A 0.5 THz Sideband Separation SIS Mixer for APEX Telescope

R. R. Monje[1,*], V. Belitsky[1], V. Vassilev[1], A. Pavolotsky[1], I. Lapkin[1,2], V. Desmaris[1], D. Meledin[1], D. Henke[1] and D. Dochev[1]

[1]*Group for Advance Receiver Development with Onsala Space Observatory, Chalmers University of Technology, Gothenburg, Sweden*

[2]*Russian Academy of Science, Institute of Applied Physics, Russia*

* Contact: raquel.monje@chalmers.se

***Abstract*— We present the design and the experimental results of a fixed-tuned sideband-separating superconductor-insulator-superconductor (SIS) mixer for 385 - 500 GHz. The sideband separation is achieved using a quadrature scheme, where two separate DSB mixer blocks are combined with an intermediate waveguide component containing the LO waveguide distribution circuitry and RF waveguide hybrid. The intermediate waveguide piece is fabricated by using copper micromachining, which gives dimensions' accuracy better than 1 µm. The RF signal coming from the waveguide hybrid is coupled to the SIS junctions through an E-probe with integrated bias-T. We implemented an on-chip LO injection solution, where the LO coupler is integrated onto the mixer chip and fabricated together with the SIS junction and the tuning circuitry. The on-chip LO coupler is made as a combination of superconducting microstrip lines and slot-lines (branches), which gives almost a lossless solution. With the fabrication accuracy better than 0.5 µm by using optical lithography, the circuitry is proven to give a good performance following the simulations expectations.**

I. Introduction

The Atacama Pathfinder EXperiment (APEX) [1] is a radio telescope using a 12 m ALMA prototype antenna operating at the Atacama Desert on the Chilean Andes at about 5100 m altitude. 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 houses single pixel heterodyne receivers covering the frequency range of 211 GHz up to 1.5 THz.

The APEX single pixel heterodyne sideband separation receiver for 385 – 500 GHz (APEX band 3) is presented in this paper. The sideband separation is achieved using a quadrature scheme where the RF signal is divided equally with 90° phase difference through a 3 dB directional coupler, and the LO is symmetrically split by an in-phase power divider and fed to two identical double sideband (DSB) mixers. The intermediate frequency (IF) outputs from mixer 1 and mixer 2 are connected to quadrature 3 dB hybrid which enables the sideband separation, into upper sideband (USB) and lower sideband (LSB) signals, through phase cancellation. The sideband separation scheme can be better explained using the phase diagrams for USB and LSB presented in Figure 1. Sideband separation technology provides better sensitivity for spectral line observation than DSB [2]. 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.

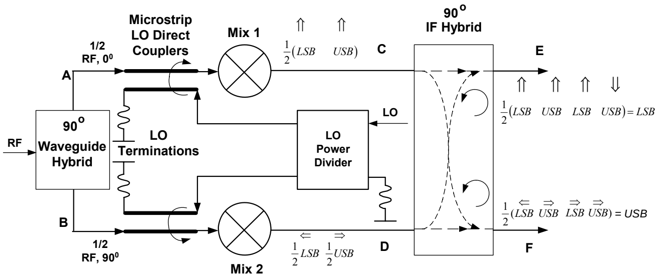

Fig. 1 Block diagram of a sideband-separating mixer. The signal vectors around every component illustrate principles of sideband separation.

Ultimately, the desired sideband separation receiver design would fully integrate all components, such as RF 3-dB hybrid, LO power divider, 16 dB coupler and SIS tuning circuit, onto a single chip. This very compact design would allow the reduction of overall receiver dimensions, being extremely important for multi-pixel array receivers or multi-channel receivers, such as the APEX or ALMA [3] receivers where several bands are integrated into a single cryostat making the space and cooling capacity critical. Furthermore, a single chip approach should facilitate fabrication and potentially improve the yield, since the chips can be done with lithography which would provide accuracy better than 1 µm. However, the drawback of this approach has been proven to be a challenge by increasing complexity and difficulty to identify the possible problems in the case of unexpected performance [4].

