Performance of a 230 GHz Finline SIS Mixer With a Wide IF Bandwidth

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***Abstract*—Here we present the design and performance of a novel unilateral finline Nb-AlO$_x$-Nb SIS (Superconductor-Insulator-Superconductor) mixer, operating around 230 GHz, with a target IF bandwidth of 2-13 GHz. The mixer is intended to be used in GUBBINS [1], a prototype high brightness sensitivity, low spatial resolution heterodyne interferometer. A key feature of the mixer design is the use of a unilateral finline taper to provide a smooth transition from high-impedance waveguide to low-impedance microstrip suitable for feeding a 1μm^2 SIS junction. The use of a finline transmission line allows other complicated planar circuits to be compactly integrated on the substrate and allows the use of an easy-to-fabricate mixer block. Also the employment of the silicon substrate allows trenches to be fabricated around individual SIS mixer devices on the wafer, allowing the devices to be separated easily without dicing. To realise the wide IF bandwidth, a separate IF matching board, consisting of a few sections of microstrip, was designed to match the dynamic output impedance of SIS mixer to the LNA.**

In this paper, the SIS mixer design will be described in detail, including the electromagnetic simulations of the passive circuit with HFSS. We have fabricated and tested several of these SIS mixers over RF bandwidth 190-260 GHz. We have obtained a best noise temperature of 75 K at 208.8 GHz over IF bandwidth 4-6 GHz. However, the noise temperature measured across IF bandwidth 2-18 GHz shows that an IF resonance exists around 8 GHz, caused by an excess capacitance due to the large surface area of the microstrip transition and RF matching circuitry. An improved design is described, suitably modified to shift the IF resonance out of the target IF band.

I. Introduction

SIS heterodyne receivers have been successfully used for radio astronomy in the millimeter and sub-millimeter band for many years. They can offer quantum-limited noise temperatures (a few times $h\nu/k$) and mixer conversion gain [2], but many designs are limited to an IF bandwidth of a few GHz. For most astronomical applications, it is desirable to have as wide an IF bandwidth as possible. This is true for both extragalactic molecular line observations and CMB continuum observations. For spectroscopic observations wide IF bandwidths allows multiple spectral lines to be included in a single observation, while for continuum sources, wider IF bandwidths enable higher brightness sensitivities. We intend to use our wide IF band SIS mixers as detectors for the GUBBINS interferometer which is designed to carry out observation of the Sunyaev-Zeldovich (S-Z) effect near the null frequency of around 227 GHz. GUBBINS is now under construction at the University of Oxford [1].

The SIS mixer described here is based on a previously reported antipodal finline SIS mixer design [3], [4]. This mixer, however, features a new unilateral finline and is fabricated on a silicon substrate. The finline taper used here provides a smooth transition from the high-impedance waveguide to low impedance, 2.5μm wide slotline over a wide RF bandwidth with low return loss (<-15dB). A planar circuit then couples the RF power from the slotline to a microstrip line which couples RF power to the SIS junction.

There are a number of key problems which need to be solved when designing an SIS mixer with a wide IF band. For the double-sideband (DSB) SIS mixer, the mixer needs to have an RF bandwidth at least twice as wide as the IF bandwidth so that both the signal and image sidebands, either side of the LO frequency can be downconverted efficiently to IF frequencies. If the frequency of the top end of the IF band is high enough i.e. a substantial fraction of the RF frequency, extra circuitry is required to prevent the IF signal from leaking into the RF circuit. In particular, the planar circuit of the SIS mixer must be carefully designed to present a low capacitance over a large IF band, to allow an IF transformer circuit to adequately match the dynamic impedance of the mixer to the input impedance of the first-stage cold LNA.

II. SIS mixer design

The SIS mixer chip, showing the RF and IF components, is displayed in Fig.1. A 1μm^2 Nb/AlO$_x$/Nb high current density (14KA/cm^2) SIS tunnel junction is employed, with $\omega R_n C \approx 2$ at 230 GHz. A target normal resistance of 20 Ω was chosen, with a characteristic capacitance of 75 fF. The planar circuit for the mixer is deposited on one side of a 60 μm thick silicon substrate. A schematic diagram of the planar circuit is shown in Fig. 2. The unilateral finline can be seen at the centre of the substrate, partially terminated by a radial stub. The extension of the finline layer acts as the ground plane for the following microstrip circuits, with 490 nm of silicon monoxide acting as an insulating layer.

