QUASI-OPTICAL TERAHERTZ SIS MIXER

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ABSTRACT

The performance of quasi-optical (QO) SIS mixers designed for operation around 1 THz is evaluated. Mixers incorporating Si elliptical lens with either double slot-line or double dipole antennas with back reflectors have been fabricated and measured. Nb/Al-AlO_x/Nb superconductor-insulator-superconductor (SIS) tunnel junctions are integrated with a NbTiN-SiO_2-Al microstrip circuit to tune out the junction's geometrical capacitance and to match the antenna impedance to the junction over a wide frequency range.

The direct response, of the mixer measured by means of a Michelson Fourier transform spectrometer (FTS), is presented showing the mixer's ~30% instantaneous bandwidth. This bandwidth appears to be limited by the material properties of the NbTiN ground plane. Noise temperatures of 245 K @ 850 GHz, 310 K @ 980 GHz and 400 K @ 1020 GHz are presented. This is a two-fold improvement over best previously reported results for frequencies around 1 THz.

A far-field antenna beam pattern of the antenna-lens combination is measured at 900 GHz. The 1-st order side lobe level is –(16-18) dB and total power in the cross-polar beam is 0.3 % of the power in the co-polar beam.

INTRODUCTION

Heterodyne receivers incorporating Nb/Al-AlOx/Nb SIS junctions are known to be extremely sensitive in the sub-mm wave band. Noise temperatures of receivers operating below 680 GHz and using fully superconducting Nb tuning structures are only a few times greater than the quantum limit [1,2]. Above 680 GHz (so-called gap frequency), the microstrip lines based on Nb exhibit increased rf losses.

Alternative, non-superconducting metals microstrip have been used to push the operating frequency of SIS receivers above the gap frequency of Nb. In particular, a mixer based on Al microstrip lines has shown high sensitivity up to 1.1 THz [3,4]. The rf loss in

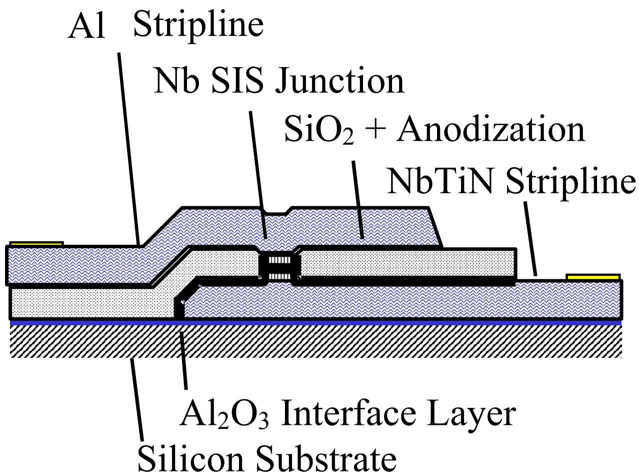

Fig. 1 Cross-section of a Nb SIS mixers with NbTiN/SiO_2/Al stripline on a Si wafer.

such a microstrip line does not strongly depend on frequency, however, it is higher than in a superconductor below its gap frequency.

Other superconducting materials with higher critical temperature T_c (and therefore higher gap frequencies) have also been used as a microstrip wiring material. The most promising results have been obtained with NbTiN ($T_c \approx 15$ K) at frequencies as high as 800 GHz [5]. The gap frequency for bulk NbTiN material is around 1.15 THz and good mixer performance is expected to extend up to this limit. In this paper we present SIS mixers based on a combination of a NbTiN ground plane, Al top wiring layer, and Nb/Al-AlO_x/Nb SIS junctions.

Waveguide (WG) mixers are commonly used in the mm-wave band. However, as frequency increases, the size of the waveguide decreases and production becomes more difficult. The planar antenna lens combination has been introduced as an alternative technological solution for high frequencies [6]. The main problem for this quasi-optical (QO) configuration is a concern about the receiver beam quality. Thus, this property of the QO mixer will also be addressed in this paper — the measured beam patterns for the double slot line antenna (DSA) on a silicon elliptical lens are presented.

