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Alexandre Karpov, David Miller, F. Rice, J. A. Stern ...+3 more authors

Institutions: California Institute of Technology

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Low Noise 1 THz–1.4 THz Mixers Using Nb/Al-AlN/NbTiN SIS Junctions

A. Karpov, D. Miller, F. Rice, J. A. Stern, B. Bumble, H. G. LeDuc, and J. Zmuidzinas

***Abstract*—We present the development of a low noise 1.2 THz and 1.4 THz SIS mixers for heterodyne spectrometry on the Stratospheric Observatory For Infrared Astronomy (SOFIA) and Herschel Space Observatory. This frequency range is above the limit for the commonly used Nb quasi particle SIS junctions, and a special type of hybrid Nb/AlN/NbTiN junctions has been developed for this project. We are using a quasi-optical mixer design with two Nb/AlN/NbTiN junctions with an area of 0.25 μm^2. The SIS junction tuning circuit is made of Nb and gold wire layers. At 1.13 THz the minimum SIS receiver uncorrected noise temperature is 450 K. The SIS receiver noise corrected for the loss in the LO coupler and in the cryostat optics is 350–450 K across 1.1–1.25 THz band. The receiver has a uniform sensitivity in a full 4–8 GHz IF band.**

The 1.4 THz SIS receiver test at 1.33–1.35 THz gives promising results, although limited by the level of available LO power. Extrapolation of the data obtained with low LO power level shows a possibility to reach 500 K DSB receiver noise using already existing SIS mixer.

***Index Terms*—Niobium alloys, radio astronomy, satellite applications, submillimeter wave receivers, superconductor-insulator-superconductor mixers, THz technology.**

I. Introduction

THE Stratospheric Observatory For Infrared Astronomy (SOFIA) is an ambitious project aiming to use a 2.5 meter telescope mounted in a Boeing 747-SP airplane to run observations at an altitude about 14 km, well above the most of the atmospheric air mass [1]. This location allows observations at the wavelengths obscured by atmosphere and not accessible from ground based telescopes. The band of the frequencies above 1 THz is one of the main targets in the receiver development for SOFIA.

Below 1 THz frequency the SIS mixers have already been proven to operate close to the quantum limit of the heterodyne receiver sensitivity [2]. The upper limit of about 1 THz was related to the increasing losses in the SIS junction tuning circuit and to the frequency limit of the quantum assisted tunneling effect. The quantum assisted tunneling in SIS junctions is vanishing at about double gap frequency. The commonly used Nb/AlOx/Nb junctions have the gap voltage about 2.8 mV allowing building sensitive receivers up to the frequency of about 1.1 THz [3], [4]. The introduction of the new type of high quality Nb/AlN/NbTiN junctions with the gap voltage of about 3.5 mV made our work possible [5]. The frequency limit of these new devices is around 1.5–1.6 THz.

In our work the main goal was to study the feasibility of the low noise 1–1.4 THz receivers using the newly developed low loss THz circuit and SIS junction technology. This work is part of an effort in the development Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver (CASIMIR) designed for SOFIA [6] and the 1.2 THz band of the HIFI (Heterodyne Instrument for the Far-Infrared) of the Hershel Space Observatory (HSO) [7].

