SIS Mixer for 385 – 500 GHz with On-Chip LO injection

Raquel Monje, Victor Belitsky, Christophe Risacher, Vessen Vassilev and Alexey Pavolotsky

Group for Advanced Receiver Development (GARD), Department of Radio and Space Science with Onsala Space Observatory, Chalmers University of Technology, SE 41296 Gothenburg, Sweden

ABSTRACT

We present the design and first experimental results of a 385-500 GHz fixed-tuned double sideband (DSB) receiver based on a superconductor-insulator-superconductor (SIS) junction mixer with on-chip LO injection circuitry. At high frequency, branch waveguide couplers are difficult to manufacture with required accuracy as the branches (slots) become extremely narrow. In order to solve this problem, we propose a coupler integrated onto the mixer chip and fabricated together with the SIS junction and the tuning circuitry. The on-chip LO directional coupler is made of superconducting lines with slot lines in the ground plane. Thus, the coupler is integrated into conventional SIS junction fabrication steps, benefiting from the processing accuracy better than 0.5 μm by using optical lithography only. Furthermore, the mixer design includes a novel component, an ellipse termination for the idle LO port, made of thin-film resistive material. This termination gives very broadband performance using a compact area. Moreover, it is very tolerant to the sheet resistivity of the film, geometry and does not require any physical grounding [1]. The mixer is to be used at the Atacama Pathfinder EXperiment (APEX) telescope in Chile [2].

Keywords: SIS mixer, waveguide probe, directional couplers, E-probe, substrate-based coupling structure.

1. INTRODUCTION

The Atacama Path Finder EXperiment (APEX) [2] is a 12 m telescope; it is a prototype antenna of the Atacama Large Millimeter Array (ALMA) [3]. APEX is placed in Cerro Chajnantor in the Chilean Atacama desert, at an altitude of about 5000 m. The site is one of the best places for submillimeter astronomy on the Earth because of the extremely low content of water vapour. For spectroscopy studies APEX will house single pixel heterodyne receivers covering the frequency range of 211 GHz up to 1.5 THz and heterodyne arrays consisting of 7 x 2 pixels CHAMP+ [4] operating at 650 and 850 GHz.
The work presented here is part of our development for APEX band 3 (385 – 500 GHz), a sideband separation SIS mixer with 4-8 GHz IF output. This technology provides better sensitivity for spectral line observation than double sideband (DSB) [5]. Besides, DSB observations may lead to spectral line-confusion or degrade the system noise temperature and the receiver sensitivity with strong atmospheric absorption bands falling into the image band. This is a driving reason to choose this technology considering that some of the important molecules for this band are very close to telluric absorption line, as in the case of deuterated water, HDO, with its fundamental transition frequency at 465 GHz.

2. MIXER DESIGN

2.1 Mixer Chip Design

The mixer design integrates several novel RF components in the same substrate, making the design very compact and innovative. The mixer chip comprises a waveguide-to-microstrip transition with integrated bias-T; two hammer-type chokes; a 50-Ohm LO probe; an on-chip - 16 dB directional coupler for the LO injection and an ellipse termination for the idle port of the coupler.
The RF probe couples the input waveguide signal to the SIS junction while having an isolated port at the opposite side of the substrate, where the IF signal can be extracted and DC current can be injected to bias SIS junctions, minimizing its influence

on the performance of RF [6]. The RF probe is shaped using a combination of rectangular and radial probe in order to achieve a broadband matching between the waveguide and the probe output. A low impedance probe is important for the matching of the SIS junction with typical impedance at RF of ~ 5 – 10 Ω. According to our HFSS simulations [7], the impedance observed at the microstrip (output of the probe) is approximately 35 Ω [8]

