (PCTJ) with Nb/AlN/NbN trilayer and NbTiN/SiO_2/Al microstrip tuning circuit on quartz substrate. Its frequency response is measured by a Fourier-transform spectrometer (FTS), showing an FWHM frequency coverage of 762-925 GHz. The measured uncorrected double sideband (DSB) receiver noise temperature is approximately equal to 450 K at 840 GHz. With the vacuum window and beamsplitter losses corrected, the receiver noise temperature is less than five times the quantum-limited noise. Detailed mixer design and measurement results will be presented.**

***Keywords*–Terahertz, SIS, Mixer, NbN, DATE5**

I. INTRODUCTION

Dome A in Antarctic is an exceptionally dry site because of high altitude (4093 m) and low temperature (with a recorded lowest temperature of −83 °C). Measurements of the atmospheric transmission in the range of 0.75-15 THz by a Far-Infrared/THz Fourier transform spectrometer (FTS) strongly suggest that Dome A is a an ideal site for ground-based THz astronomical observations, especially for the 200- and 350-μm windows [1]. A 5-m THz telescope (DATE5) will be built there for Chinese Antarctic Kunlun Observatory [2]. This telescope will operate at 200- and 350-μm windows (i.e., 1.5 THz and 0.85 THz) with two heterodyne receivers, respectively, in which the 0.85 THz one is an SIS receiver.

SIS mixers with all-Nb junctions [3] have been widely used in many radio astronomical projects such as the Atacama Large Millimeter/submillimeter Array (ALMA) and the Herschel Space Observatory (HSO). Currently, all-Nb SIS mixers with high energy gap superconducting materials such as NbTiN as tuning circuits can operate approaching 1 THz [4]. With continuous optimizations and iterations, the noise performances of the all-Nb SIS mixer for the ALMA Band 10 has reached the state-of-the-art performance below 1 THz [5]. In spite of that, all-Nb SIS mixers should be operated at 4.2 K or below. By contrary, all-NbN SIS mixers can operate at temperatures around 10 K [6]. Their noise performance, however, is not yet comparable with all-Nb ones around 1THz [7], partly due to large dark current (or shot noise). As the DATE5 telescope will be operated on a site with limited power supply, superconducting receivers for this telescope are required to perform well at temperatures which may exceed 4.2 K. Hence we propose to develop a 0.85-THz SIS mixer with Nb/AlN/NbN hybrid tunneling junctions, which have already demonstrated potential at high frequencies [8].

II. MIXER DESIGN

The fabricated 0.85-THz waveguide mixer block is shown in Fig. 1 together with the SIS mixer chip design. In our design, a diagonal horn with an aperture of 2.47 mm and a length of 21 mm connects with a rectangular waveguide measuring 304×152μm via a taper structure. Between the feed-horn end and the back-short cavity, an E-plane slot is inserted for accommodating the SIS mixer chip. The radio frequency (RF) and local oscillation (LO) signal will be coupled by the diagonal horn and then transmitted to the SIS mixer chip. The SIS mixer chip based on quartz substrate is composed of a bowtie-shaped waveguide probe, a conventional RF choke filter consisting of high- and low-impedance microstrips, and an integrated SIS junction circuit including a quarter-wavelength impedance transformer and parallel-connected tunnel junctions (PCTJ). As introduced before, we chose Nb/AlN/NbN tunnel junctions with an integrated tuning circuit made of NbTiN/SiO_2/Al thin-film microstrip line.

III. FREQUENCY RESPONSE

In order to measure the response bandwidth of the 0.85-THz SIS mixer, a Michelson Fourier transform spectrometer (FTS) was used. For this measurement, the SIS mixer was mounted on the 4.2 K stage of a wet Dewar and used as a direct detector. To suppress the DC Josephson current of the SIS junctions, a magnetic field of the order of 100 Gauss was applied. The RF signal radiated from a broadband glow mercury lamp source was coupled to the SIS mixer through the Michelson interferometer in a purged nitrogen atmosphere. Fig. 2 shows a typical measured response. It can be clearly seen that the measured FWHM is about 163 GHz (762-925 GHz) and the fractional bandwidth is greater than nineteen percent. It should be pointed out that dips at 750 GHz and 900

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GHz are due to the absorption of water vapor, corresponding to simulated transmission curve shown in Fig. 2, because there was a signal path exposed to the air between the FTS and the wet Dewar.