II. SIS Mixer

A. SIS Junction

In order to build a low noise 1–1.4 THz SIS mixer we use a Nb/AlN/NbTiN tunnel junction with a high critical current density and a low loss tuning circuit made of normal metal and Nb thin films in a quasi-optical mixer design. In contrast to previous works we do not use NbTiN ground plane in the mixer circuit, but an epitaxial Nb film. The gap frequency of Nb is about 700 GHz, and at the 1–1.4 THz frequency it behaves as a normal metal. The use of Nb ground plane at a frequency well above the gap frequency of Nb is suitable for two different reasons. First, this approach simplifies the integration of the Nb/AlN/NbTiN junction in the mixer circuit. When a normal metal or NbTiN are used in the ground plane of the mixer circuit, the Nb base electrode of the junction must be deposited on the top of the ground plane film. Some intermediate layers may be needed to have a good interface. The etching through the additional layers in the junction structure makes the production process more difficult, and reduces the yield. Our approach improves the reproducibility of the mixers and the junction production yield. The second reason is related to the possibility of low RF loss in the epitaxial Nb film. The resistivity of the Nb film in our device is about 0.28 $\mu\mathrm{Ohm}$ cm at 10 K temperature. This is about 20 times improvement, compared with the Nb films usually used in the SIS mixers. The 0.28 $\mu\mathrm{Ohm}$ cm resistivity is close to the best achieved with the normal metals films made of gold, silver, or aluminum. The estimated loss at 1–1.4 THz in the circuit using the epitaxial Nb is only 10–15% larger, compared with estimation for the circuit using an ideal NbTiN film, still superconducting at this frequency. Another advantage of our design is a better thermal conductivity of the epitaxial Nb, allowing a good thermalization of the SIS junction in the mixer.

We use Nb/AlN/NbTiN SIS junctions with critical Josephson current densities around 30 $\mathrm{kA/cm^2}$ [5]. This junction is composed of two different superconductors with different critical temperatures. The bottom electrode is made of Nb with critical temperature $\mathrm{T_C} = 9.2$ K and the top electrode of NbTiN. The critical temperature of NbTiN films are around $\mathrm{T_C} = 15.6$ K,

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A. Karpov, D. Miller, F. Rice, and J. Zmuidzinas are with Physics department of California Institute of Technology, Pasadena, CA 91125 USA (e-mail: karpov@submm.caleh.edu).

J. A. Stern, B. Bumble, H. G. LeDuc are with Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

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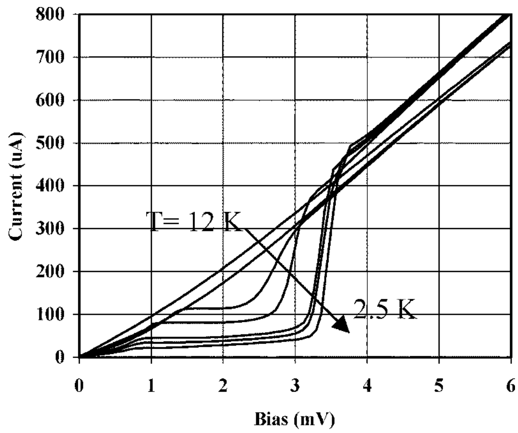

Fig. 1. Current-Voltage characteristics of Nb/AlN/NbTiN junction measured at the different temperatures 12 K–2.5 K. Below the critical temperature of Nb base electrode (9.2 K), the junction type changes from SIN to SIS. At the temperature of 2.5 K the sum gap voltage is about 3.5 mV.

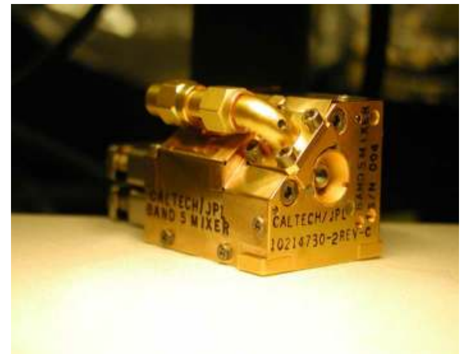

Fig. 2. A general view of the 1.2 THz mixer we delivered for integration in HIFI of Herschel Space Observatory. The silicon lens is visible at the mixer front. The SIS mixer chip is mounted at the back side of the lens. The mixer structure is solid and sustains well the vibrations levels possible at launch. The same design will be used at SOFIA. For more design details see [8].