The RF radiation is coupled into the device via a spline horn [5] attached to the waveguide port of the mixer block. The Nb b

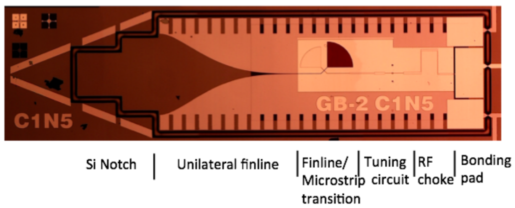

Fig. 1. Overview of a 230 GHz unilateral finline mixer, showing the planar circuits including the finline transition, slotline-to-microstrip transition, tuning circuit and RF choke, deposited on a 60 μm silicon substrate.

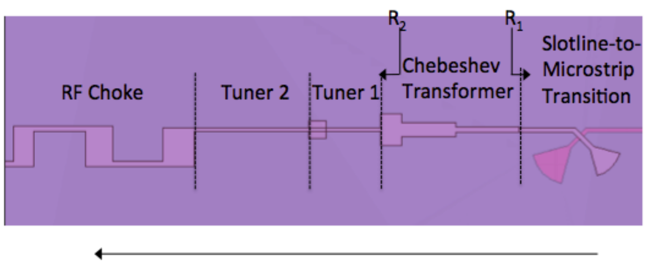

Fig. 2. Magnified view of the broadband power coupling and tuning network around the SIS junction, consisting of a Slotline-to-Microstrip Transition, a Chebyshev Transformer, Tuner1, Tuner2 and an RF Choke.The arrow indicates the power propagation direction.

unilateral finline, transmits the RF signal from the waveguide mode, to the slotline line mode with low return loss over an RF bandwidth of 100 GHz, centred at 230 GHz.

The unilateral finline intrinsically has a cutoff frequency above the IF frequency along the whole finline transition. This prevents the IF signal leaking into the finline transition and thus no RF bandpass filter is required between the finline and the tuning circuit. Compared with antipodal finline [4], the total length of the unilateral finline is much smaller, with no sacrifice of the IF or RF performance. The reduced length of the unilateral finline reduces the capacitance between the finline metalization and the waveguide groove, which is desirable when designing a mixer with a wide IF bandwidth.

The profile of the unilateral finline was designed using the transverse resonance technique in conjunction with the optimum taper method, as described in [6]. The slotline width is reduced smoothly from the waveguide width to 2.5μm to match to the characteristic impedance of the following microstrip line (20-30Ω), where the SIS junction is embedded. The optimum taper method [6], allows the length of the finline taper to be kept as short as possible, without limiting the RF bandwidth. The profile of the finline was further verified in Ansoft's 3D electromagnetic simulation software, HFSS, including the effect of the superconductivity of the Nb film. A two-stage notch in the substrate is employed

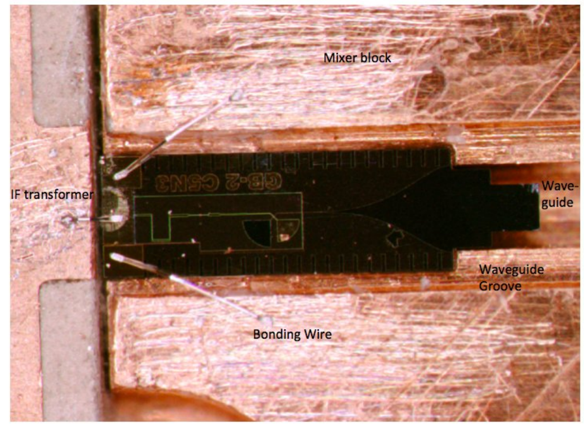

Fig. 3. The SIS mixer chip mounted in the WR4 waveguide, supported by grooves on either side of the waveguide. The SIS mixer is connected to the IF transformer by 25μm diameter aluminium wires. The mixer block provides a ground connection to the device via bonding wires at either sides of the device.

(Fig.1), to minimise the impedance mismatch between the empty waveguide and the waveguide loaded with the silicon ($\epsilon_r = 11.8$)) substrate.

