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# Noise performance of a 200–280 GHz mixer with Nb-AlN-NbN superconducting tunnel junctions

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## ABSTRACT

Superconductor–insulator–superconductor (SIS) mixers remain the choice of heterodyne mixers for single-dish telescopes and interferometers at millimeter and submillimeter wavelengths. Compared with conventional $Nb/AlO_x/Nb$ superconducting tunnel junctions, Nb/AlN/NbN ones have larger gap voltage and may reach critical-current density beyond $10kA/cm^2$, which are both of particularly interest in developing broadband SIS mixers. Here we report on the design and measurement of an SIS mixer based on Nb/AlN/NbN parallel connected twin junctions (PCTJ) incorporating $NbTiN/SiO_2/Al$ microstrip circuit. The junctions have a gap voltage of 3.18mV and a critical-current density of $15kA/cm^2$. The measured receiver noise temperatures reach $5h\nu/k_B$ among 200-260GHz band, and the mixer's fractional bandwidth is about 40% centered at 230GHz.

**Keywords:** SIS junction, heterodyne mixer, gap voltage, critical-current density, terahertz

## 1. INTRODUCTION

The terahertz band (0.1-10THz) accounts for nearly half of the photon energy of the universe after the cosmic microwave background (CMB)[1], and is very rich in molecular and fine-structured atomic spectrum lines. Therefore, terahertz astronomical observations are very important for understanding the star and galaxy formation, planet and planetary system formation[2,3].

Astronomical spectral line detection needs heterodyne mixers which can detect signal's amplitude and phase simultaneously. Superconductor–insulator–superconductor (SIS) mixers, with near quantum-limit sensitivity, remain the choice of heterodyne mixers for single-dish telescopes and interferometers at millimeter and submillimeter wavelengths[4,5].

SIS mixers with wider frequency coverage (RF bandwidth) can improve the observation efficiency and reduce the overall cost. Theoretically, the SIS mixer's bandwidth depends on the energy gap voltage and critical-current density. The wider RF bandwidth requires higher critical-current density, while this cause to a thinner insulation layer and defects such as pinholes, leading to a larger leakage current and a lower quality factor. Compared with conventional $Nb/AlO_x/Nb$ superconducting tunnel junctions, Nb/AlN/NbN ones have larger gap voltage and may reach critical-current density beyond $10kA/cm^2$ with high quality factor[6].

In this paper, we designed and characterized an SIS mixer based on Nb/AlN/NbN parallel connected twin junctions (PCTJ) incorporating $NbTiN/SiO_2/Al$ microstrip circuit. The noise performance of the mixer at different bias voltages, local oscillator (LO) frequencies, and bath temperatures are characterized in detail.

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## 2. MIXER DESIGN AND FABRICATION

Figure 1(a) demonstrates the electromagnetic (EM) structure model of the SIS mixer, the RF signal input from port 2 is coupled to the feed-point through the waveguide probe, and the IF signal is output to port 3. The chip's substrate (in green) is quartz with a dielectric constant $\varepsilon_r$=3.8. RF choke filter structure (in brown), is composed of superconducting film microstrip circuit. The dimensions of the RF choke filter, waveguide probe, and chip slot are optimized simultaneously by HFSS[7], as shown in table 1. The embedding impedance of the feed-point is normalized to 41Ω at 200-260GHz frequency band, as shown in the Smith chart of figure 1(b).

The twin Nb/AlN/NbN tunnel junctions are designed at a center frequency of 230GHz with a critical-current density of 15kA/cm$^2$. And the junction area is selected as 1μm$^2$, corresponding to a normal resistance of 11Ω in terms of IcRn =1.65 and a junction capacitance of 95fF by assuming a specific capacitance of 95fF/μm$^2$.

