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Characterization of an All-NbN Superconductor-Insulator-Superconductor Mixer for HSTDM

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Abstract

An all-NbN Superconductor-Insulator-Superconductor (SIS) mixer working at 410-510 GHz is developed for the High-Sensitivity Terahertz Detection Module (HSTDM) which will be accommodated on the Space Station of China. HSTDM will be the first use of all-NbN SIS mixers for astronomical observation from space. Ground test performances of the all-NbN SIS mixer show very good adaptability to space environment and noise characteristics in the observation band.

1 Introduction

Superconductor-Insulator-Superconductor (SIS) mixers can achieve a quantum-limited ultra-high sensitivity in terahertz band and are widely used for astronomical observation [1]. The application of the SIS mixers to ground-based observations had been limited due to the absorption and disturbance of the Earth's own atmosphere. In 2009, the Heterodyne Instrument for Far-Infrared (HIFI) achieved the first high sensitivity observation using space-borne superconductive mixers for astronomy [2]. In recent years, more and more space observation programs have been proposed.

The High-Sensitivity Terahertz Detection Module (HSTDM) will be installed on the Space Station of China and will be launched in 2023 to observe molecular spectral lines in 410-510 Ghz band using SIS mixers. Since the HSTDM will operate on space station with limited power supply, superconducting SIS mixers for the HSTDM are required to perform well at temperatures exceeding 4.2 K and even up to 8 K. It is well known that all-NbN SIS mixers currently have the highest operating temperature [3] among various types of SIS mixers. They have already demonstrated the potential of application for space-based observations [4]. In this paper, we will introduce an all-NbN SIS mixer we developed for the HSTDM including mixer design and ground test results.

2 Mixer design

The design of all-NbN SIS mixer is shown in Figure 1. It consists of an SIS device, an RF/LO coupler, two magnets, an IF/DC circuit, a corrugated horn, a diagonal horn, and mounting blocks A and B. The SIS devices were installed and electrically grounded to mounting block A. Details of the design of the SIS devices have been reported by Ref. [5]. Briefly, they are fabricated on an MgO substrate with NbN/AlN/NbN parallel-connected twin junctions (PCTJ) [6, 7] and NbN/MgO/NbN tuning circuit. The

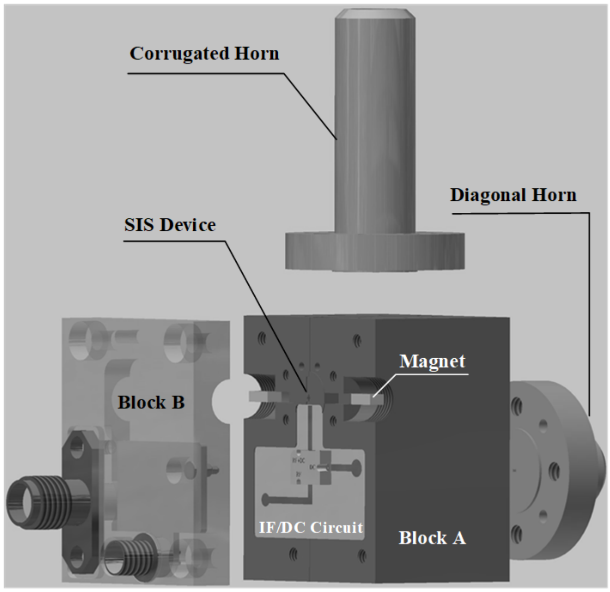

Figure 1. Schematic drawing of the all-NbN SIS mixer components.

RF/LO coupler (as shown in Figure 2) with coupling factor of -16 dB is used to couple the LO signal from the diagonal horn and the RF signal from the corrugated horn at the same time. An absorber is located at the end of the LO branch to absorb excess LO signal. Two permanent neodymium magnets on both sides of the SIS device supplying a magnetic field to the SIS junctions suppress the Josephson effect. The IF/DC circuit used to connect the SIS devices, SMA connector and DC bias circuit consists of three segments of microstrip and a bias tee. The SMA connector and DC bias circuit located on block B are linked to the IF/DC circuit by two pogo pins which have been adopted by HIFI [8].

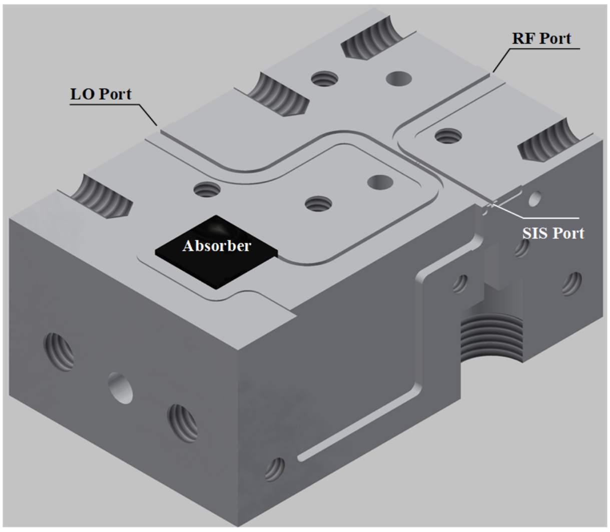

Figure 2. Schematic drawing of the coupler.