The mixer device is mounted in the E-plane of a WR-4 rectangular waveguide, supported by grooves on either side of the waveguide. As shown in Fig.1, serrations of length $\lambda_g/4$ are added to both sides of the finline to provide a virtual RF short for the finline to the waveguide walls [3]. The RF signal is then coupled from the 2.5μm slotline, to a 2.5μm microstrip by employing a double radial-stub fabricated across the dielectric layer. On top of the 2.5μm slotline which terminates the finline transition, a 490 nm SiO insulating layer and a 2.5μm microstrip line is deposited. This allows the RF power to be directly coupled from the slotline to the microstrip line, via the SiO layer (see the 'Finline/Microstrip Transition' section in Fig.1). To optimise the coupling, the microstrip stub is terminated by an open-ended quarter-wave radial stub, while the slotline stub is terminated by a short-ended quarter-wave radial stub. So at the crossing point, the slotline stub ends up as an open circuit, whilst the microstrip ends up as a short circuit. This design forces the RF signal to propagate from the slotline to the microstrip with minimal mismatch loss. At the crossing point, the minimum width of both the microstrip and the slotline, fabricated using photolithography, is only 2.5μm. If the width can be further reduced, better coupling can be obtained since the characteristic impedance between the slotline and the microstrip becomes more closely matched.

The RF signal is coupled from the 2.5 μm width microstrip to the SIS junction (shown as a square in Fig.2) via a series of RF transformers. Two inductive stubs, labelled "Tuner 1" and "Tuner 2" in Fig.2, lie before and after the SIS junction. These stubs are designed to tune out the junction capacitance

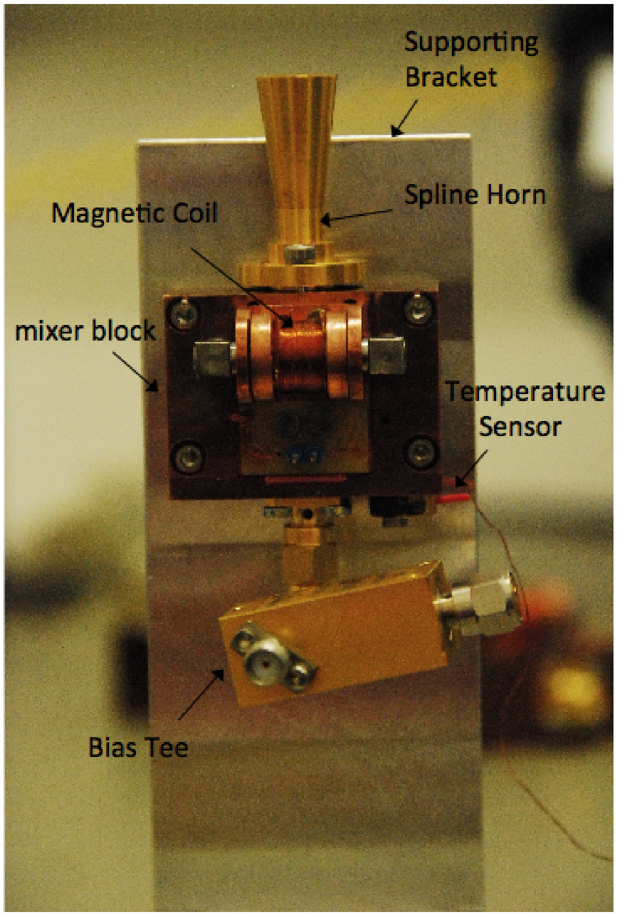

Fig. 4. Assembly of the mixer block, fed by a spline horn. It is equipped with magnetic coil, bias tee, temperature sensor and is bolted to a supporting bracket.

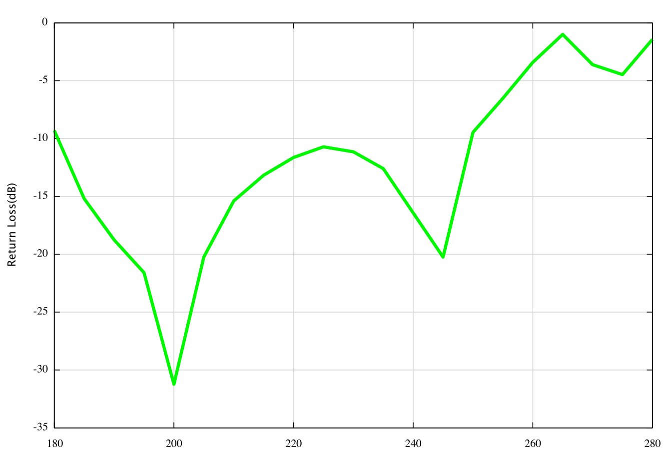

Fig. 5. HFSS calculated S-parameter as a function of RF frequency.