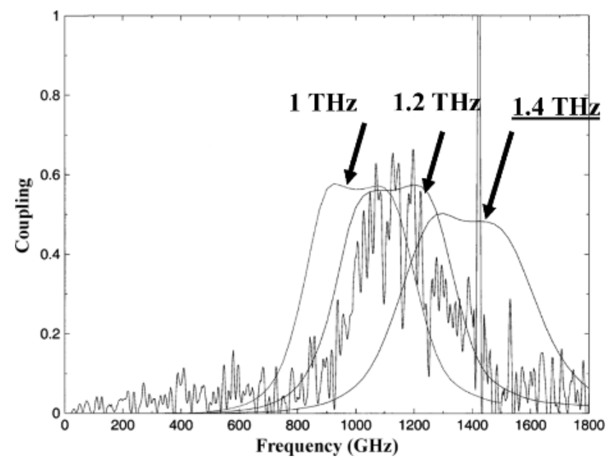

Fig. 3. Model prediction of the coupling of SIS junction to the antenna on the 1 THz, 1.2 THz and 1.4 THz mixer chips. The direct detection response of a 1.2 THz mixer measured with FTS matches well the model prediction.

however, the layer immediately on top of the barrier is reduced to 13 or 14 K. The composition of the junction is well readable over the temperature dependence of the junction current-voltage characteristic (CVC) in Fig. 1. The CVC are measured at the temperature 12–2.5 K. These temperatures are below $T_C = 15.6$ K of NbTiN and allow observing the transition over the T_C of Nb. The Josephson current is suppressed with a magnetic field. The upper curve is measured at 12 K, and looks like a typical CVC of an SIN junction. Here the NbTiN top electrode of the junction is already superconducting, and the bottom electrode of Nb is still in a normal state. At the temperature below 9 K a small knee structure starts to form around the NbTiN gap voltage. With the decrease of the temperature to 2.5 K, the differential gap voltage decreases down to 0.7 mV and the junction sum gap voltage rises to 3.5 mV. We can deduce the gap voltage of Nb $\Delta_{Nb}/e = 1.4$ mV and the $\Delta_{NbTiN}/e = 2.1$ mV. The sum gap voltage of the junction is slightly lower then expected 4 mV, apparently due to a reduced gap voltage in NbTiN electrode in a vicinity of the AlN barrier. At the temperature of 2 K, used in our experiments, this junction has a sub-gap to normal state resistance ratio of about $R_{SG}/R_N = 12$. In some other samples we observed a ratio $R_{SG}/R_N = 30$ and higher.

B. Mixer Design

In this work we are using a quasi-optical SIS mixer design, similar to one described in [8]. In the mixer we are using a two SIS junction circuit coupled to the double slot antenna. The SIS junction circuit with a double slot planar antenna is mounted at the back of silicon lens. In Fig. 2 is a general view of a similar mixer we produced and delivered for integration in the HIFI instrument of the Herschel Space Observatory. The Si lens is visible in the center of the mixer front panel. The mixer design is solid and has been found able to sustain the vibrations possible at the launch of a spacecraft. The same design will be used at SOFIA.

The SUPERMIX program [9] was used for the mixer circuit design and optimization. The model prediction for the three mixer chip designs is presented in the Fig. 3. Plotted is the frequency dependence of the expected SIS junction coupling to the double slot antenna. The coupling loss is relatively small and is increasing only slightly with frequency. The 1.4 THz band device coupling is about 15% less compared to the 1.2 THz circuit and one can expect similar performance of the mixers with these circuits. The measured direct detection response of a 1.2 THz mixer is plotted in the same Fig. 3. It was measured using a Fourier Transform Spectrometer. Although noisy, it matches well to the central frequency of the model predicted response.

III. Experiment

The SIS mixers were tested in an Infrared Laboratory HL-3 cryostat. The cryostat vacuum window is Mylar 12 μm thick. An infrared filter made of Zitex is located at the 77 K stage of the cryostat. The intermediate frequency range is 4 GHz–8 GHz and the IF amplifier noise is about 3 K. The physical temperature at the mixer block was about 2.0 K. In the 1.2 THz band the local oscillator power is coupled to the mixer beam using a Mylar beam splitter 5 or 12 micron thick, depending on the available LO power. In the main part of the 1.2 THz frequency band the LO power was sufficient for the optimum performance of the SIS mixer. In 1.4 THz band, having an LO source with a lower power level we used a grid as a beam splitter, introducing a loss of about 4 dB in the signal pass.