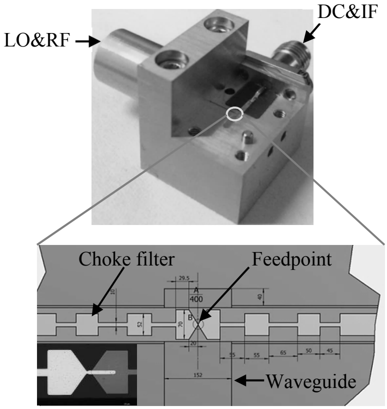

Fig. 1. Photograph of the mixer block which houses the SIS mixer chip. The lower portion of the figure details the SIS chip which is mounted in the slot of the mixer block. The inset is the zoom-in of the central part of the chip.

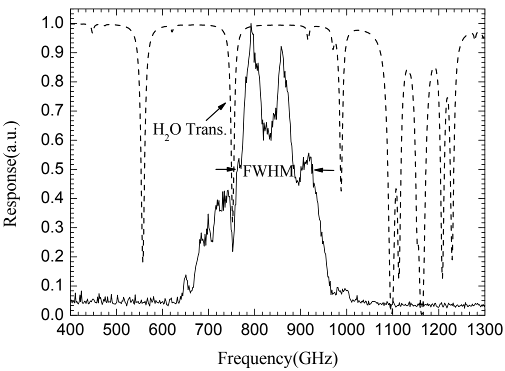

Fig. 2. Measured FTS response (solid lines) of SIS mixers with Nb/AlN/NbN junctions and NbTiN/SiO_2/Al microstrip. The dash line is the curve representative of RF signal transmission through the water vapor between the FTS and the Dewar.

IV. Noise Performance

The noise temperature of the 0.85-THz SIS mixer was measured by the conventional Y-factor method. We used room temperature (295 K) blackbody as a hot load and blackbody immersed in liquid nitrogen (77 K) as a cold load. The mixer block was cooled down to 4.2 K. The measurement setup is shown in Fig. 3. The RF and LO signal were combined by a 15-μm thick Mylar film beamsplitter, which couples approximately 86% of the RF signal power into the SIS mixer at 0.85 THz. The combined RF and LO signal traveled into the 4-K Dewar through a 2-mm thick HDPE vacuum window at room temperature and a Zitex IR filter at 77 K. The down converted intermediate frequency (IF) signal was firstly amplified by a 0.1-3 GHz cryogenic low noise amplifier (LNA) at 4.2 K and then by two 30-dB gain room-temperature amplifiers for 1.4-1.6 GHz. After passing through a bandpass filter (centered at 1.5 GHz and 40 MHz bandwidth), the signal was recorded by a power meter.

Fig. 4 shows the measured dc current-voltage characteristics with and without LO power and IF power dependence versus bias voltage at an LO frequency of 840 GHz. It can be clearly observed that the gap voltage of the Nb/AlN/NbN tunnel junctions is about 3.3 mV, corresponding to a gap frequency of about 800 GHz. The measured normal state resistance (R_n) is about 6.9 Ω, which is slightly larger than the designed value (5.3 Ω) due either to lower J_c or smaller junction area. It can be also clearly seen from Fig. 4 that the sub-gap current is fairly small, giving a quality factor ($R_{sub}(2mV)/R_n$) of about 40. Since the Josephson effect was not completely suppressed, there are a few spikes on the IF power curves. In Fig. 4, a maximum Y factor (P_{295K}/P_{77K}) of 1.41 was measured at a bias voltage of 2.0 mV, corresponding to an uncorrected DSB receiver noise temperature (T_{rx}) of 450 K. Note that due to the limit of LO power, the LO pumping level is below the optimum one. Nevertheless, we managed to measure the mixer noise performance in a large frequency range. As plotted in Fig. 5, the uncorrected T_{rx} in the measurement bandwidth (816-864 GHz) is lower than 600 K.

