A 275-370 GHz SIS mixer for the APEX telescope

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ABSTRACT

Atacama Pathfinder EXperiment (APEX) submillimeter telescope is currently under completion on Chajnator, at an altitude of 5050 m on the Atacama Desert, in the Northern Chile. The telescope facility heterodyne receivers should have 3 bands covering 211-500 GHz. We present design of a 275-370 GHz SIS mixer to be used as a first light APEX Band 2 receiver. A novel waveguide-to-microstrip transition with integrated bias-T is used in this mixer. This structure allows coupling of the RF signal from a full height waveguide to a thin-film superconducting line via E-probe. The wide side of the probe is connected to another port via a specially shaped high impedance line that provides RF/DC isolation. This port is used to extract the IF signal and to inject a DC current that creates a local magnetic field parallel to the plane of the SIS junction to suppress the Josephson effect. The main advantage of this type of Josephson suppression circuit is its compactness as it uses the existing superconducting lines from the SIS integrated tuning circuitry. The entire structure with the probe, SIS junction with its tuning circuitry is placed on a quartz substrate. For more advanced designs, as a sideband separating or balanced mixer that we intend to have for the final version of the APEX telescope heterodyne receiver, the SIS junctions of two balanced or quadrature mixers will be at a very close distance. The standard solution of using superconducting coils to suppress Josephson effect is very difficult to implement and, therefore, this new structure should be of a great advantage.

Keywords: Superconductor-insulator-superconductor (SIS), Josephson effect, waveguide-to-microstrip transition, bias-T

1. INTRODUCTION

Atacama Pathfinder EXperiment (APEX) 12m telescope, which is currently under construction in the Chajnantor region of Northern Chile at an altitude of 5050m, near the Atacama Desert. This site is one of the best for sub-millimetre wave observations, together with the South Pole and Mauna Kea in Hawaii. The antenna is a prototype antenna of the Atacama Large Millimeter Array (ALMA), but with improved surface accuracy (18 µm rms expected) to allow higher frequency operation. This telescope will have both heterodyne and continuum instruments, covering the frequency range (230 GHz–1.5 THz). The work presented here is done for APEX band 2, covering the frequency range 275-370 GHz with centre frequency at approximately 345 GHz.
The mixer that is described in this paper is double sideband (DSB) and is planned for installation on the telescope for the first measurements the fall of 2004. This development will serve as a base for a future sideband separating mixer (2SB) [2] that will replace the DSB version in 2005.

2. MIXER DESIGN

2.1. Probe design

The mixer design is based on a novel waveguide-to-microstrip transition with an integrated wideband bias-T [3]. The novelty of this probe comes from the fact that it couples the input waveguide signal to the SIS junction and tuning circuitry lines via a radial probe (see Fig. 1) while having an isolated port at the opposite side of the substrate where the IF signal can be extracted and DC current injected to bias SIS junctions or suppress Josephson current. Shi and Inatani proposed a similar device [4] for a half-height waveguide. The transition used a probe crossing the entire waveguide height and directly connected to an RF filter choke. In contrast, we propose a design suitable for a full-height waveguide, therefore with reduced RF losses and more easily machined, important advantages that become especially critical for mm and sub-mm frequency waveguide components with small dimensions and high losses. The waveguide dimensions chosen for the mixer are 380 x 760 μm^2.

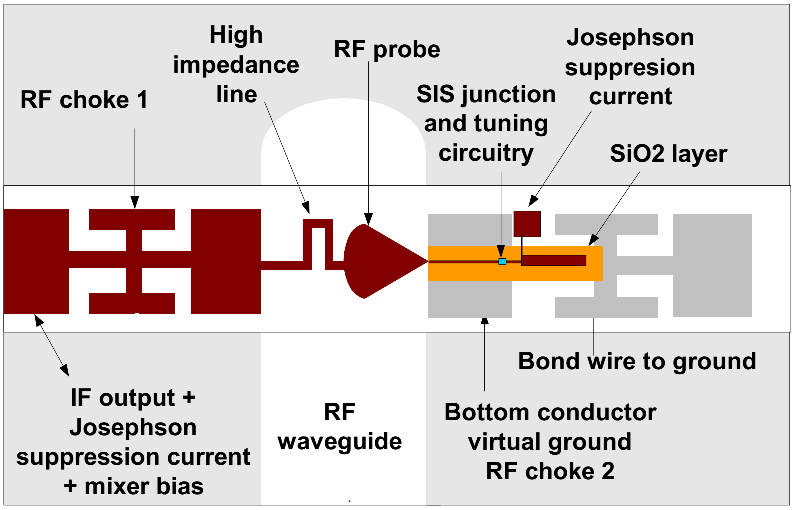

Fig. 1. Mixer layout.