RECEIVER LAYOUT

The receiver chip cross-section is shown in fig. 1. The substrate material is high resistivity silicon. The NbTiN ground plane is deposited at room temperature on a thin Al_2O_3 buffer layer. The Nb/Al-AlO_x/Nb SIS junctions and the SiO_2 insulator layer are fabricated using standard technology [7]. The junction area is 1 μm^2 and the current density is about 8 kA/cm^2. The normal state resistance R_n and the quality factor (R_j/R_n) of the junction is about 30 Ω and more than 20 respectively. The top wiring is a sputtered Al film. Aluminum has been chosen as the top electrode material instead of NbTiN for

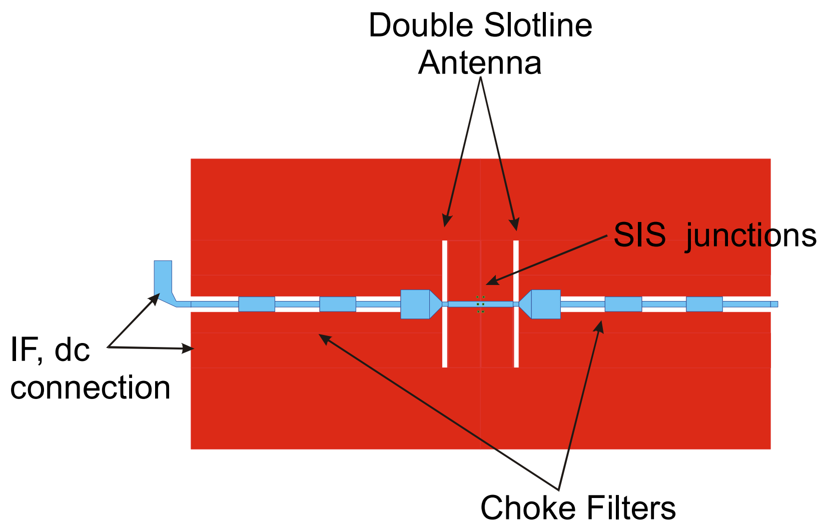

Fig. 2 Receiver chip layout: (slot-line antenna). Ground plane is red.

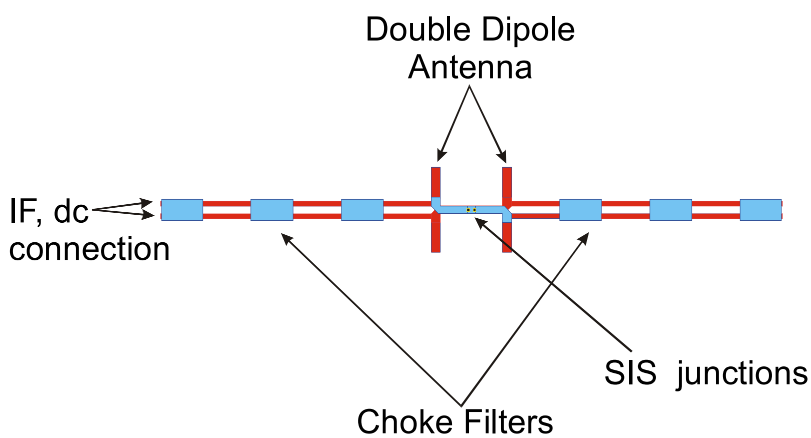

Fig. 3 Receiver chip layout: (double dipole antenna). Ground plane is red.

several reasons. The first reason is to avoid the heating of the Nb SIS junction which is observed in a full NbTiN/Nb-SIS/NbTiN combination due to Andreev reflection at the Nb/NbTiN interface [8]. The second reason is to improve on the stability of the magnetic field across the junction by removing the SQUID loop. Finally, this allows the frequency dependence of the rf properties of the NbTiN ground plane to be studied, due to relatively frequency independent rf properties of the Al top wiring.