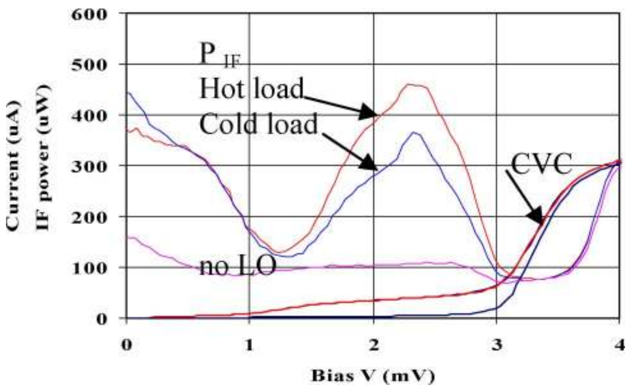

Fig. 4. SIS receiver test at 1128 GHz LO frequency. The SIS mixer CVC are measured with and without LO power, and the receiver IF power data are measured with hot, cold loads and without LO power. The receiver noise is about 450 K $(\mathrm{Y} = 1.41)$. Note a good suppression of the Josephson current.

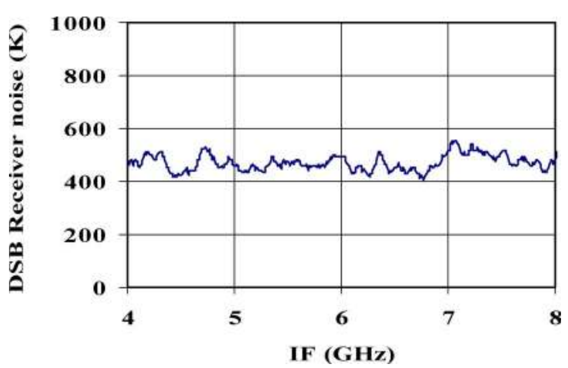

Fig. 5. Measured dependence of the receiver noise versus Intermediate Frequency at 1128 GHz LO frequency. The noise is constant within the precision of the measurements.

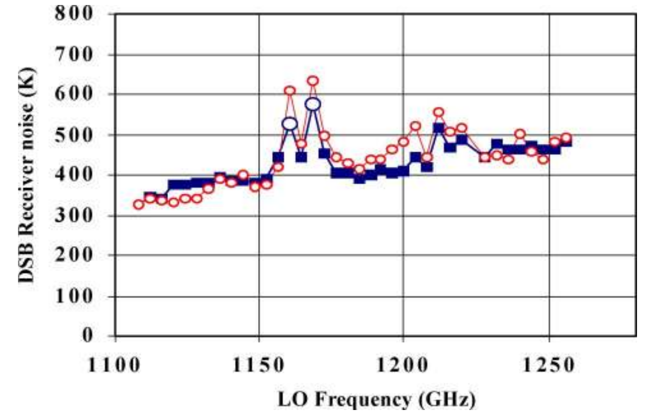

Fig. 6. Measured test receiver DSB noise temperature with the two different SIS mixers. The receiver noise is corrected for the beam splitter and for the cryostat window loss. The corrected receiver noise is 350–450 K in entire 1.1–1.26 THz band. The minimum corrected receiver noise is 330 K, about 6 $\mathrm{h}\nu/\mathrm{k}$. Note a double maximum in the noise centered at the frequency of an absorption line of water vapor at 1163 GHz.

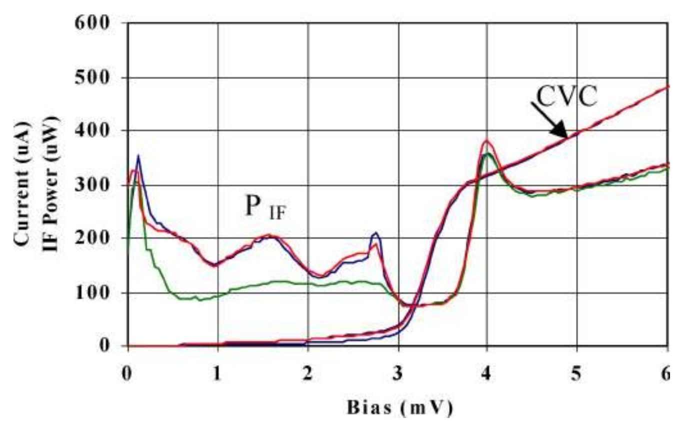

Fig. 7. SIS receiver test at 1332 GHz LO frequency. The SIS mixer CVC are measured with and without LO power, and the receiver IF power data are measured with hot, cold loads and without LO power. The coupled LO power is 5–6 times below the optimum level.