In the suggested structure, the input waveguide couples the RF signal to the thin-film superconducting lines and is isolated from the DC-IF microstrip line. The substrate is crystalline quartz placed in a channel with sub-critical dimensions to prevent propagation of the waveguide modes. The RF probe is a radial line with a radius occupying 40 % of the waveguide height and can have an impedance 30 - 100 Ω. We use an RF choke in the DC/IF channel, to get a virtual ground in the waveguide wall plane, then we connect it to the radial probe with a (2n-1)λ/4 long and very high impedance line. An X-band version of the probe has been constructed (Fig. 2.a) and tested. Measurements are compared with simulated results in Fig. 2b.

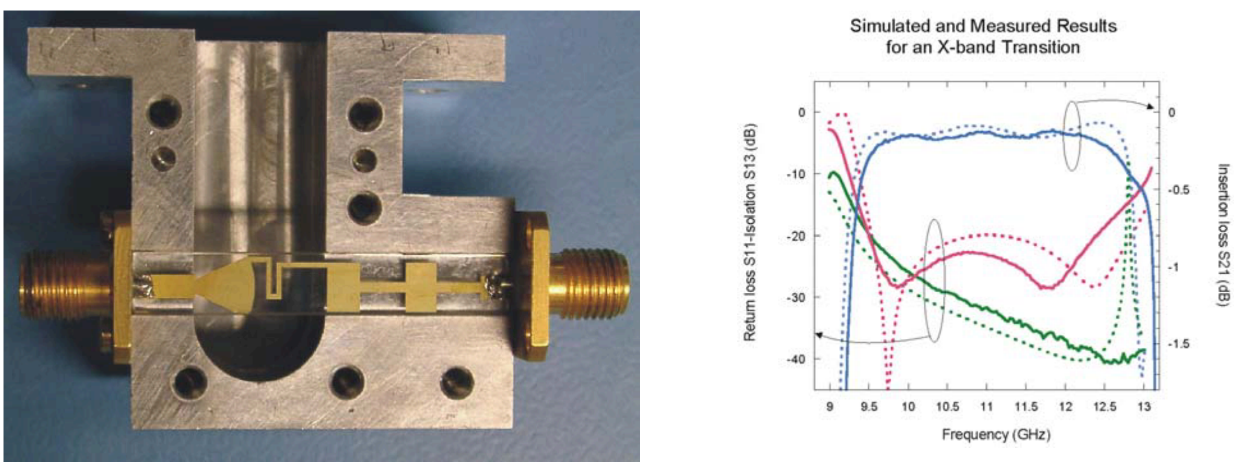

Fig. 2. Left: X-band scale model of a 50 Ohm probe. Right: Continuous lines are for measured results and dashed lines for simulated results. Center frequency is 11 GHz. Upper curves are insertion loss, middle curves are return loss and lower curves are isolation between waveguide RF port and DC-IF port.

2.2. Josephson effect suppression

The standard solution to suppress Josephson effect is to use solenoids, usually, superconducting coils. For the sideband separating or balanced mixers, that we intend to have for the final version of the APEX telescope heterodyne receiver, the SIS junctions will be at a very close distance (typically about 1 mm spacing). Thus, using exclusively of superconducting coils to suppress Josephson effect would not provide independent suppression of the Josephson current in both SIS junctions independently. The main motivation for using this novel type of waveguide transition is to have an additional port available to apply a DC current through the wiring superconducting lines as demonstrated in [5]. This current creates a localized magnetic field parallel to the plane of the SIS junction and therefore suppresses the Josephson effect. The main advantage of this type of Josephson suppression circuit is its compactness as it uses the existing superconducting lines from the SIS integrated tuning circuitry.

2.3. Mixer chip designs

Three different chip designs were fabricated and the masks are shown in Fig. 3. The probe impedance for design 1 and 2 is of 60 Ohm with a slight inductive part, and design 3 has a probe impedance of 30 Ohm with a slight capacitive part. The calculations of the probe impedance were done using High Frequency Structure Simulator (HFSS) [6] and are shown in Fig. 3.