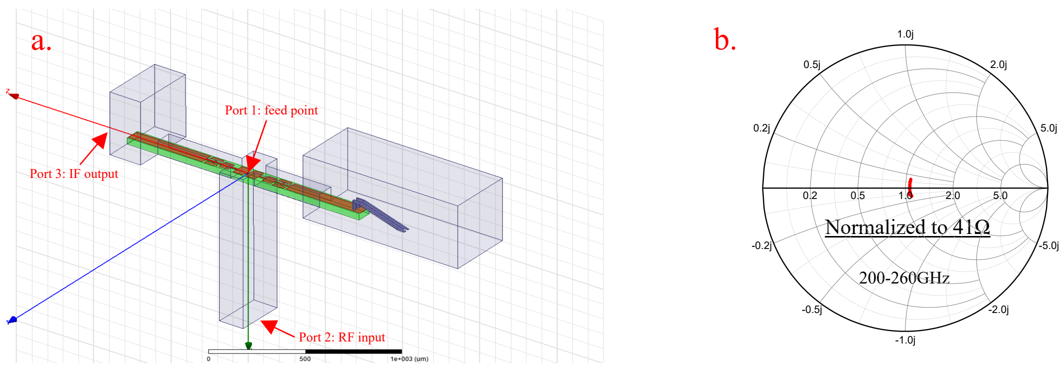


Figure 1. (a) Electromagnetic (EM) simulation model of the mixer. (b) Smith chart of the normalized feed-point embedding impedance at 200-260GHz frequency band.

Table 1. The optimized EM model's parameters.

| **Parameter** | **200-260GHz** |
|---|---|
| Waveguide | 1092μm×546μm (WR-4.3) |
| Slot size | 350μm×330μm(W*D) |
| Chip size | 4000μm×340μm×138μm |
| Substrate | Quartz ($\varepsilon_r$=3.8) |

Based on the quasi-five port equivalent model of Tucker's quantum mixing theory[8], the dimensions of the tuning circuit of PCTJ and feed-point embedding impedance matching circuit are obtained by optimization, as shown in figure 2(a). The power coupling efficiency between the feed-point and the superconducting tunnel junctions are calculated. In figure 2(a), the red curve with blank squares is SIS1's coupling efficiency, the blue curve with blank triangles is SIS2's coupling efficiency, and the pink curve with solid dots is PCTJ's total coupling efficiency, which is 80%-85% at 200-260GHz frequency band. Figure 2(b) is the simulated results of mixer double sideband (DSB) conversion gain and mixer noise temperature, the conversion gain closes to 0dB, and the noise temperature is 10-15K at 200-260GHz.

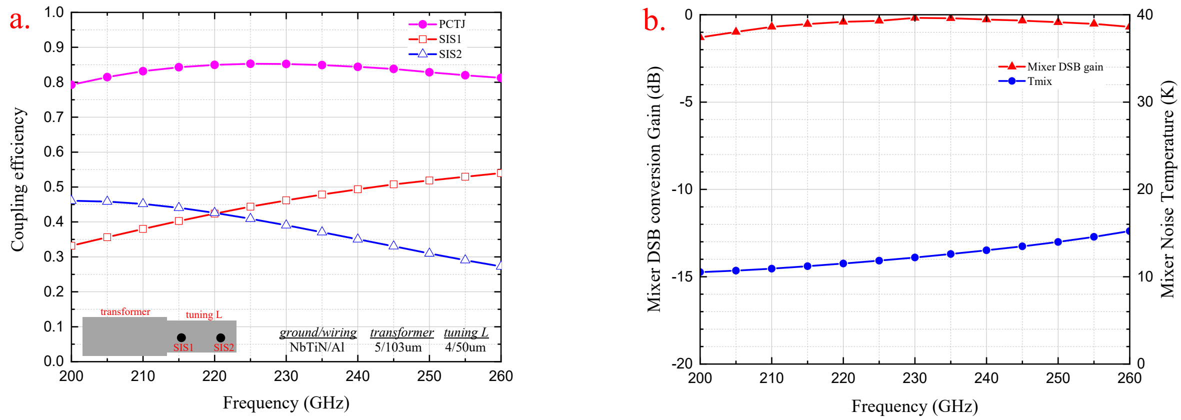


Figure 2. (a) Power coupling efficiency between SIS tunnel junctions and feed-point, insert image demonstrates the parameters of the tuning circuit of PCTJ and feed point impedance matching circuit. (b) Simulated results of mixer DSB conversion gain and mixer noise temperature.

The mixer chips are fabricated at the Kotelnikov Institute of Radio Engineering and Electronics, Russia Academic of Science[9]. Figure 3 show the optical microscope images of the mixer chips. The left is an overall image of the area on a piece of wafer. The right is a magnified image of the core area of a chip, the bow-tie probe structure, the chip feed-point, the impedance matching and tuning circuits, and the exact location of the PCTJ are clearly.

