Low Noise SIS Mixer for Far Infrared Radio Astronomy

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ABSTRACT

We present a low noise SIS mixer developed for the 1.2 THz band of the heterodyne spectrometer of the Herschel Space Observatory. The device of this design will be among the first SIS mixers flown in space at Herschel. The developed SIS mixer has a quasi-optical design, with a double slot planar antenna and an extended spherical lens made of pure Si. The SIS junctions are Nb/AlN/NbTiN with the critical current density of about 30 KA/cm2 and with the junction area of a quarter of a micron square. For the ease of the Josephson current suppression, the SIS junctions are diamond-like shaped. The simultaneous suppression of the Josephson currents in the two SIS junctions is a particular advantage of the used shape. A low loss Nb/Au micro-strip transmission line is used for the first time in the mixer circuit well above the gap frequency of Nb.
Using the new mixer we demonstrated the minimum uncorrected Double Sideband receiver noise of 550 K (Y=1.34). The minimum receiver noise corrected for the local oscillator beam splitter and for the cryostat window is 330 K, about 6 hν/k, apparently for the first time in the THz frequencies range.

Keywords: Low noise receiver, NbTiN, Niobium, SIS receiver, THz detector.

1. INTRODUCTION

In the last decade, SIS heterodyne receivers using Nb/AlOx/Nb junctions and super conducting Nb circuits have become the best practical solution for the ground-based radio astronomy at mm and submm wavelengths [1]. The minimum submm SIS receiver noise is only three times above the quantum limit [2]. This type of ultra low noise receiver is needed to cover the upper part of the atmosphere transparency band accessible to ground-based radio astronomy facilities. One upper frequency limit of these SIS receivers is determined by the gap frequency of Nb (f_{Nb}=0.65-0.7 THz); above this frequency the Nb will have losses like a normal metal. Another frequency limit for Nb devices is near 1.7 f_{Nb} =1.0 THz-1.1 THz; above this frequency the bias voltage region where reverse quantum assisted tunneling does not occur is shrinking rapidly, and this bias region is non-existent at $2f_{Nb}$.

The SIS mixers may be also useful at the frequencies over 1 THz for sensitive receivers for airborne and space observatories. This motivates research on alternative materials to provide the low loss THz circuits as well as new types of SIS junctions with higher gap voltages. Recent progress in thin film NbTiN technology [3] has given the possibility to create low loss circuits above 0.6-0.7 THz and to improve the performance of the SIS mixers with Nb/AlOx/Nb junctions up to 1 THz [4, 5]. Another approach, using a low loss normal metal circuit to build a low noise 1.05 THz SIS mixer, has been demonstrated in [6, 7]. The development of the NbTiN/AlN/Nb SIS junctions along with NbTiN circuits [3] allows a substantial improvement of the SIS mixer operation up to 900 GHz, with the minimum noise within a factor of ten of the quantum limit [8]. The gap voltage of the existing Nb/AlN/NbTiN junctions is about 3.5 mV [3], potentially allowing the extension of SIS mixer operation above 1.4 THz. The goal of our work is to extend the low noise performance of the SIS receivers into the THz band using the NbTiN and Nb technology.

2. APPROACH

Our approach to build a low noise 1.1-1.25 THz SIS mixer is to 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 work we do not use a NbTiN ground plane in the mixer circuit, but an epitaxial Nb film. The gap frequency of Nb is about 700 GHz, and at the frequency of 1.2 THz 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, a 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 [3]. 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 μOhm cm at 10 K temperature. This is about 20 times improvement, compared with the Nb films usually used in the SIS mixers at the frequency below 700 GHz, where Nb behaves as a superconductor. The 0.28 μOhm cm resistivity is close to the best achieved with the normal metals films made of gold, silver, or aluminum. The estimated loss at 1.2 THz in the circuit using the epitaxial Nb is only 10% larger, compared with estimation for the circuit using an ideal NbTiN film, still super conducting 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.