We propose a less complex sideband separation mixer design, yet still with the benefit from the combination of low-loss waveguide components with integrated on-chip solutions; as for example LO injection with a planar ellipse termination for the through port of the LO coupler.

II. Mixer Design

A. *Mixer Chip Design*

The mixer chip design for the frequency range of 385 – 500 GHz uses the on-chip LO injection design described in [5 - 6]. Therefore, both the RF and LO signals should be coupled from the waveguide to the microstrip propagating mode. For the RF probe we used the novel approach presented by [7], which consists of a waveguide-to-microstrip transition with integrated bias - T. The advantage of this probe comes from the fact that it couples the input waveguide signal to the SIS junction and tuning circuitry lines via and E-probe while having an isolated port at the opposite side of the substrate for the IF extraction and DC biasing. The RF probe is shaped in order to achieve a broadband matching and to obtain as low impedance as possible at the microstrip port. The LO signal is coupled from the waveguide to the chip by the use of a simpler waveguide-to-microstrip transition, see Figure 2.

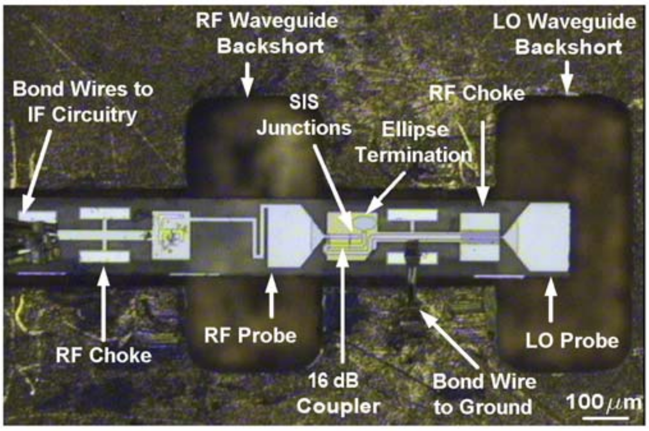

Fig. 2 Photograph of the mixer chip mounted into the mixer block in the back-piece layout.

Typical tuning circuits incorporate one or more microstrip transformer sections to match the characteristic impedance from the E-probe to the impedance of the active component. In this design we use a quarter wavelength transformer which also forms part of a 16 dB directional coupler to couple the LO signal into the RF signal.

The on-chip LO coupler is made with superconducting lines coupled via lumped links; two perforations forming skit-holes in the ground plane on the same SiO_2 dielectric (ε_r = 3.74) as the SIS junction and the RF tuning circuitry. The RF signal comes from the waveguide-to-microstrip probe and the LO signal comes from another probe on the other side of the mixer chip. One of the output signals goes to the SIS mixer and the idle port of the LO coupler is terminated with an elliptical termination [8]. The termination is made of resistive material by sputtering titanium mixed with nitrogen in order to reach the required resistivity.

The SIS junctions are made in-house using the Chalmers MC2 clean room facility. The designed Nb-AlOx-Nb SIS junctions have an area of 3 μm^2 and a normal resistance (R_n) of ~ 7 Ω. The design uses two junctions connected through a short line [9] equivalent to inductance, L_t, at RF. The junctions resulting complex impedance is designed to be real and is then matched to the RF source impedance.

B. *DSB Mixer Block*

The DSB mixer block consisting of the following elements: a mixer back piece that houses the mixer chip with the DC and IF circuitries, an intermediate piece containing the waveguides for the RF and LO signal injection, a magnetic coil with two magnetic concentrators, a diagonal LO horn and a corrugated RF horn (see Figure 3 left). This configuration enables the use of the same mixer back piece for both DSB and 2SB modes. The mixer back piece (Figure 3 right) and the intermediate piece are manufactured by direct milling (the split-block technique is used when machining the intermediate piece). The blocks are fabricated using copper-tellurium alloy, which has a similar conductivity to pure copper at room temperature but is easier to machine, and plated with a thin layer of gold (~ *2 μm*). Although gold has worse conductivity than copper, it facilitates bonding with gold wires and protects the blocks from corrosion.