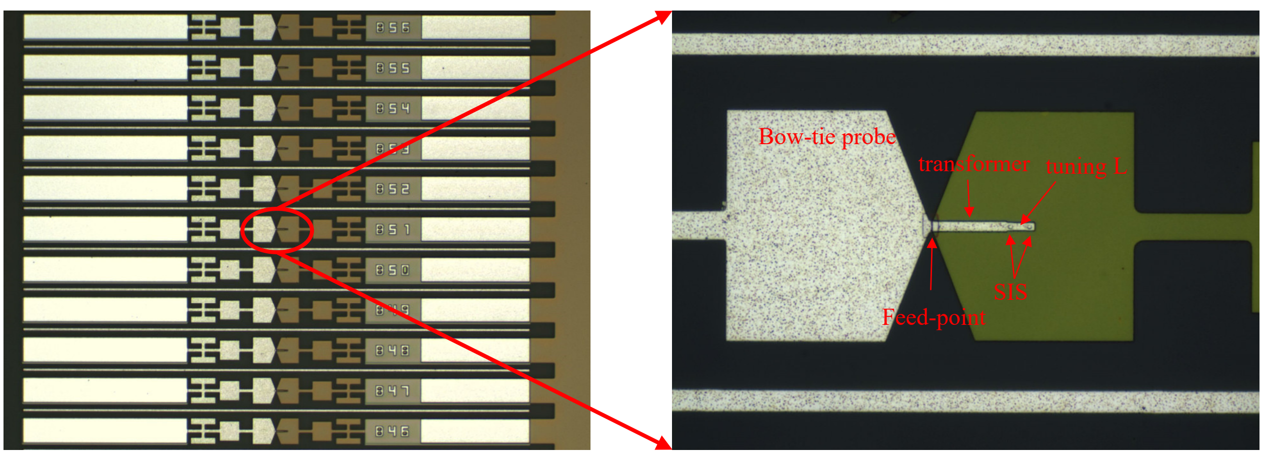


Figure 3. Optical microscope images of the mixer chips.

## 3. MEASUREMENT

### 3.1 Measurement setup

The mixer's noise performance is measured by the Y-factor method. Figure 4(a) is the setup of mixer's performance measurement system. The dewar is cooled by Gifford-McMahon cycle refrigerator. LO signal and RF signal are combined by a beam splitter and then coupled to the SIS mixer by a diagonal horn through the vacuum window of the dewar. The mixer's output intermediate frequency (IF) signal is amplified by two stages of a cryogenic low-noise amplifier (CLNA) and a room-temperature amplifier, and then acquired by the power meter through a 1.5GHz±50MHz band-pass filter.

Figure 4(b) is the LO multiplier chains, and coupling optical path of the LO and the RF signal. LO multiplier chains consist of an active multiplier chain followed by a WR-12 waveguide isolator, adjustable attenuator and a passive tripler, with output frequency coverage of 180-270GHz. Fundamental frequency signal is generated by an analog signal generator. Beam splitter is 13μm mylar film. Hot and cold load are provided by room-temperature blackbody and liquid nitrogen cooled blackbody. Noise temperature of the system is calculated by formula (1) and (2). The noise temperature in this paper is uncorrected DSB receiver noise temperature (Trx).

$$Y = P_h / P_c \tag{1}$$

$$T_{rx} = \frac{T_h - Y \cdot T_c}{Y - 1} \tag{2}$$

The SIS mixer chip is mounted in the mixer block, the feed-point is located at the waveguide center, as shown in figure 4(c). The parabolic mirror, mixer block, bias-tee, CLNA are installed on the 4K cold plate, as shown in figure 4(d). The LO and RF signal is focused by the parabolic reflector and coupled to the diagonal horn. The CLNA is LNC0.2-3GHz from Low Noise Factory, which has a gain of 29.5dB and a noise temperature of 1.5K at 4K environment.