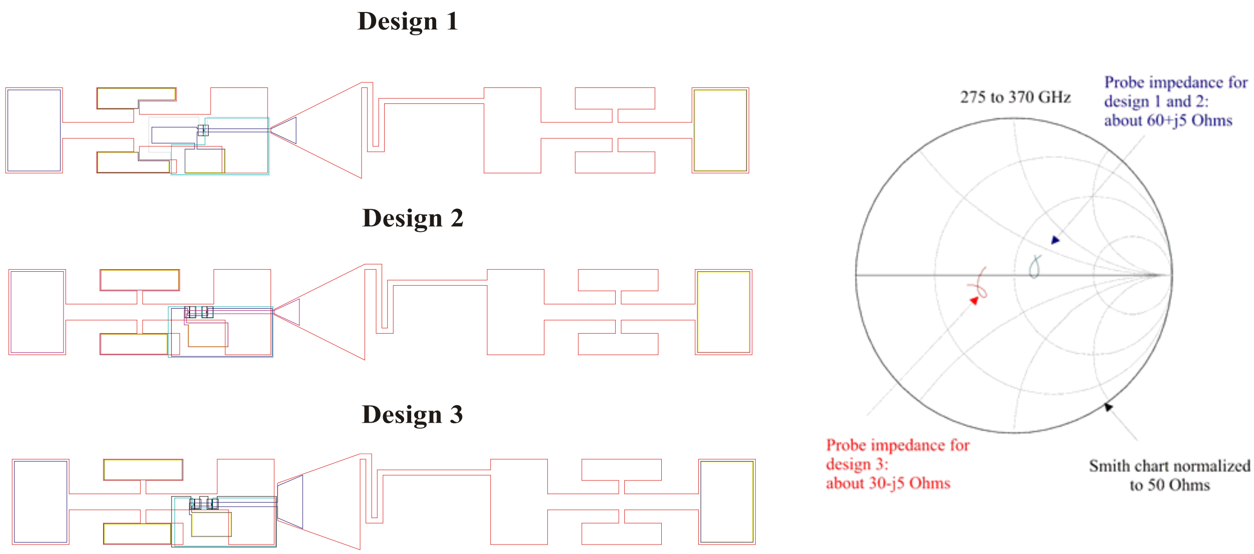

Fig. 3. Left: Different mixer chip designs: 1: Single junction with 60 Ohm probe, 2: Twin junction with 60Ohm probe, 3: Twin junction with 30 Ohm probe. Right: The probe impedance for the different designs

The choke structures are of the hammer-type allowing getting a much more compact design, as opposed to the standard choke structure of consecutive low and high $\lambda/4$ impedance lines. As a comparison this choke structure has a length of 460 μm; in order to reach equivalent performance, the standard choke filter would need at least 1 mm length.

2.4. SIS and tuning circuitry design

In order to match the complex impedance of the SIS junction to the nearly real impedance of the signal source (probe), the capacitance Cj of the junction should be resonated out at RF. We use relatively large area for the junctions ($3\ \mu m^2$) given that we use photolithography to define the junction area, and want to have very identical junctions for the 2SB version of the mixer. The drawback of having a large area for the junction is that it becomes more difficult to get wideband performance (30% relative bandwidth is required). The SIS capacitance is of the order of 265 fF.

The equivalent circuit of the SIS junction at RF is shown in Fig. 4. Two different tuning circuitry designs were employed. The first one uses a single junction with a parallel inductive line. A short microstrip line (L2), equivalent to inductance, L_t, at RF, is connected in parallel. A $\lambda/4$ open stub (low impedance line L3) provides ground for L_t. The second design uses two junctions connected through a short line (L2), equivalent to inductance, L_t, at RF. R_{RF} is then matched to the RF source impedance by a $\lambda/4$ transformer (L1).

The calculations of the SIS impedance in presence of LO power is derived with the help of a program, which calculates R_{RF} vs. frequency and LO pumping power based on the measured or modelled IV characteristic of the junction [7]. Table 1 indicates the dimensions of the lines used in different designs, together with the thickness of SiO2. To calculate these line dimensions, we used a model to calculate superconducting lines parameters based on the calculation of the surface impedance of the superconductor, and taking into account the frequency dependence of the penetration depth [8].