For the Gaussian beam-to-waveguide converter at the RF side, a corrugated feedhorn is preferred since it provides wider bandwidth and a higher coupling efficiency. The feedhorn is coupled through a circular to full-height waveguide transition. For the LO side, a diagonal horn was used instead, since the coupling efficiency is not so critical and they are easier to manufacture, allowing in-house fabrication.

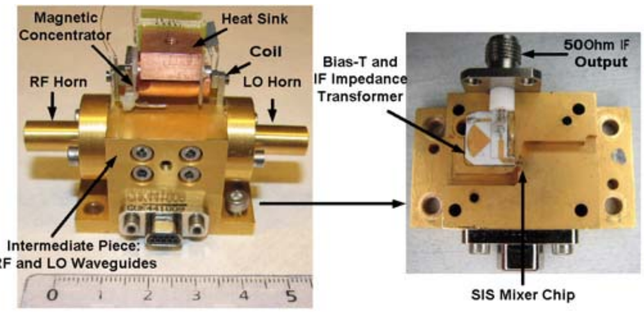

Fig. 3 The left picture shows the DSB mixer block. Two magnetic iron concentrators guide the magnetic field from an external coil to the vicinity of the junctions. On the right, the mixer back piece is pictured, containing the mixer chip, the bias-T with 20 to 50 Ohm transformer and the DC circuitry in the back side; this piece is compatible with the 2SB mixer.

For the suppression of the Josephson Effect a magnetic coil extracted from a commercial relay with approximate number of turns around 10,000 was used. The coil is thermally isolated from the mixer block through a fiberglass bracket, and furthermore, the coil was embedded into a copper block that was thermally connected to the 4 K plate to sink any heat generated by the coil. The magnetic field is guided from the coil to the SIS junctions through two iron magnetic field concentrators.

The mixer chip with dimensions 1200 x 150 x 65 μm^3, was placed on a suspended microstrip channel and glued to the mixer block through a non-conductive wax. This approach gave the advantage of shorter overall waveguides since the mixer back piece housed only the mixer channel and the waveguide backshorts. One bond wire connected from the mixer block to the RF choke provides DC ground, as shown in Figure 2, and several bond wires connect the mixer chip to the IF/DC circuitry. The DC circuitry for the SIS biasing is placed on the backside of the mixer block.

C. 2SB Mixer

The sideband separation mixer was built with two mixer back pieces described in previous section, being common for the DSB and 2SB designs, and an intermediate piece. On the contrary to the DSB mixer, the intermediate waveguide piece contains the LO in-phase power divider and the 3 dB 90-degree waveguide RF hybrid in order to achieve sideband separation using the quadrature scheme. Similar to the DSB receiver, the mixer block was fabricated using Copper-Tellurium alloy. The intermediate piece was fabricated using micromachining, a novel approach developed at GARD. This innovative technique combines photolithography with electroplating to fabricate the waveguide structure, providing an accuracy better than 1 μm [10–11].

Figure 4 illustrates the 2SB receiver assembly; note that the top mixer back piece is a mirrored version of the bottom mixer block. Hence, the SMA connectors face the same side and this configuration provides a more compact IF chain, optimizing the space inside the dewar.

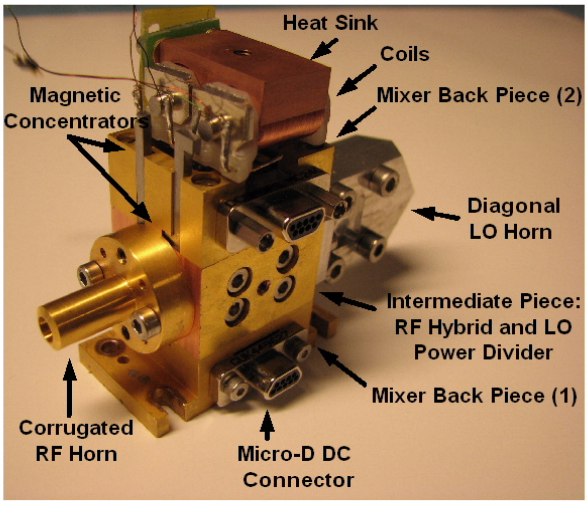

Fig. 4 The 2SB mixer block consists of two mixer back pieces, where the mixer chip is placed together with the DC input and IF output, and two intermediate pieces, containing the LO power divider and the RF 3dB 90° hybrid.