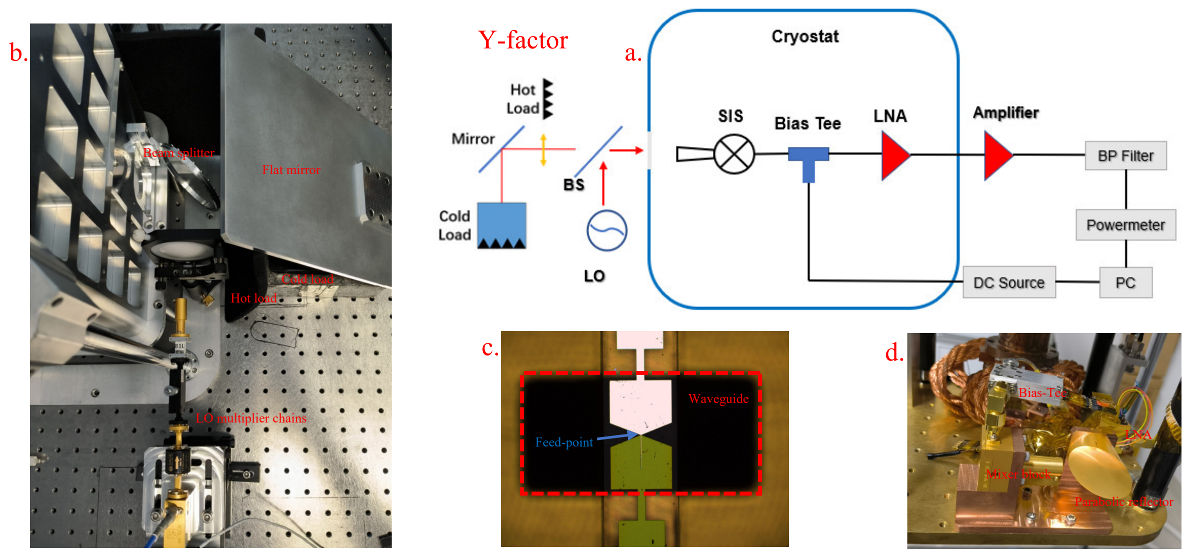


Figure 4. (a) Schematic diagram of mixer's performance measurement setup. (b) LO multiplier chains, and coupling optical path of the LO and the RF signal. (c) The SIS mixer chip mounted in the slot, feed-point located at the waveguide center. (d) Parabolic mirror, mixer block, bias-tee, CLNA installed on 4K cold plate.

### 3.2 Receiver noise performance

Figure 5 shows the measured DC I-V curves and IF output power at different bias voltages, and corresponding receiver noise temperatures. The gray curve is unpumped (LO-off) I-V curve, showing an energy gap voltage of 3.19mV and a normal resistance of 9.1Ω for the PCTJ, which is larger than the designed value due to either a smaller junction area or a smaller critical-current density. The pink curve is pumped (LO-on) I-V curve at a LO frequency of 220GHz, two photon-assisted quasi-particle tunneling steps can be clearly seen. The green curve is unpumped output power. The blue and red curves are the IF output power at 1.5GHz with cold and hot loads in front of the dewar window respectively, the curve's envelope corresponds to the photon-assisted quasi-particle tunneling steps. The receiver noise temperature calculated by Y-factor (formula 1 and 2) is shown as the black curve, corresponding to the right coordinate axis. The minimum receiver noise temperature found at bias voltage 2.7mV is about 50K.

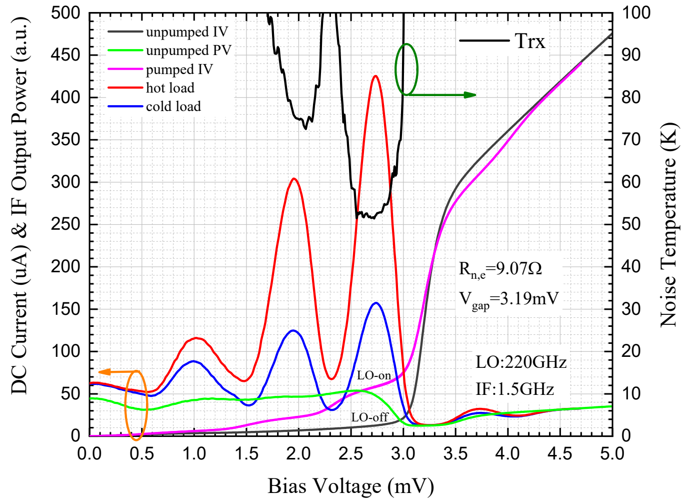


Figure 5. The left axis shows the DC I-V curves & IF output power varies with bias voltage, the grey curve is unpumped IV, the pink curve is pumped IV, the green curve is unpumped output power, the red and blue curve are output power corresponding to hot load and cold load. The black curve is the receiver noise temperature, show as the right axis.

By changing the LO frequency and repeating the above measurement, we obtain the receiver noise performance in the 180-280GHz frequency band, as shown in figure 6, which is about 5 times the quantum-limit noise. The mixer's fractional bandwidth is around 43%. The blue curve marked with triangle is RF noise, which is measured by the cross-line method[10,11]. RF noise includes the overall loss on the signal optical path in front of the mixer, such as the beam splitter, dewar window at 300K, IR filter at 50K, and parabolic reflector, diagonal horn of mixer block, and waveguide etc. In our results, RF noise accounts for 40%-50% of the receiver noise.