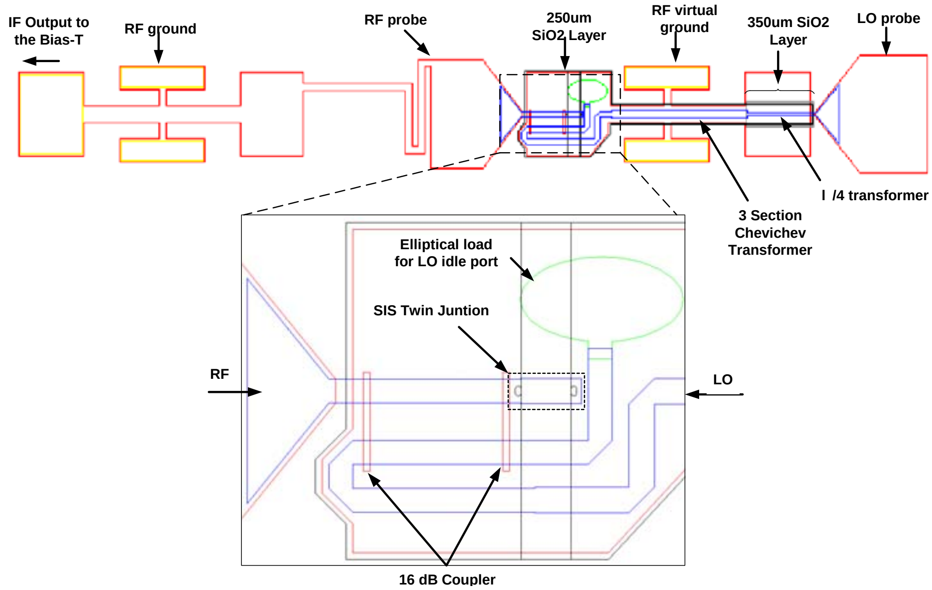

Fig. 1. Drawing of the mixer chip design for APEX Band 3 (385 – 500 GHz). The quartz substrate containing the RF and LO probe and two hammer type choke to provide RF ground and IF port. A zoom view of the 16 dB coupler with the tuning circuitry and the twin junctions.

The LO is fed through a waveguide-to-microstrip probe at the opposite side of the substrate and is coupled to the RF signal through a - 16 dB directional coupler, see Figure 1. The 50 Ohm LO probe impedance is transformed into a 9 Ohm - impedance of the coupler- by a quarter of wavelength transformer followed by a three sections Chebishev transformer.
The on-chip LO directional coupler is placed on the same dielectric (SiO_2 with $\varepsilon_r = 3.74$) as the SIS junction and the RF tuning circuitry. The coupler consists of two parallel superconducting lines coupled via lumped links - two perforations forming slot-lines in the ground plane. This way, the RF signal coming from the waveguide-to-microstrip probe is coupled to the LO signal and directed to the SIS twin junctions while the idle port of the LO coupler is terminated with an elliptical termination [1].
In order to match the complex impedance of the SIS junction to the nearly real impedance of the signal source (probe), the capacitance C_j of the junction should be resonated out at RF. The use of photolithography to define the junction area limits us to use relative large junction area (~ 3 μm^2). For a given critical current density, the SIS capacitance is of the order of 300 fF. The tuning circuitry uses two junctions connected through a short line, equivalent to an inductance, L_t, at RF. A quarter of wavelength transformer transforms the impedance of the probe into the RF impedance of the twin junctions [9]. The tuning circuitry provides a power matching better than -10 dB over the band of interest [8].

2.2. Mixer Block Design

The double sideband mixer block, shown in Figure 2 top-left, is fabricated using Copper-Tellurium alloy, which is easier to machine. A very thin layer of gold (2 μm) is plated to allow bonding with gold wires and to protect the block from corrosion. The DSB mixer block consists of two parts; the mixer back piece where the mixer chip is placed together with the DC circuitry and IF output (see Figure 2 top-right); and the intermediate piece containing the waveguides for the RF and LO signal injection. Those parts are manufactured by direct milling, using the split-block technique. Figure 3 shows the sideband separation mixer block which consists of two mixer back pieces, being common for the DSB and 2SB design, whereas the intermediate waveguide piece will be substituted with a unit containing the LO in-phase power divider and a 3 dB 90 degrees waveguide hybrid for the RF signal in order to achieve sideband separation using quadrature scheme [8]. This

intermediate piece is intended to be fabricated by using copper micromachining, an innovate technology developed at GARD and successfully used for the APEX T2 [10].
The mixer chip is placed in a 65 µm-deep channel milled in the mixer back piece with a 10 µm x 120 µm air-gap underneath the substrate. The use of suspended microstrip increases the cut-off frequency of the substrate channel and allows increasing its width. The substrate dimensions are 1200 µm x 150 µm x 65 µm, one bond wire connects the ground of the mixer chip to the mixer block. The IF circuitry made on alumina substrate is integrated in the mixer block. It comprises a bias-T and 20 Ohm-to-50 Ohm IF transformer. Three bond wires connect the mixer chip to the IF circuitry, which tune 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 pieces.