The layout of the center part of the chip is shown in fig. 2 for the DSA and in fig. 3 for the double dipole antenna (DDA). Two SIS junctions are used in both designs. The rf signal couples in anti-phase to the junctions, forming a virtual ground in the interconnecting tuner made from microstrip line. This twin-junction tuning circuit was proposed in [9,10]. The antenna impedance is matched to the junction+tuner impedance by means of a quarter-wave microstrip line transformer.

Fig. 4 Antenna-lens combination.

In the DSA design, the combined choke filters are used to reflect the rf power coupled in the direction of the dc/IF leads. The low impedance sections are made of microstrip line and the high impedance sections are made of coplanar waveguide lines. This produces a large impedance ratio, which is also independent of material losses. A series dc resistance of ~ 0.2 Ω is expected in the Al top wiring. The calculated central frequency and bandwidth for this design is 950 GHz and 250 GHz respectively. Three tuner lengths and three junction sizes were included in the mask design. This compensates for the potential spread in device parameters due to fabrication tolerances.

In the DDA design, additional measures were taken to ensure that rf currents flow through the NbTiN ground plane. The DDA is formed entirely in ground plane to make it electrically symmetrical. Only the quarter-wave transformer and the junction tuner are made using the Al top wiring. Furthermore, different antenna and tuner sizes were used to cover the 800-950 GHz and 950-1100 GHz ranges.

The antenna lens combination of the quasi-optical receiver is schematically shown in fig. 4. The receiver chip is 2 x 2 x 0.3 mm^3. Two antennas of the same design are placed on each chip, with a 250 μm offset from the chip center, to increase the device yield. The receiver chip is mounted on the back surface of an elliptical Si lens. The diameter of the lens is 10 mm. A Stycast™ antireflection coating with a central frequency of 1 THz is applied to the front surface of the lens and the antenna is placed at the focal point of elliptical surface. A back reflector is used for the DDA - 20 μm thick Si covered on one side by a Nb film. This back reflector is fixed to the mixer chip surface by means of vacuum oil. The DSA is used without a back reflector.

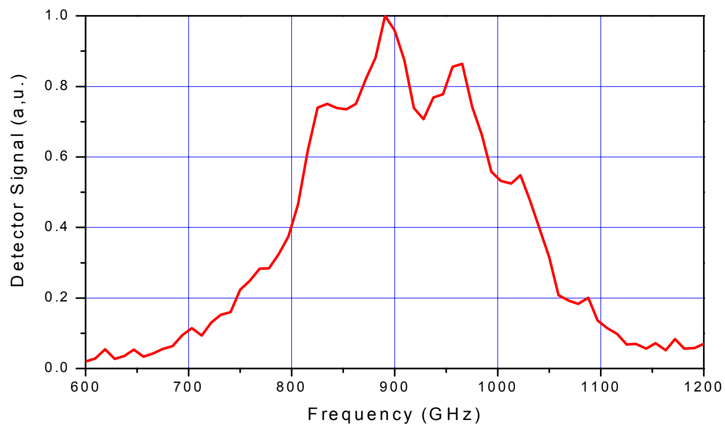

Fig. 5 Typical FTS response of double slot line antenna mixer.

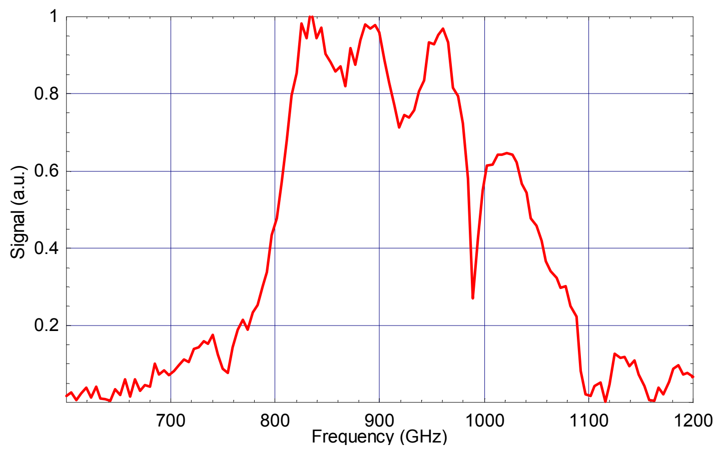

Fig. 6 Typical FTS response of double dipole antenna mixer.