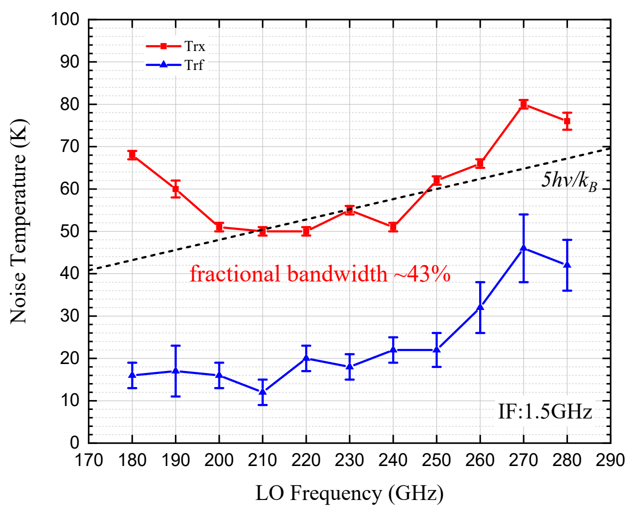


Figure 6. Receiver noise temperature and RF noise temperature, varies with LO frequency.

Figure 7(a) shows the I-V characterization varies with the bath temperature. With increasing of the bath temperature, the energy gap voltage of the superconducting material will gradually decrease. When approaching 9K, Nb is loss of superconductivity and I-V curve is close to a straight line. The pink curve in figure 7(b) is the theoretical fitting of energy gap voltage with temperature variation, the energy gap voltage of the Nb/AlN/NbN hybrid tunnel junction is about 3.32mV at zero temperature, and the equivalent superconducting transition temperature is 9.6K. The red curve shows the variation of the receiver noise temperature with the bath temperature at LO frequency of 220GHz. When the bath temperature rises to 7K, the noise temperature rises from 50K to 100K, if the bath temperature continues rising, the performance deteriorates rapidly. If necessary, the hybrid tunnel junction can still work at 7K environment.

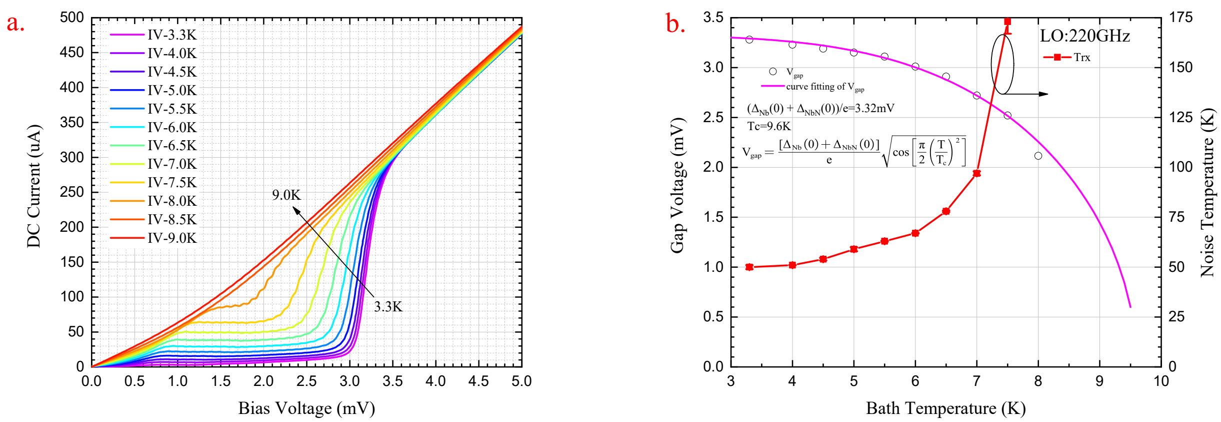


Figure 7. (a) IVCs vary with the bath temperature. (b) Theoretical fitting of energy gap voltage with temperature variation, receiver noise performance varies with temperature raising.

## 4. CONCLUSION

In this paper, a 230GHz band SIS mixer based on Nb/AlN/NbN parallel connected twin junctions (PCTJ) incorporating NbTiN/$SiO_2$/Al microstrip circuit was designed and characterized. The receiver noise temperatures reach 5hν/$k_B$ among 200-260GHz band, the mixer's fractional bandwidth is around 43% at center frequency(230GHz). The mixer's noise performance deteriorates by 3dB when the bath temperature rises to 7K from 3.3K, still acceptable, could be a candidate for future's space and polar astronomical observations.

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