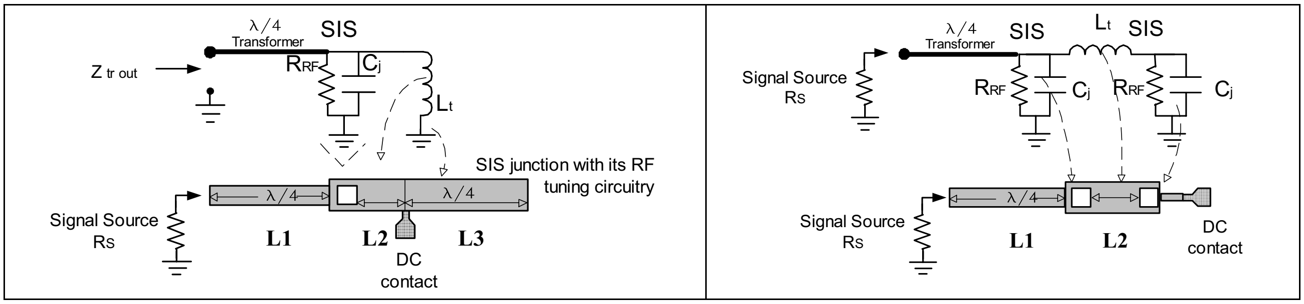

Fig. 4. Integrated tuning circuitry for single junction (left picture) and twin junction (right picture) designs.

Table 1. Dimensions of the tuning circuitry lines.

Tuning circuitry dimensions	Design 1	Design 2	Design 3
λ/4 transformer L1 SiO2 thickness (nm)	150	400	400
λ/4 transformer L1 length – width (µm)	111 - 5	111 - 6	109- 8
Inductive line L2 SiO2 thickness (nm)	150	150	400
Inductive line L2 length – width (µm)	13 - 5	29 - 6	19 – 6
λ/4 transformer L3 SiO2 thickness (nm)	150	*NA*	*NA*
λ/4 transformer L3 length – width (µm)	79 - 30	*NA*	*NA*

Fig. 5 shows the calculated power matching for the different designs. The single junction design is the worse, having a matching of about -7 dB, whereas the twin junction designs are below -12 dB over most of the band. Even though it seems obvious that the twin junction circuitry is superior in performance, the drawback is that it has twice more junctions, so any asymmetry in the two junctions will cause problems, like for instance impossibility to suppress completely the Josephson effect.

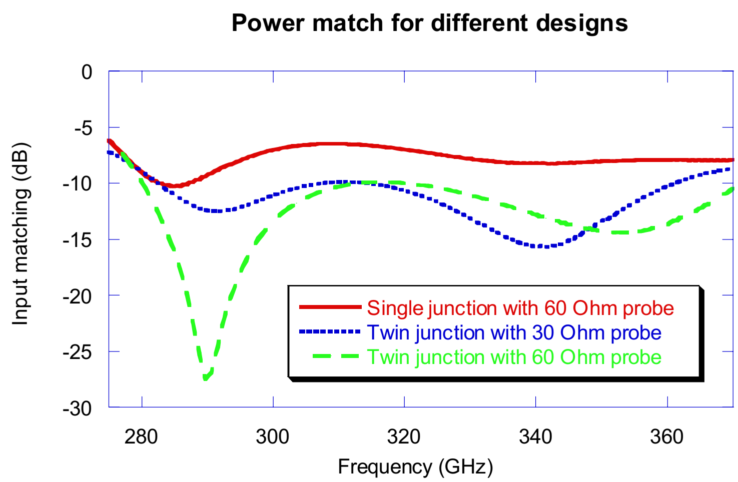

Fig. 5. Power matching for the different designs.

3. RESULTS

3.1. SIS fabrication

The SIS junctions are fabricated by GARD at Chalmers new clean room facility. The Nb-AlOx-Nb SIS junctions are designed to have an area of 1.7 x 1.7 μm^2, a normal resistance Rn = 7 Ω implying a critical current density Jc 7.5 kA/cm^2. The chips were fabricated on 65 μm thick crystalline quartz substrates glued on a 250 μm 1'' square substrate. The process flow for the SIS chips was based on Nb/Al-AlOx/Nb trilayer growth technique [9], which proved to provide the most reproducible properties of the SIS junctions. The results of the first run on quartz substrate gave a yield higher than 85%, with Rn having the specified value with deviations of less than 10%. The final chip size is 1 mm x 200 μm x 65 μm. An example of IV curve is shown in Fig. 6. The sub-gap to normal resistance ratio is typically of 20-25.