3. SIS JUNCTION

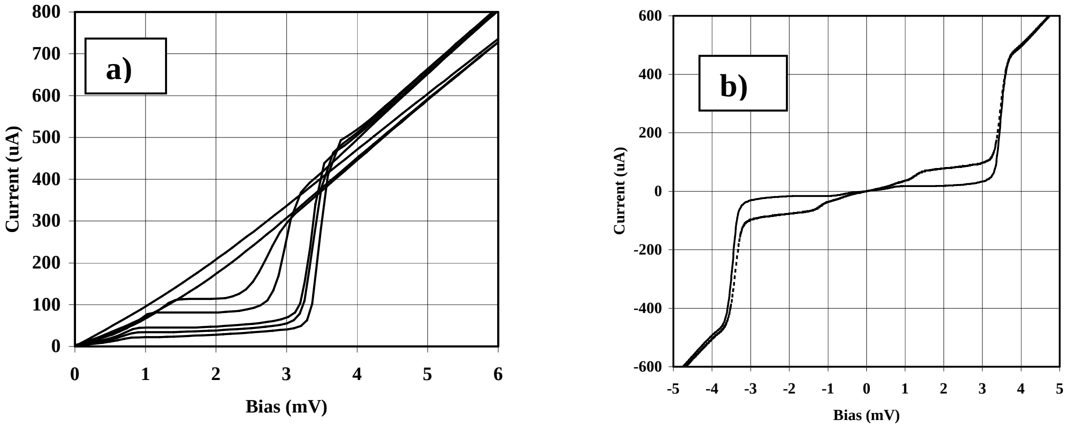

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Fig. 1. a) Current-Voltage characteristic of the Nb/AlN/NbTiN junction measured at the different temperatures 12 K – 2.5 K. Below the critical temperature of the Nb base electrode (9.2 K), the junction type changes from SIN to SIS. One can see evolution of the sum gap voltage up to 3.5 mV. At 2.5 K the critical Josephson current density is about 30 KA/cm^2

b). A CVC of a Nb/AlN/NbTiN junction with and without 1.13 THz LO signal. We can see a sharp quantum step feature when the LO power is applied. The quantum step width is reduced due to the mutual cancellation of the steps from the positive and negative branches of CVC.

We use Nb/AlN/NbTiN SIS junctions with critical Josephson current densities around 30 kA/cm^2 [3]. This junction is composed of two different superconductors with different critical temperatures. The bottom electrode is made of Nb with critical temperature T_C=9.2 K and the top electrode – of NbTiN. The critical temperature of NbTiN films are around T_C=15.6 K, 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 a). The CVC are measured at the temperature 12 – 2.5 K. This temperatures are below T_C=15.6 K of NbTiN and allows to observe 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 super conducting, 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 Δ_{Nb}/e=1.4 mV and the Δ_{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 2.5 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.

The quantum assisted tunneling in a Nb/AlN/NbTiN SIS junction is demonstrated in Fig. 1 b. A sharp quantum step appears at the junction CVC when the local oscillator (LO) radiation is applied at 1.13 THz. The quantum step width is reduced from $h\nu/e$=4.8 mV to $h\nu/e-4\Delta/e$=2 mV, due to the mutual cancellation of the two quantum steps, at the positive and the negatives branches of CVC.

For a stable operation of an SIS mixer, the Josephson currents have to be suppressed applying a magnetic field B. The full suppression of the Josephson DC current is more difficult in a mixer with two junctions, as the optimum B may differ in a couple. In our mixer design is used a couple of the SIS junction of a relatively small area, and the junction inequality may be important. For the ease of the Josephson current suppression, we are using diamond-like shaped SIS junctions. Their specific advantage is a broad minimum in the DC Josephson current versus magnetic field, and we are not sensitive to the small differences of the SIS junctions in the couple. The DC Josephson current is well suppressed by the magnetic field (fig. 2), down to below 1% at the magnet current of 2 mA. The final result for the operation of the SIS receiver is denoted in Fig. 2 b), where the SIS receiver IF power (upper line) is plotted versus the current in the electrical magnet. There is a clear and broad minimum in the IF power at 5 mA and it is nearly constant when the magnet current is above 10 mA