III. Results

This section presents the measurement configuration and experimental results for the noise temperature and sideband rejection of the sideband separation mixers, over the frequency ranges of 385 – 500 GHz, corresponding to APEX band 3.

A. Receiver Characterization

Figure 5 shows a photograph of the laboratory test cryostat, a liquid helium Oxford Instrument cryostat, used for our measurements. The measurement setup contains both warm and cold components. Internal to the dewar, the cold items include the DSB or SSB mixer, the optical components (lens, IR filter, windows), isolator, low noise amplifier (LNA), thermal links to provide necessary cooling to low temperature to all components and stainless steel coaxial cables. The warm components are a room temperature amplifier, a filter (when necessary) and the IF power detector.

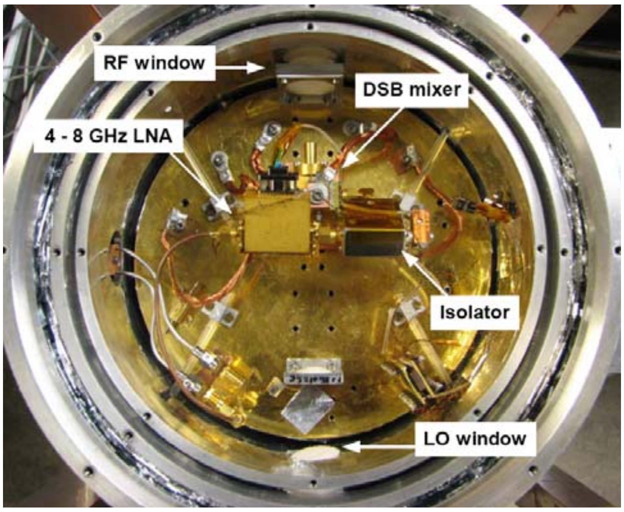

Fig. 5 View of the DSB receiver installed in the cryostat

The mixer is attached to a copper support that ensures optical alignment with the cryostat windows and good thermal contact with the 4.2 K plate. A corrugated feedhorn, followed by a cold Teflon lens with a focal distance of *25 mm*, provides the desirable coupling of the RF power. The cryostat vacuum windows, for both RF and LO, are made of 1.5 mm high density polyethylene (HDPE) with an anti-reflecting grooved surface optimized for these frequencies. Infrared filters made of 200 μm Zitex placed on the 77 K stage, minimize radiative thermal coupling through the windows.

The local oscillator is an x36 frequency extension module from VDI giving an average output power across the band around 0.6 mW (-2.22 dBm). The local oscillator is coupled quasioptically to minimize the power loss.

B. Measurement of Receiver DSB Performance

The noise temperature measurements were performed with the standard Y-factor technique using a hot (293 K) and cold load (77 K) placed in front of the RF window. Figure 6 shows the measured receiver noise. The measurements give an equivalent DSB receiver noise temperature within 5 to 9 quanta across the band of interest. For local oscillator frequencies between 370-400 GHz the noise temperature is within 80-150 K. The upper side of the LO frequency band 410-480 GHz presents a noise temperature in the range of 180-210 K. There is a rapid increase in the noise for LO frequencies above 480 GHz.