3 Test results

3.1 Test system

A schematic view of the 4-K Dewar and optics of the ground test system for the SIS mixers is shown in Figure 3. The SIS mixer was mounted in the center of cold plate of the 4-K Dewar. The LO and RF signals were coupled by the diagonal horn and the corrugated horn of the SIS mixer after passing through a 0.5-mm-thick HDPE vacuum window and a Zitex infrared filter, respectively. The down converted intermediate frequency (IF) signal was firstly amplified by a 0.1-1.1 GHz cryogenic low noise amplifier (LNA) at 4.2 K and then by two 30-dB gain room-temperature amplifiers for 0.1-1.5 GHz. After passing through a bandpass filter (710-850 MHz), the signal was recorded by a power meter.

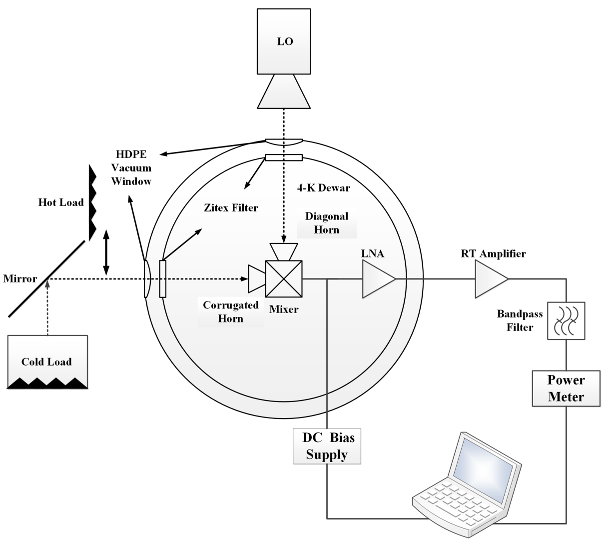

Figure 3. Schematic view of the ground test system.

3.2 DC and noise characteristics

The noise temperature of the all-NbN 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. Figure 4 shows the IF output power and junction DC current vs junction DC bias voltage for the all-NbN SIS mixer with and without the 430 GHz LO power. From the I-

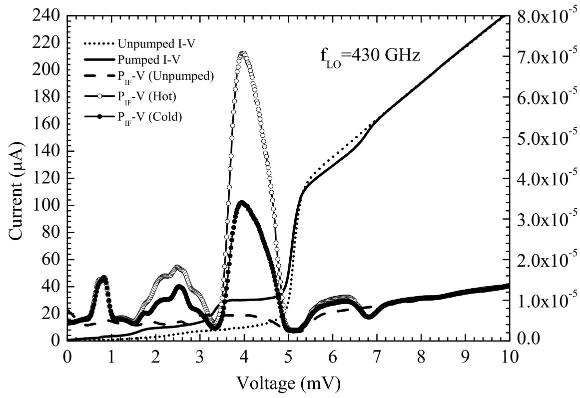

Figure 4. IF output power and junction DC current vs junction DC bias voltage for the all-NbN SIS mixer with and without the 430 GHz LO power.

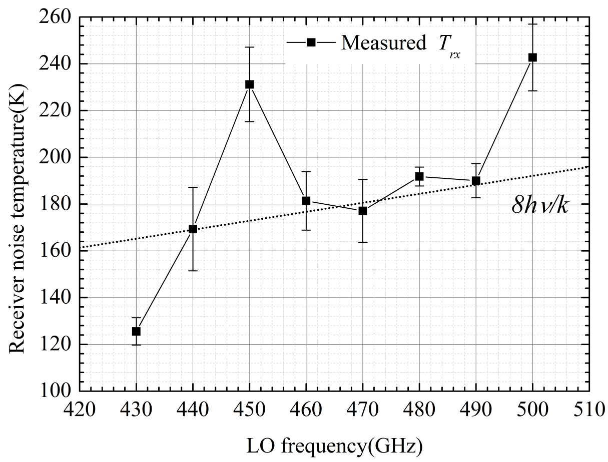

Figure 5. The measured uncorrected DSB receiver noise temperature (T_{rx}) vs LO freauency for the all-NbN SIS mixer.

V curve, we can get the gap voltage (V_{gap}), normal state resistance (R_n) and quality factor ($R_{sub}(2\ mV)/R_n$) of the all-NbN SIS mixer which are 5.2 mV, 40 Ω and 10, respectively. In Figure 4, a maximum Y factor ($P_{295\ K}/P_{77\ K}$) of 2.08 was measured at a bias voltage of 4.0 mV, corresponding to an uncorrected DSB receiver noise temperature (T_{rx}) of 125 K (about six times the quantum limit). Furthermore, we measured a rf noise temperature of around 54 K using the method proposed by Blundell *et al* [9]. We also measured the noise temperatures of different frequencies which are shown in Figure 5. From the Figure 5, we can see the error-bars of T_{rx} can reach ±15 K at some frequencies. It is due to the lack of an isolator between the SIS mixer and the LNA. Then the mismatch between them will increase the error-bar of T_{rx}. As plotted in Figure 5, the uncorrected T_{rx} in the measurement bandwidth (430-500 GHz) is about eight times the quantum limit.