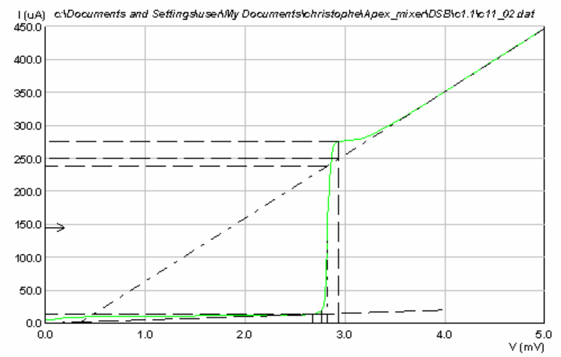

Fig. 6. Typical IV curve of a single junction (design1). Rn is 7 Ohms and Rj/Rn = 20

3.2. Mixer block

The mixer block was fabricated using Copper-Tellurium alloy, which has similar conductivity as the usual copper at room temperature but is easier for machining [10]. We used the split-block technique mixer block (Fig. 7). The mixer chip is placed in a channel milled in one half of the mixer block. A very thin layer of gold (2 μm) is plated to allow bonding with gold wires.

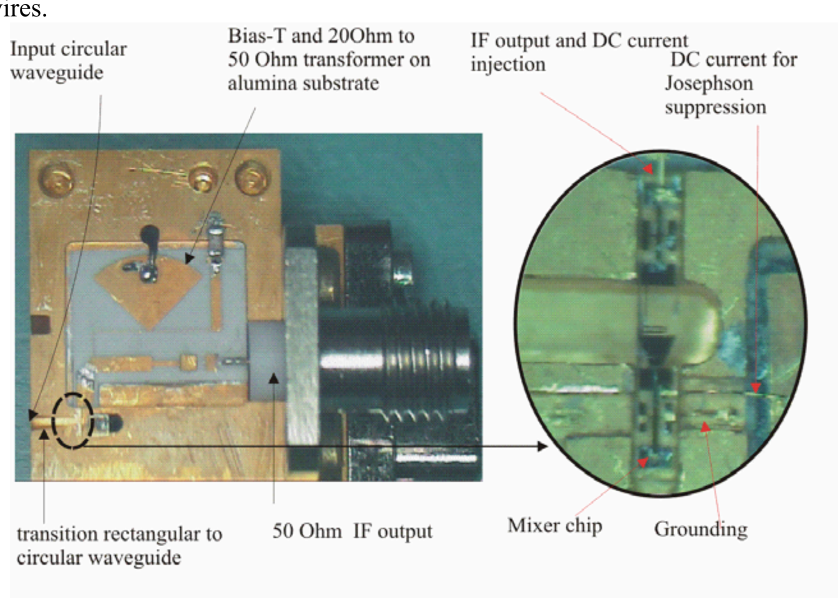

Fig. 7. Left picture shows the lower half of the mixer block incorporating the mixer chip, the bias-T and 20 Ohm to 50 Ohm transformer on alumina substrate. The right picture shows the mixer chip placed on the channel and the bond wire connections for IF and DC.

The IF circuit integrated in the mixer block comprises a bias-T and 20 Ohm-to-50 Ohm IF transformer on an alumina substrate and placed on the same half of the mixer block, with a 0.3 mm bond wire connecting the mixer chip to the alumina substrate that tunes out the IF capacitance of the SIS and tuning circuitry lines. The DC circuitry for the SIS biasing is placed on the back side of the mixer block piece. The mixer block also includes a transition from rectangular to circular waveguide. For the first tests, a simple conical horn of length 30 mm and half angle 5° was fabricated.

3.3. IF chain

The APEX IF bandwidth is specified to be 4 - 8 GHz. An isolator [11] with 0.2-0.4 dB losses at 4K was used between the mixer IF output and a 4-8 GHz LNA developed at GARD [12]. The measured noise temperature and gain at 12K of the LNA with isolator at the input is of about 6-7 K and 25 dB gain (Fig. 8).