at two slightly different frequencies either side of the centre frequency, thus broadening the RF bandwidth. Also, compared to a radial-stub tuning circuit [7], the straight-stub tuning used here has a smaller surface area and hence smaller capacitance, which makes it easier to achieve a broader IF bandwidth. The port impedance Z_1 has a substantial mismatch with the port impedance Z_2, denoted in Fig.2. Thus we employ a 3-stage Chebyshev transformer to minimise the mismatch between them. Fig.5 shows the calculated S-parameter for the full SIS mixer chip in RF band, given by HFSS.
A six-step RF choke follows the tuning circuit, blocking the RF power over a wide RF bandwidth, while providing maximum transmission in the IF band. 'Tuner 2' also acts as part of the RF choke. The IF power from the RF choke is transmitted to the IF bonding pad, at the rear of the device. On either side of the IF bonding pad, there are two ground bonding pads to provide ground contact to the mixer block. These bonding pads are gold sputtered to prevent the Nb layer from oxidising. The IF pad is connected to an IF transformer circuit, fabricated on 0.635mm thick Roger's Duroid 6010LM, through one or two 20μm diameter aluminium bond wires.

A multi-stage impedance matching transformer is incorporated onto the IF board to match the IF output impedance of the mixer to the 50Ω input impedence of the IF amplifier. The design process for the IF transformer is as follows:

1) Obtain the S-parameter data in the IF band for the mixer chip's planar circuit before and after the junction, also including the IF bonding pad.
2) Represent the mixer chip as an RLC equivalent circuit at IF frequencies in Ansoft Designer, using the S-parameters obtained in step (1). Obtain the output impedance from the IF output port.
3) Design an IF impedance matching circuit from the complex output impedance obtained in (2), to a purely real 50Ω impedance. Constrained by the available size of the pocket for the IF board in the mixer block, a six-stage microstrip line IF transformer was employed. The first two stages tune out the capacitance at slightly two different frequencies and the left four stages act as a Chebyshev transformer to match the resistance. The overall IF transformer is then further optimised in Ansoft Designer to obtain the best performance.

The mixer block for housing the SIS mixer chip was fabricated in Arizona State University and is shown in Fig.4. Inside the block, the SIS mixer sits in the E-plane of the waveguide, supported by the grooves by either sides of the waveguide, which are recessed in the lower half of the block. The SIS mixer is fed by a spline horn [5], attached to the input port of the waveguide. The magnetic field, used to suppress Josephson pair tunnelling of the SIS junction, is provided by a magnetic coil mounted on the top half of the mixer block. The DC bias voltage is supplied to the SIS mixer, by a bias tee, connected to the IF transformer board via a standard SMA connector.

III. Experimental description and results analysis

The apparatus used for the RF testing of the SIS mixers is shown in Fig.6. Outside the dewar, the RF and LO signal were combined together using a partially reflecting Mylar beamsplitter. The Y-factors for the mixer were measured using using hot (300 K) and cold (77K) Eccosorb loads. The IF signal was amplified by a 3-13 GHz 4K lnP LNAs (Low Noise Amplifier) supplied by S. Weinreb (batch number: 111-CIT-4254-077). and further amplified by a warm (300K) amplifier chain. The amplified IF power is then detected by a diode detector.

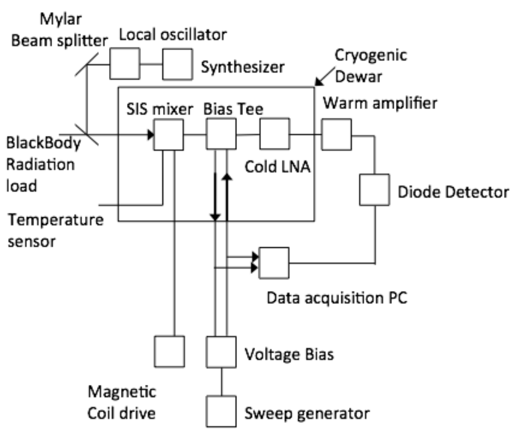

Fig. 6. Experimental setup used for measuring the mixer performance.