DIRECT RESPONSE MEASUREMENT RESULTS AND DISCUSSION

The direct response spectra for DSA and DDA samples measured with an evacuated Mihelson FTS are shown in fig. 5 and fig. 6, respectively. This data is measured with the critical current suppressed by an external magnetic field to avoid Josephson direct detection that can change the response significantly in this frequency band. The 3 dB bandwidth for both the DSA and the DDA designs is about 250 GHz. The measurements in both figures are shown in the same relative scale. The 50 GHz ripple seen in all measurements is due to the transmission of the Michelson interferometer, and is not seen in heterodyne measurements.

All measurements show a decrease in detected power at frequency above 1 THz. This decrease is independent of the tuner length, and may be attributed to increased surface losses in the NbTiN ground plane. The rf quality of NbTiN film sputtered on the Si substrate appears to be worse than expected from measured critical temperature, $T_c = 14.3$ K. A significant improvement may be expected if a MgO substrate is used for NbTiN film deposition.

NOISE TEMPERATURE MEASUREMENT RESULTS AND DISCUSSION

Noise temperature measurements are performed using a standard Y-factor method. Blackbody radiators at 80 K and 300 K temperatures and the Raleigh-Jeans relation were used to express the equivalent noise power of the source. No vacuum setup was used during heterodyne measurements.

The copper mixer block was mounted on the cold plate of a vacuum LHe cryostat. No additional lenses or mirrors are used to direct the receiver beam out of the cryostat. A thin 15 µm Kapton™ vacuum window is used. Two far-infrared radiation filters (at 80 K and 4.5 K) are made from 1 mm Zitex™ G104. The local oscillator power was injected using a Mylar™ beam splitter of 15 or 6 µm thickness. A L-band (1.2-1.7 GHz) amplifier with a circulator, followed by room temperature amplifiers, is used in the receiver IF chain. A narrow pass-band (Δf = 85 MHz) filter followed by a power meter is used to analyze the receiver performance. A lower He bath temperature of 2 K is realized by decreasing the bath pressure to ~ 15 mBar. Two backward wave oscillators are used as local oscillators.

The measured IF response vs. SIS junction bias voltage is presented in fig. 7 for the DSA receiver. Traces of Josephson noise are present in the response because of either a small difference in the junction areas, or slightly asymmetric biasing of the junctions. The two junctions do not form a SQUID-like loop because one layer of the tuning structure is not superconducting. This results in improved mixer stability with respect to magnetic field variations. The mixer can be operated over 1 mV bias voltage span.

The receiver noise temperatures of the DSA mixer measured at different LO frequencies are presented in fig. 8. Data is presented for a 2 K bath temperature. The rise in the receiver noise temperature at higher frequencies can be explained by additional rf loss in NbTiN layer of junction tuning structures. The same tendency is observed in the mixer direct response. The noise temperatures of about 340 K (uncorrected for losses in 15 µm thick beam splitter) have been measured for the same receiver in the 840-920 GHz range at 4.2 K He bath temperatures.

Only preliminary sensitivity results are available for the DDA mixer. A receiver noise temperature of 600 K is measured with a 15 µm Mylar™ beam splitter at a 4.5 K bath temperature, which can be corrected for LO insertion loss to 400 K.