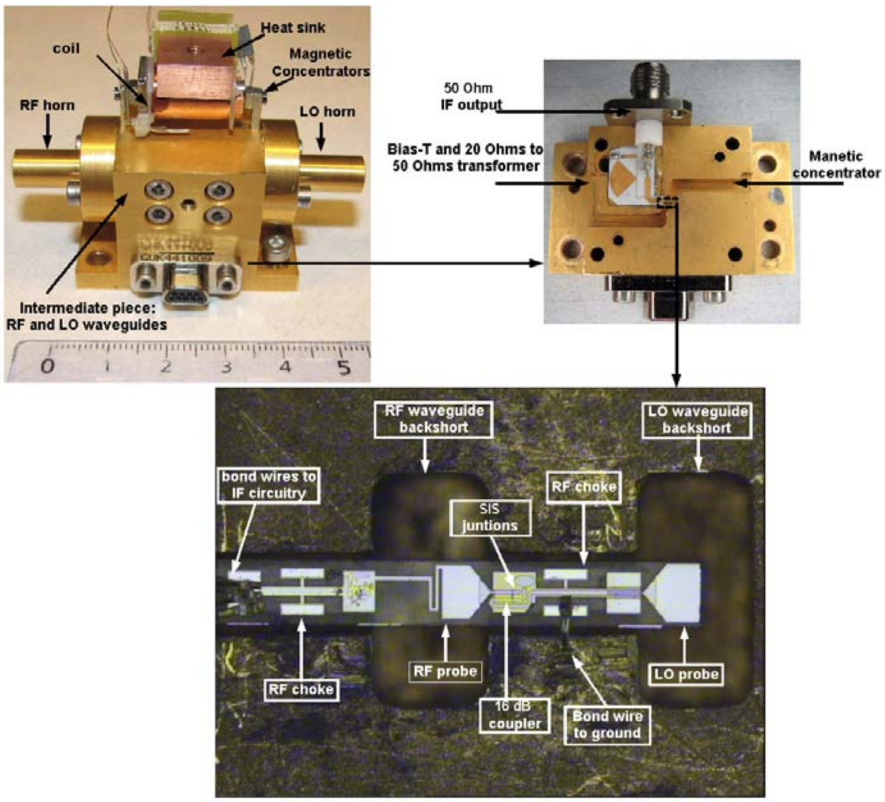

Fig. 2. Top left picture shows the DSB mixer block: two magnetic iron concentrators guide the magnetic field from an external coil to the vicinity of the junctions; Top right picture of the mixer back piece containing the mixer chip, the bias-T and the 20 to 50 Ohm transformer and the DC circuitry in the back side, this piece is compatible with the 2SB mixer; bottom centered picture of an optical microscope view of the mixer chip.

3. MEASUREMENTS

3.1. Measurement setup

The laboratory test measurements are performance in a liquid helium Oxford Instrument cryostat. The mixer uses a corrugated horn followed by a cold Teflon lens with a focal distance of 25 mm. The vacuum window is a 1.5 mm high density polyethylene (HDPE) window with anti-reflecting grooved surface optimized for these frequencies. We use a 200 µm Zitex film as infrared filters. The local oscillator is a multiplier chain (x36) from VDI and is quasioptically injected at the opposite side of the RF window with the help of a combination of horns and a Teflon lens of 36 mm focal distance.

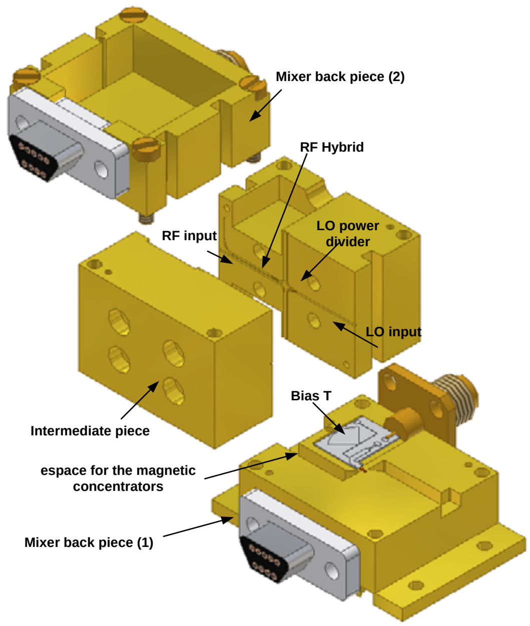

Fig. 3. Drawing of the 2SB mixer block. The mixer block consists of two mixer back pieces where the mixer chip is placed together with the DC input and IF output, and two intermediate pieces containing the LO power divider and the RF3dB 90° hybrid.

3.2. Noise temperature performance and diagnosis

The noise temperature measurements were performed with the Y factor technique using a hot (293 K) and a cold load (77 K) placed in front of the input window. Figure 4 shows the measured uncorrected receiver noise temperature.

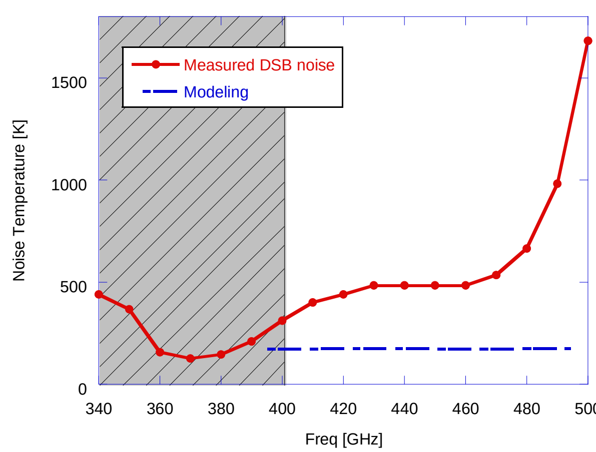

Fig. 4. Measured DSB receiver noise temperature.