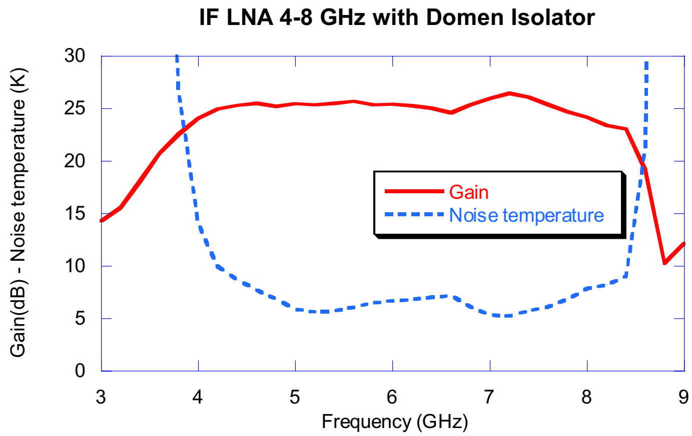

Fig. 8. Measured noise temperature and gain of the IF LNA with isolator at the input at 12 K

3.4. Noise Temperature measurements

First measurements are currently ongoing. Preliminary results have been obtained over few frequency points. Only design 1 was tested, (single junction). At frequencies of 300 GHz, 331 GHz and 350 GHz, an uncorrected Y factor between 2 and 2.5 dB was measured. Note that due to a lack of available LO power, a Mylar film of 50 µm was used as beam splitter; this induces a loss in the signal path of 30%. By correcting for these losses, a noise temperature of about 80 K for most part of the IF band is calculated (see Fig. 9).

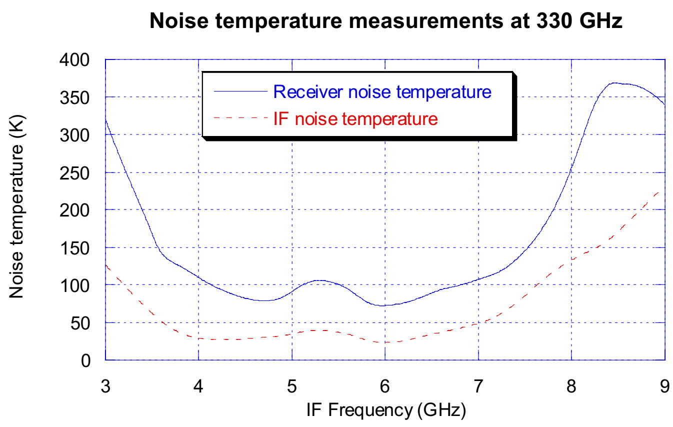

Fig. 9. Measured noise temperature for the receiver across the IF band at 330 GHz, corrected for the beam splitter loss, and IF noise temperature calculated with the shot noise technique [13].

The presented results are preliminary, from the very first mixer tests when some problems for the IF matching and of the mixer block cooling precluded reaching the ultimate mixer performance. Improvement in the mixer cooling and the IF match along with better LO source beam matching are expected to improve the mixer performance.

3.5. Josephson effect suppression

The first results on the suppression of the Josephson effect indicated that we couldn't reach the first null in the sin(x)/x dependence of the Josephson current. A field of about 60 Gauss is required to reach that null, or according to measurements (Fig. 10), a current over 45 mA is required (about 100 mA in [14]). The highest current that we could apply before a part of the superconducting circuitry switched to the normal state was between 20 and 40 mA depending on the chip temperature. Figure 11 shows the Josephson supercurrent versus the control line current for the twin junction for the design 3 of the mixer chip.

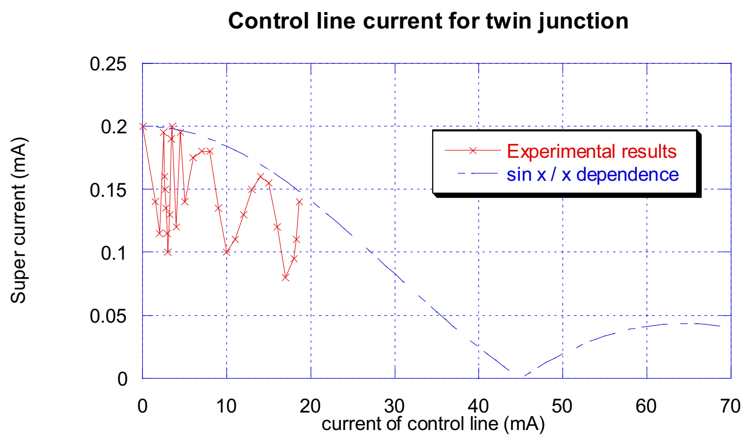

Fig. 10. Supercurrent suppression for twin junction, design 3. A current of 45 mA is expected to reach the first null. The twin junction behaves as a SQUID, therefore is very much sensitive to the magnetic field.