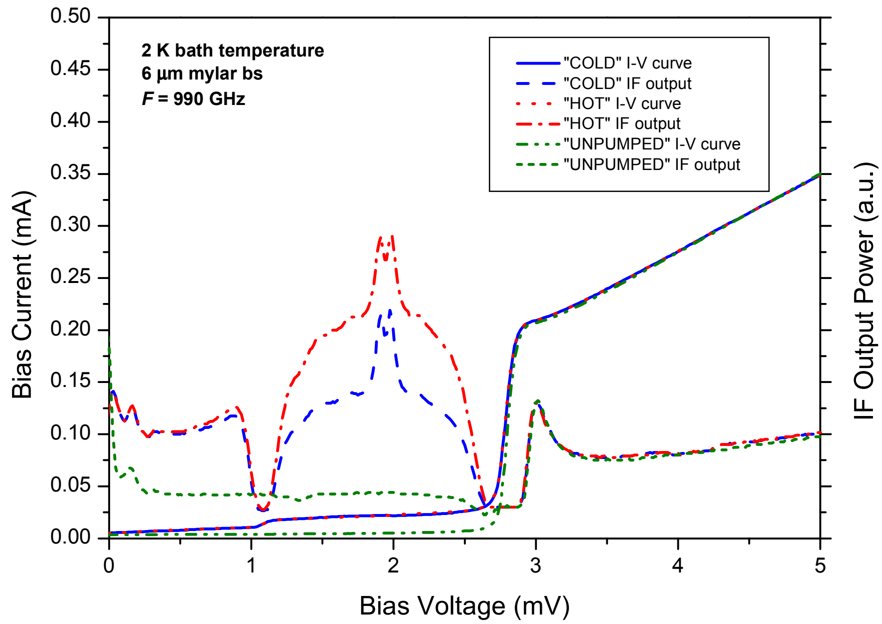

Fig. 7 Receiver Noise temperature for the double slot line antenna mixer at 2 K bath temperature. The noise temperature is 300 K @ 990 GHz, not corrected for beam splitter losses.

ANTENNA BEAM PATTERN MEASUREMENT RESULTS AND DISCUSSION

A 2-axis rotational setup is used for the antenna beam pattern measurements. In this setup, the dewar is rotated about two perpendicular axes with the lens-antenna combination placed at the center of rotation. The measured beam pattern is thus independent of the antenna beam pattern of the test source.

Both the cross- and co-polar far-field antenna beam patterns are measured for the DSA receiver at 900 GHz. Results are shown in fig. 9 and 10. The change in pumping level of the SIS mixer is used as a measure of the received power. The co-polar radiation pattern has a good main-lobe symmetry and the first order side-lobe level of –(16-18) dB, which is expected theoretically. The F/# ≅ 15 is estimated from the –11 dB taper. The fraction of the power contained in the main-lobe is 83% of total power. The cross-polar radiation pattern has peak power of –26 dB relative to the co-polar pattern. The total power in the cross-polar pattern is only 0.3% of the power in the main-lobe of the co-polar beam.

CONCLUSIONS

Quasi-optical mixers, employing a novel microstrip line material combination of NbTiN and Al, were developed and tested around 1 THz. The DSA receiver demonstrates a two-fold improvement of the sensitivity over previously reported mixer results at these frequencies. Noise temperatures of 245 K @ 850 GHz, 310 K @ 980 GHz and

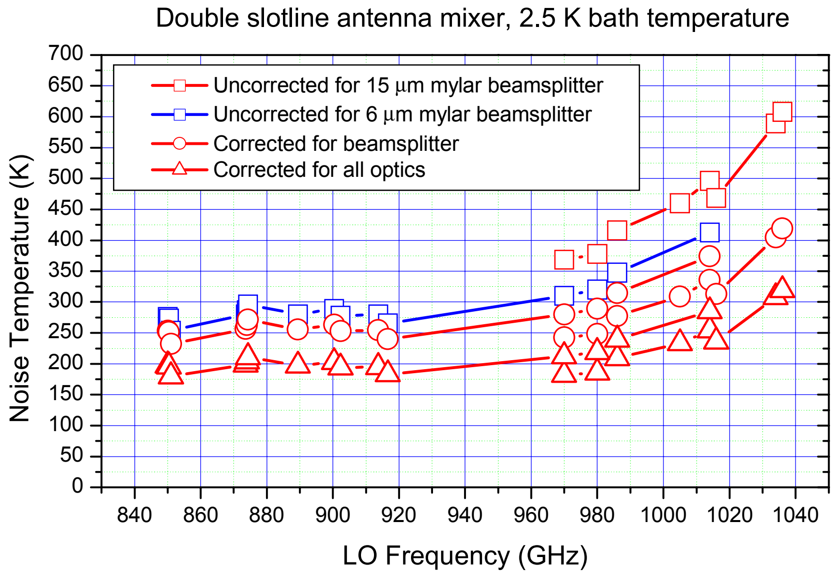

Fig. 8 Receiver Noise temperature for double slot line antenna mixer at 2.5 K bath temperature.