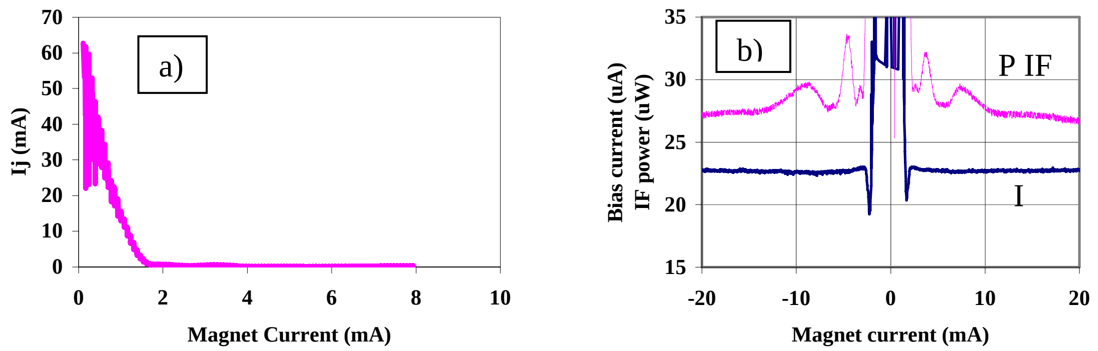

Fig. 2. a) The DC Josephson current of a mixer with a couple of a diamond-shaped SIS junctions reaches the 1% level at about 2 mA magnet current. b) The SIS receiver IF power (upper line) and SIS junction bias current versus magnet current. The 1.13 THz LO power is applied. The IF power is nearly constant when the magnet current is above 10 mA.

4. SIS MIXER DESIGN

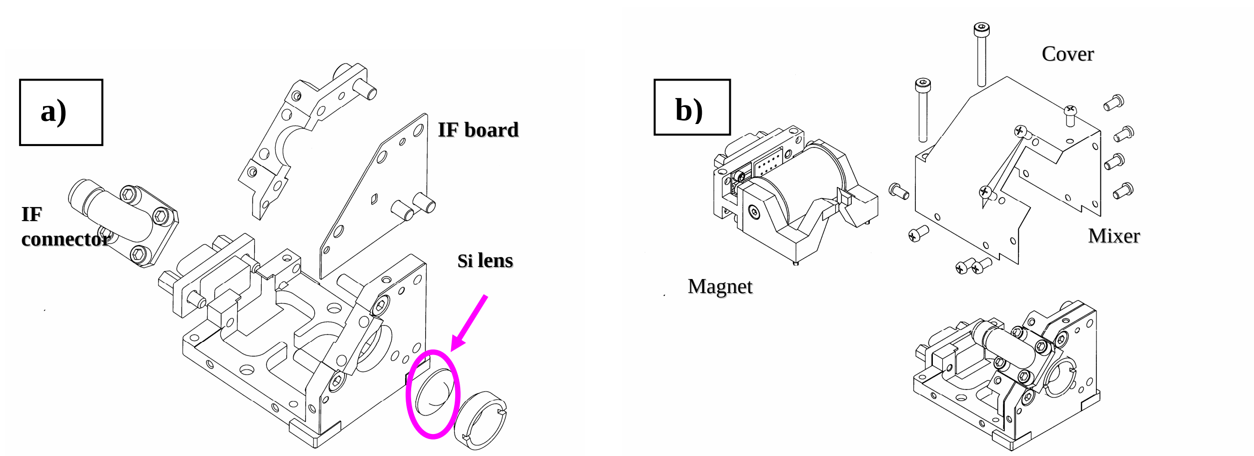

Fig. 3 a) The mixer housing contains the mixer optics, IF / DC board and connectors. b) On the final integration of the mixer a magnet and a mixer cover are attached to the mixer housing.

In this work we are using a quasi-optical SIS mixer design, similar to one described in [6]. The SIS junction with a double slot planar antenna is mounted at the silicon extended spherical lens. The SUPERMIX program [9] was used for the circuit design and optimization. We expect about 1.5 dB Ohmic loss in the mixer circuit in the 1.1 THz – 1.25 THz range when using an epitaxial Nb ground plane, a gold wiring layer and SiO insulating layer.

The mixer is build on a modular approach to separate the operations with the parts made with a standard technology and the operation with expensive custom developed parts, as the SIS junctions. The mixer housing structure is outlined in the left part of the Fig. 3. It is build of the main frame, of the IF / DC bias board, of the Si lens, and of the

DC and IF connectors. The mixer main frame is made of the 7075-aluminum alloy and provides the mechanical and thermal interfaces of the SIS mixer. It serves for the precise positioning of the mixer optics. The SIS mixer chip is attached at the center of the back side of the Si lens with an UV solidified glue. The lens is clamped between the retaining ring (front part) and the IF board. The wire bonding is used to connect the mixer chip to the IF board. At the second step of integration we attach the magnet and the mixer cover (Fig 3, b). The mixer total mass is below 75 gr., as required for the use in the space observatory. The final view of the mixer is in the Fig. 4.