The highest bath temperature of the mixer will be 8 K. So, we studied the temperature dependence of the noise performance of NbN SIS mixers below 8 K. The measured uncorrected DSB receiver noise temperatures (T_{rx}) of the all-NbN SIS mixer at different bath temperatures are plotted in Figure 6 when the LO frequency is 430 GHz. Apparently, the all-NbN SIS mixer has a nearly constant noise temperature up to 8 K. As a comparison, the noise performance of an all-Nb SIS mixer will deteriorate sharply when the bath temperature exceeds 4.2 K [4]. The test results can demonstrate that the all-NbN SIS mixers are very suitable for applications with limited power supply, such as the HSTDM. Because the higher operating temperature of all-NbN SIS mixers will greatly reduce the power of the refrigerator.

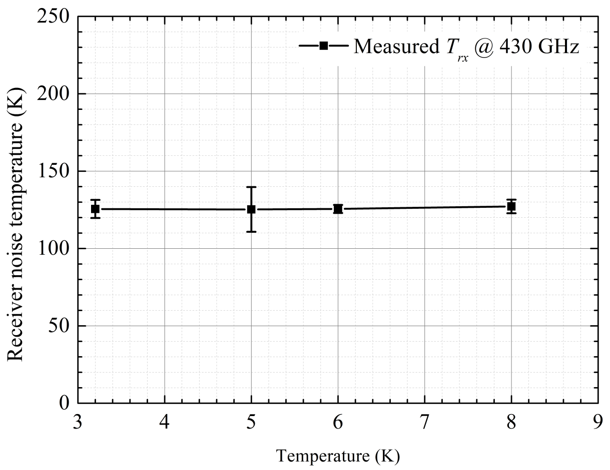

Figure 6. The measured uncorrected DSB receiver noise temperatures (T_{rx}) of the all-NbN SIS mixer at different bath temperatures when the LO frequency is 430 GHz.

3.3 Test of space environment adaptability

Since the all-NbN SIS mixer will operate in space, we did a lot of space environment adaptability tests, such as space particle irradiation test. We used ^{60} Co γ ray as a source of radiation. The dose rate and total dose of the particle irradiation test are 0.1 rad(Si)/s and 20 k rad(Si), respectively. Notice that the particle irradiation test cannot be performed in a cryogenic refrigerator. So, we only compared the changes in DC and noise characteristics of an all-NbN SIS mixer before and after irradiation, and we cannot determine whether there is an annealing effect. In order to prevent possible damage to the device caused by the particle irradiation,we replaced the previous all-NbN SIS device with another one and tested it. The I-V and P-Vcurves of the all-NbN SIS mixer before and after the particle irradiation have been plotted in Figure 7. From the Figure 7, we can see the DC I-V curves are the same in the two tests and the IF power curves of the hot and cold loads are almost the same at the first photon step when the the LO pumping levels in before and after tests are the same. The slight deferences of the IF power curves are due to the different gains and mismatches of the IF link in the two tests. And according to our calculation, the T_{rx} of the all-NbN SIS mixer are the same before and after irradiation. The test results show that the space particle irradiation will not affect the all-NbN SIS mixer performance.

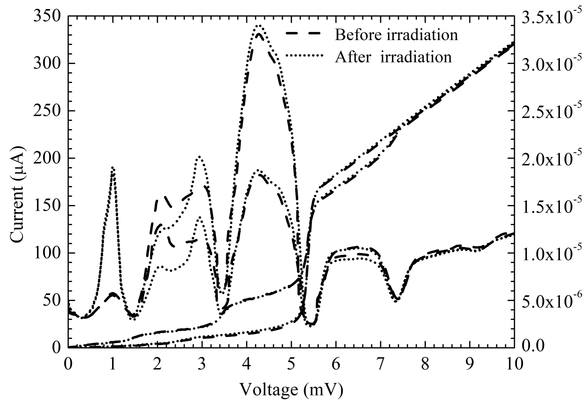

Figure 7. The I-V and P-V curves of the all-NbN SIS mixer before and after the particle irradiation.

4 Conclusion

We have developed a SIS mixer with NbN/AlN/NbN parallel-connected twin junctions (PCTJ) and NbN/MgO/NbN tuning circuit. The measured uncorrected DSB receiver noise temperatures (T_{rx}) of the all-NbN SIS mixer in frequency range of 430-500 GHz is about eight times the quantum limit. It has very high noise stability below 8 K, and it also has good adaptability to space environment. So, all-NbN SIS mixers may play a very important role in the terahertz astronomy regime, especially for airborne and space-based observations.

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