400 K @ 1020 GHz are obtained and a 30% relative bandwidth is demonstrated. Good main antenna beam pattern quality and low level cross-polar response is experimentally demonstrated. This demonstrates that THz quasi-optical mixers are well suited for use in astronomical receivers.

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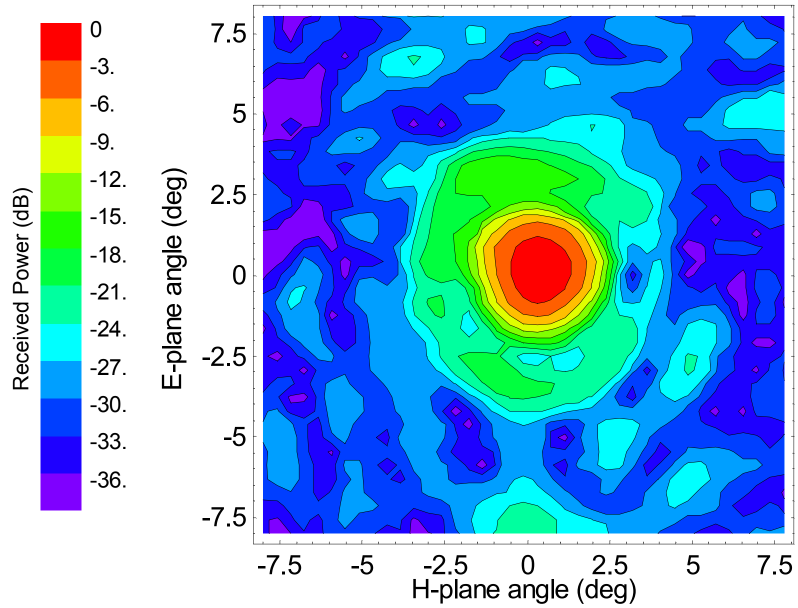

Fig. 9 Main-polarization antenna beam pattern of the double slot line antenna at 900 GHz.

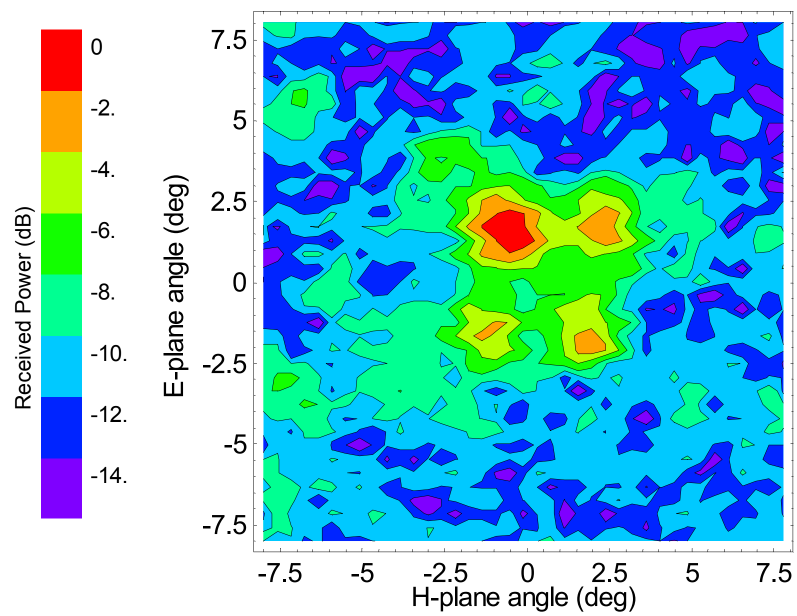

Fig. 10 Cross-polarization antenna beam pattern of the double slot line antenna at 900 GHz. 0-dB power level corresponds to –26 dB power in fig. 9.