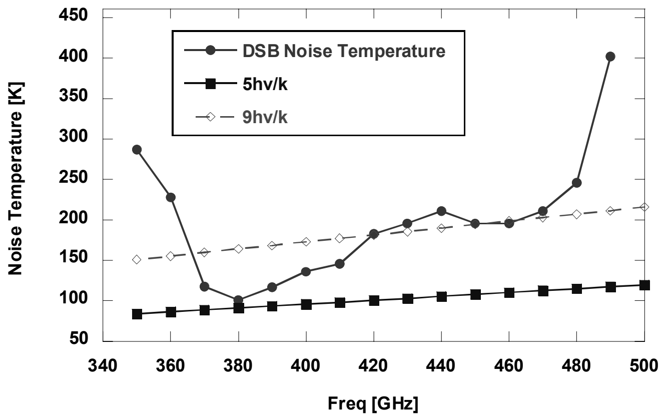

Fig. 6 DSB receiver noise temperature

C. 2SB Measurement Results

After completing the DSB tests, and selecting two chips with similar performance, the two blocks were then used to construct the sideband separating receiver assembly. Figure 7 shows the single sideband noise of the receiver. The 2SB noise temperature is consistent with the DSB noise measurements for the lower band of the LO frequency (370 – 420 GHz). At the frequencies where the 2SB noise is greater than twice the DSB noise temperature of the individual mixer blocks, this may indicate a dependence on the RF loss in the waveguide hybrid and added IF noise due to the additional components required for sideband rejection, such as the IF hybrid.

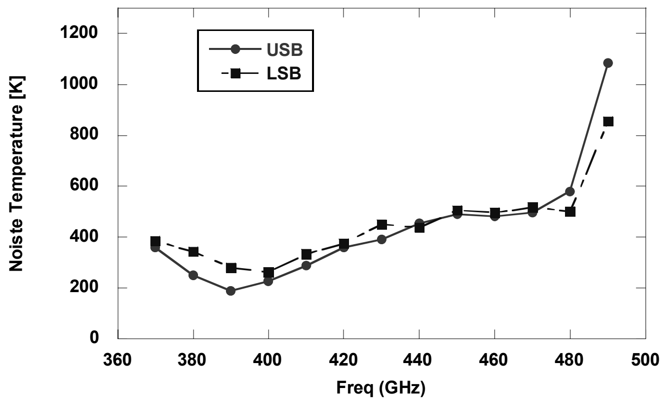

Fig. 7 2SB receiver noise temperature for the upper and lower sideband.

The sideband ratio of a receiver can be measured by injecting a continuous wave (CW) signal into the upper and lower sidebands and measuring the IF response at each band. Since we can not accurately determine the amplitude of the CW signal, the conversion gains of the sidebands can be determined using an interfering source (of unknown amplitude) and measuring the resulting power ratios, combined with hot/cold measurements, as described in [12]. Ideally, the sideband ratio is infinite however in practice cases the ratio is on the order of 10 dB. Figure 8 shows the sideband separation ratio for this receiver. It can be seen from the figure that the rejection ratio is typically worse for one of the sidebands outputs (USB). However, if we take only the LSB output, results are better than 10 dB for most of the band with the worst cases better than 7 dB otherwise.

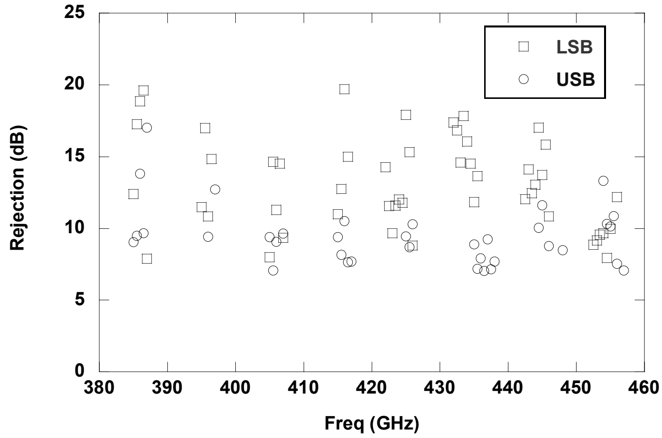

Fig. 8 Corrected sideband rejection ratios for the USB and LSB.

CONCLUSIONS

In this paper, we present the design and first measurements of a 2SB 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 demonstration of all these new technologies was achieved via successful mixer measurements resulted with competitive double sideband and sideband separation noise temperature better than 180 K and 400 K, respectively, measured at the center frequency 442 GHz. Furthermore the sideband separation mixer presents a rejection ratio better than 10 dB for most of the band.

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