This twin junction behaves in fact as a SQUID, and is therefore much more sensitive to the applied magnetic field. A very short period of the sin(x) dependence of the squid is visible at around 2 mA where we have more measurements points. After 5 mA, measurements points are more spaced.
The critical current density of Niobium superconductor is between 10^6 and 10^7 A/cm^2 depending such factors, as quality, or stress in the film. A stress in the film actually improves the critical current density [15] and,, in our case, we have little stress in the films. Actually, a way to improve the limit of current that we can apply is to introduce more stress in the film. Another way to proceed that was employed for the noise temperature measurements, is to use permanent magnets to get closer to the first null, and then fine tune with the control line.

4. TOWARDS INTEGRATED SIDEBAND SEPARATING AND BALANCED RECEIVERS

The present development of a DSB mixer for 275-370 GHz will be used as a prototyping for a 2SB version. We will select the best of the 3 designs of the DSB mixer, and use it for the future mixer designs (Fig. 11). In order to reach 2SB performance, the LO is injected in the middle waveguide near the center of the chip and coupled by a double probe transition [16] that equally divides the power with 180° phase difference. The LO is then further coupled to the SIS with microstrip superconducting lines. The RF signal is separated in a 3 dB–90° branch-line coupler. The IF signals are extracted from the ends of the chip and then combined in an IF 3 dB–90° hybrid. A 3 mm version of a 2SB mixer was successfully developed using a similar layout [17]. Finally, the two control lines would allow to independently suppress the Josephson effect in both junctions.

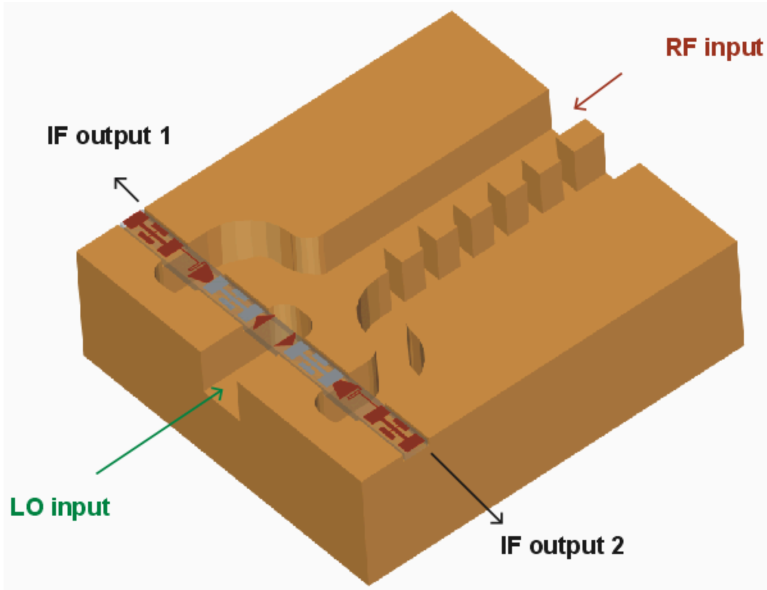

Fig. 11. Sideband separating mixer layout. The mixer chip will be about 2500 x 200 x 65 µm. The LO is injected in the middle of the chip, and the RF signal is separated in a 3 dB – 90° branch-line coupler. The IF signals are extracted from the ends of the chip.

5. CONCLUSION

We present the design and the first results for a 275-370 GHz DSB SIS mixer, featuring a novel probe structure that couples the signal from a full-height waveguide to thin-film superconducting lines while having an isolated port connected on the wide side of the radial probe. This additional port allows extracting of the IF signal and injecting DC currents to bias the junctions and to use existing wiring circuitry lines to drive a DC current on top of the junction therefore creating a local magnetic field parallel to the SIS junction. First results showed that at different frequency points, a mixer noise temperature as low as 80 K is obtained, and that the concept for the Josephson suppression works even though we couldn't reach the right value of magnetic field without help of additional permanent magnets. We expect further improvements of the receiver noise temperature down to 50 K across the band.

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