The test receiver noise temperature was measured by Y factor method. In the measurements we used liquid nitrogen cooled and ambient temperature calibration loads. The signal from calibration load was passing about 5 cm in open air before the test cryostat vacuum window. The receiver IF power was detected in the entire 4–8 GHz band. In the 1.2 THz band the minimum uncorrected receiver noise measured with a 5 micrometer thick beam splitter is about 450 K $(\mathrm{Y} = 1.41)$. The mixer CVC and the IF power detected with cold and hot loads are presented in Fig. 4. A good suppression of the Josephson current was due to a diamond shape of SIS junctions.

The receiver sensitivity is uniform in the full band of intermediate frequencies. In Fig. 5 is presented the receiver noise as a function of the IF measured at 1128 GHz LO frequency. The uncorrected receiver noise is about 450 K in a full 4 GHz–8 GHz IF band.

The measured 1.2 THz receiver noise with two different mixers is presented in the Fig. 6. We prepared and delivered these two SIS mixers for the band 1.2 THz of the HIFI at the Hershel Space Observatory. The measured test receiver noise is corrected for the loss in the beam splitter and in the cryostat optics. The performance of the receiver with two different mixers is almost identical. The receiver noise versus LO frequency has a nearly linear dependence, except some residual spikes related to the effect of the laboratory atmosphere. A noticeable double maximum in the receiver noise is centered at the frequency of absorption line of water at 1163 GHz. It is due to the absorption of the signal from calibration loads in the laboratory air. The twin structure of the maximum is related to the consecutive obscuration by absorption line of the upper or lower sidebands of the test receiver. The minor spikes in the receiver noise around 1220 GHz are of the same origin. This absorption will not affect the receiver when operated in nearly vacuum conditions at SOFIA or at HSO. The corrected receiver noise is 330 K–450 K in the 1.1 THz–1.26 THz band.

We tested the 1.4 THz SIS mixer design at the frequency close to the center of the band, at 1332 GHz. The available LO power was sufficient to pump the SIS mixer, but to a level below optimum. The SIS mixer CVC and IF power dependence versus bias voltage are presented in Fig. 7. The curves have a typical shape for the under pumped SIS mixer.

The level of the LO power is outlined in Fig. 8, where we give the measured mixer conversion gain as a function of the local oscillator induced current I_{LO}. Here we are using the data measured at 1332 GHz with the 1.4 THz mixer and at 1128 GHz with the 1.2 THz mixer respectively. The measured conversion gain is corrected for the loss in the beam splitter and in the cryostat window. The area and shape of the junctions are identical in the 1.2 THz and 1.4 THz mixers and we can expect similar conditions for the optimal operation. The optimum receiver noise

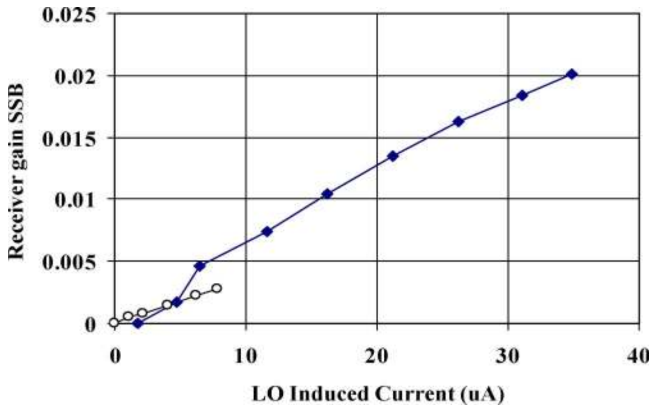

Fig. 8. Measured mixer conversion gain as a function of the local oscillator induced current ILO. Here we are using the data measured at 1332 GHz (open circles) and at 1128 GHz (dots). The measured conversion gain is corrected for the loss in the beam splitter and in the cryostat window. The optimum receiver noise at 1128 GHz is achieved with 35 μA of LO induced current, when the maximum I_{LO} at 1332 GHz is 7.5 μA, about 0.21 of the optimal level. At both frequencies the gain is proportional I_{LO}: $G_{MIXER} = \beta I_{LO}$.