The measured noise is almost five times greater than the noise expected through modeling for this mixer. A possible reason for such disagreement with the design expectations is thought to be due to high RF losses originated from the ground perforations for the on-substrate LO injection circuitry. The slots cause weak-links – areas where the line gets thinner than two times the London penetration depth, loosing superconductivity properties- in the strip counter layer and detune the circuitry resulting in the frequency-dependent mismatch. Figure 5 illustrates different points where we can have such weak links, e.g. at the probe-to-microstrip transition, where the probe (made of Nb line of 350nm) is deposited over quartz substrate and it is connected to the microstrip line placed over a SiO_2 layer of 250 nm. In such places, the line is thinner than on flat surfaces and, hence, might have structural defects acting as weak-links. Figure 5 shows how this effect appears in the DC IVC and IF power.

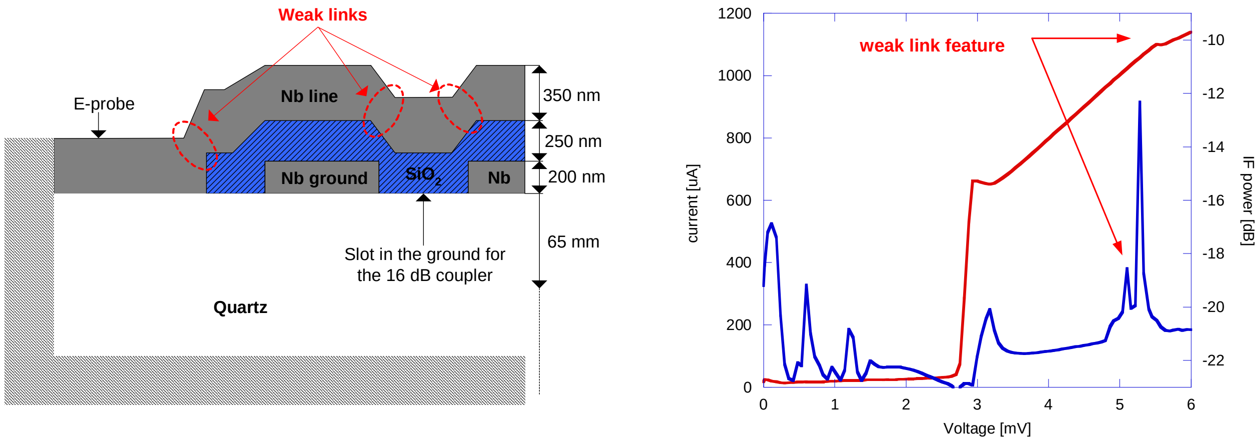

Fig. 5.Left picture shows a cross section of a mixer chip; right picture shows the DC measurements of the IVC (red curve) and IF power (blue curve).

A new iteration of the wafer has been produced adding Nb patches in those critical regions on top of the counter Nb layer (referred as Nb line on Figure 5 left), increasing the thickness of the lines in the discontinuity areas. DC features at the IVC and IF power were no longer detected, nevertheless, no significant changes in the noise performance were measured. These results indicates that discontinuities on the lines still introduce extra parasitic inductance in the mixer RF tuning circuitry, coming from possible cracks in the transitions areas or from regions where the Nb top layer get closer to the ground layer. Currently, a new study is been carrying out to planarize the ground-plane by filling the perforations with SiO_2 to avoid any RF effects due to discontinuities in the strip layer.

4. CONCLUSIONS

In this paper, we present the design and first measurements of a DSB fixed-tuned SIS mixer for APEX band 3 (385-500 GHz). The mixer design introduces novel components such as a waveguide probe with integrated bias-T, allowing to extract IF signals and to inject DC current, and an on-chip integrated LO injection circuitry employing a high-performance ellipse termination for the directional coupler idle port. All these components are fabricated together with the SIS junction and the tuning circuitry. The first measurements show perfect functionality of the LO injection over the entire mixer band 385-500 GHz, while we have measured a higher noise than the expected especially at the higher frequency band. The analysis of the measurements results point out to imperfections in the manufacturing of the chips, that produced weak links or cracks in the top Nb line and introduce extra parasitic inductance, which at these frequencies could affect the tuning circuitry considerably and therefore, increase the conversion losses of our mixer.

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