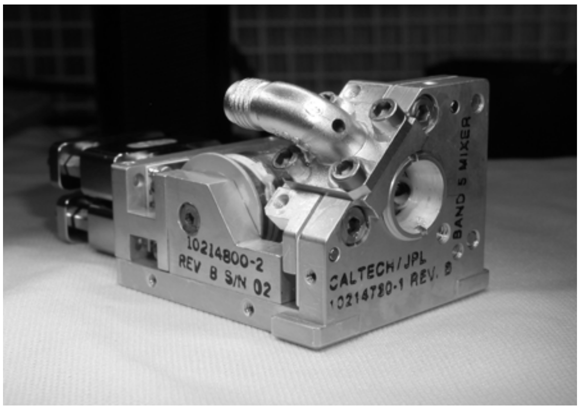

Fig. 4 The assembled 1.2 THz SIS mixer without cover.

We are using the SIS junctions with a relatively low cross sections to reduce the LO power. To suppress the Josephson current this type of junctions requires a magnetic field of the order of B=300-800 G. The electrical magnet serves to suppress the Josephson currents in the SIS junctions. We found useful to wind this magnet with 2.4 kilometers of fine Nb-Ti wire with a diameter of about 25 microns, to meet the requirements on the maximum mass of the SIS mixer and on the maximum current available to feed the electrical magnet. The magnet provides the magnetic field close to 95% of the theoretical maximum.

The mixer chip layout is presented in Fig. 3. In the left part of the Fig. 3 we give the details of the mixer circuit design. The mixer double slot antenna is etched in the epitaxial Nb ground plane. The gold matching circuit (white color in the Fig. 3) covers two SIS junctions 0.24 μm^2 each.

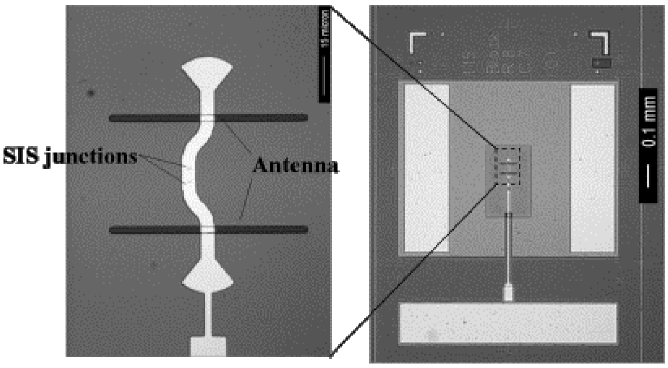

Fig. 5. The SIS mixer chip layout. At the left - the details of the mixer circuit. The two SIS junctions are coupled to a double slot antenna in a circuit with anti parallel excitation.

5. EXPERIMENT

The SIS mixer was tested in an Infrared Laboratory HL-3 cryostat. The cryostat vacuum window is in Mylar 12 μm thick. An infrared filter made of Zitex is located at the 77 K stage of the cryostat. The local oscillator power is coupled to the mixer beam using a Mylar beam splitter 5 or 12 micron thick. 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 2.5 K.

An example of the SIS receiver operation at LO frequency of 1.13 THz is in the Fig. 6. There is a set of the pumped and unpumped SIS mixer current-voltage characteristics and the receiver IF power data. The IF power was measured in entire 4-8 GHz band. The SIS receiver Y factor has a maximum of 1.34. The minimum uncorrected DSB receiver noise is 550 K. The receiver noise corrected for the beam splitter and for the cryostat window is close to 340 K, or 6 hν/k. In the entire 1.1-1.25 THz range the corrected receiver noise is below 600 K (Fig. 7). The receiver operation was stable and reproducible.

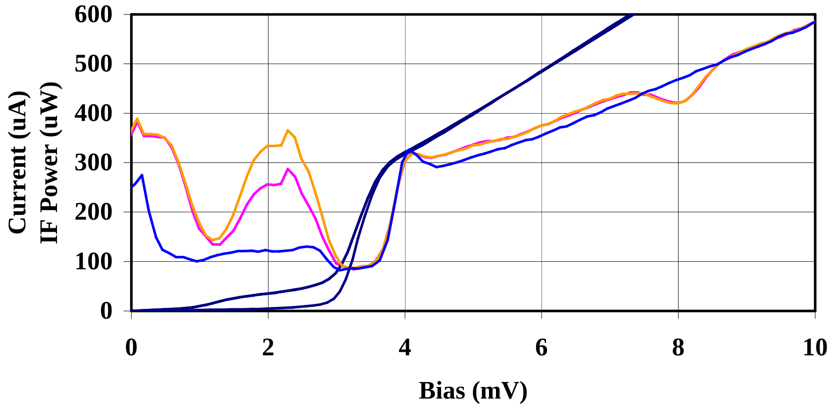

Fig. 6 Receiver operation at 1.13 THz. The receiver IF power is plotted versus bias for the receiver without LO power, with LO power and a 80 K load, and 294 K load (from lower to upper curves). The minimum in IF power at 1.1 mV corresponds to the end of the quantum step from the negative branch of the CVC. The maximum Y factor is 1.34, or 550 K uncorrected receiver noise temperature