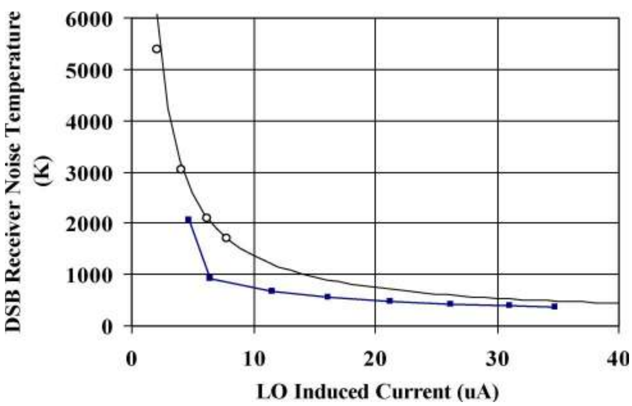

Fig. 9. The receiver noise dependence versus LO induced current. The open circles show the DSB receiver noise measured at 1332 GHz and corrected for the loss in the cryostat optics and in the beam splitter. The data are extrapolated using (1) up to the level of the optimal LO power. The black dots present T_{REC} measured at 1128 GHz. One can expect a comparable performance of the both SIS mixers at I_{LO} about 35 μA, with the DSB noise about 500 K.

at 1128 GHz is achieved with 35 μA of LO induced current, where the maximum I_{LO} at 1332 GHz is 7.5 μA, about 0.21 of the optimal level.

The measured gain of both mixers is directly proportional to I_{LO}: $G_{MIXER} = \beta I_{LO}$, where β is a constant. We can use this observation to make a rough estimation of the possible performance of the 1.4 THz mixer when pumped to the optimal level of the LO power:

$$\begin{aligned} T_{REC} &= T_{OPTICS} + (T_{IF} + T_{OUT\ MIXER})/2/G_{MIXER} \\ &= T_{OPTICS} + (T_{IF} + T_{OUT\ MIXER})/2/(\beta I_{LO}) \quad (1) \end{aligned}$$

Where T_{OPTICS} is the noise contribution of the receiver optics, T_{IF} is the noise of the IF chain, and the $T_{OUT\ MIXER}$ is the noise at the mixer IF port. This relation is used to make extrapolation of the 1.4 THz receiver noise data in Fig. 9. The open circles show the DSB receiver noise measured at 1332 GHz and corrected for the loss in the cryostat optics and in the beam splitter. The data are extrapolated using (1) up to the level of the optimal LO power. The black dots present T_{REC} measured at 1128 GHz. One can expect a comparable performance of both SIS mixers at I_{LO} about 35 μA, with the receiver DSB noise of about 500 K.

This estimation will be verified in our future work.

IV. Conclusion

We demonstrated the possibility of an efficient operation of quasi particle SIS mixers in the 1–1.4 THz band. The junction of the type Nb/AlN/NbTiN has the gap voltage of 3.5 mV allowing the use of the quantum assisted tunneling for the frequency mixing up to 1.5–1.6 THz. The receiver DSB noise temperature with the developed 1.2 THz band SIS mixer is as low as 450 K $(Y = 1.41)$. The 1.2 THz receiver noise corrected for the loss in the LO coupler is 330 K, about 6 $h\nu/k$.

The receiver with a 1.4 THz SIS mixer has a similar performance as the 1.2 THz mixer, although limited by the level of available LO power. The extrapolation of the 1.4 THz performance to the optimal level of the LO power is promising for similar results to the 1.2 THz.

The developed mixers are aimed to be used in the Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver (CASIMIR) of the SOFIA space observatory managed by USRA.

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