To understand the measured receiver noise performance, we used the intersecting line method [9] to measure the input RF noise. It is around 240 K in the frequency range of 816-864 GHz. We evaluated the losses of the beamsplitter and vacuum window in the RF signal path. Table I lists the evaluated results at 840 GHz. We used the formula of $T_{rx'} = (T_{rx} - T_{RF})G_{RF}$ to calibrate the T_{rx}. The result is also shown in Fig. 5. Obviously the corrected T_{rx} is about five times as large as the quantum-limited noise.

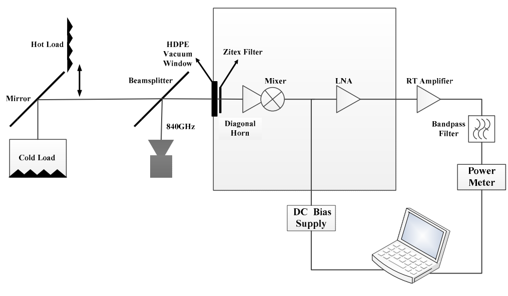

Fig. 3. Measurement setup of noise temperature. Unless otherwise noted, elements within the Dewar are mounted on a 4.2 K cold plate.

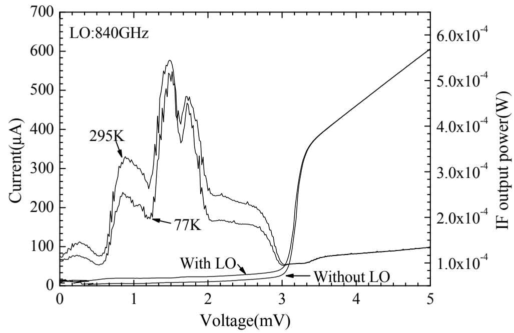

Fig. 4. Measured dc current-voltage (I-V) characteristics of SIS mixer with Nb/AlN/NbN junctions and NbTiN/SiO_2/Al microstrip with and without LO power at 840 GHz. Also shown is the IF output powers as a function of bias voltage for hot (295K) and cold (77K) input loads.

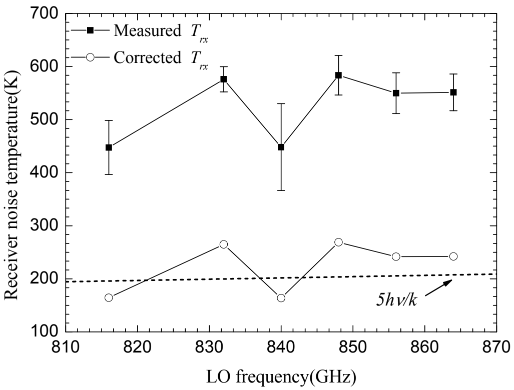

Fig. 5. Measured DSB receiver noise temperature of SIS mixers with Nb/AlN/NbN junctions and NbTiN/SiO_2/Al microstrip. The corrected T_{rx} is corrected for losses in the beam splitter and the vacuum window of Dewar.

TABLE I
LOSSES OF BEAMSPLITTER AND VACUUM WINDOW

	Material	Thickness (μm)	Transmittance @ 840 GHz (%)
Beamsplitter	Mylar	15	86.3
Window	HDPE	2000	93.8
IR filter	Zitex	100	97.0

V. CONCLUSION

We have developed a 0.85-THz SIS mixer with twin Nb/AlN/NbN tunnel junctions and NbTiN/SiO_2/Al thin-film microstrip circuit. The junctions have a gap voltage of 3.3 mV suitable for mixers operating around 1 THz. The measured FTS response demonstrates frequency coverage of 762-925 GHz. The uncorrected DSB receiver noise temperature is 450 K measured at 840 GHz. With the beamsplitter and vacuum window losses corrected, the DSB receiver noise temperatures is approximately five times the quantum-limited noise.

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