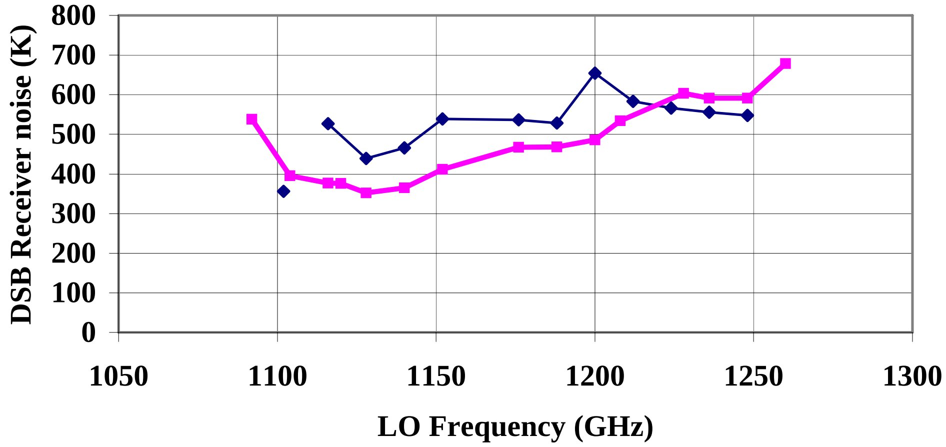

Fig. 7 The performance of the test receiver with the two different SIS mixers. The receiver noise is corrected for the beam splitter and for the cryostat window loss. The corrected receiver noise is below 600 K in entire 1.1 – 1.25 THz band. The minimum corrected receiver noise is 340 K, about 6 hν/k.

The mixer beam pattern has been measured using the heterodyne detection of a hot black body (a heater) of a small size. The signal was modulated with a chopper and detected with a lock-in amplifier. The E and H plane measured data are presented in Fig. 8. The measured beam is symmetrical. At the –11 dB level the beam f/d ratio is about 4.

VI. CONCLUSION

We developed a low noise SIS mixer developed for the 1.1 – 1.25 THz band of the heterodyne spectrometer of the Herschel Space Observatory. The SIS mixer has a quasi-optical design, with a double slot planar antenna and an extended spherical lens made of pure Si. The SIS junctions are Nb/AlN/NbTiN with the critical current density of about 30 KA/cm2 and with the junction area of a quarter of a micron square. For the ease of the Josephson current suppression, the SIS junctions are diamond-like shaped. The simultaneous suppression of the Josephson currents in the two SIS junctions is a particular advantage of the used shape. A low loss Nb/Au micro-strip transmission line is used for the first time in the mixer circuit well above the gap frequency of Nb.

Using the new mixer we demonstrated the minimum uncorrected Double Sideband receiver noise of 550 K (Y=1.34). The minimum receiver noise corrected for the local oscillator beam splitter and for the cryostat window is 330 K, about 6 hν/k, apparently for the first time in the THz frequencies range.

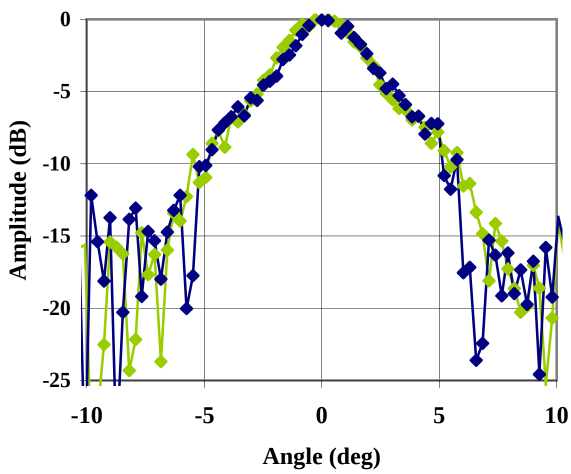

Fig. 8. The beam pattern of the SIS mixer measured at 1.13 THz.

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