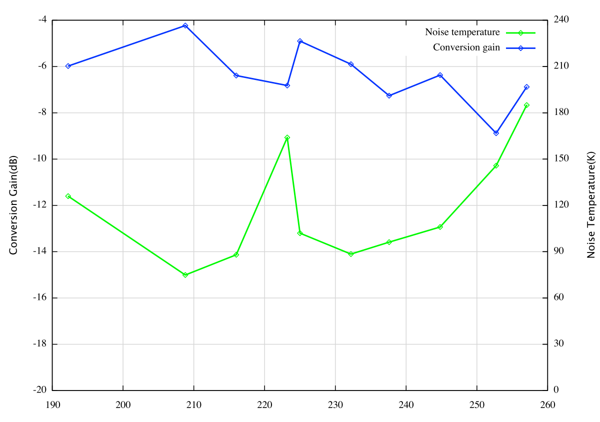

Fig. 7. The measured noise temperature and gain as a function of RF frequency. Note the double-dip shape of the noise temperature profile, consistent with the tuning circuit design.

The measured DSB noise temperature and gain across RF range in IF band 4-6 GHz is shown in Fig.7, as a function of RF frequency between 192-263 GHz. The SIS mixer was easily pumped by the LO to saturation, with the LO and RF signal combined by a 8μm Mylar beamsplitter. The noise temperature/gain results presented here were measured with

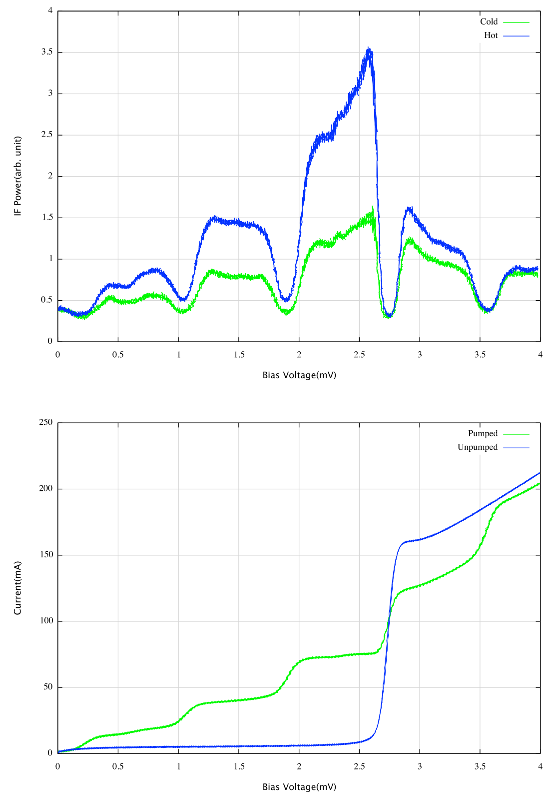

Fig. 8. The IV and IF characteristic of the SIS mixer tested with LO injection at 208.8 GHz.

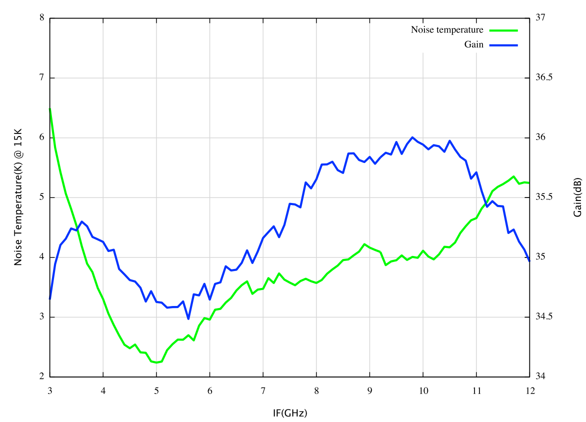

Fig. 9. The expected noise temperature and gain of the LNA @ 15K, as a function of IF frequency [8].

a 12 μm beamsplitter. We obtained a best noise temperature of 75 K at 208.8 GHz and an average noise temperature of 100 K across the RF band 190-260 GHz, presented in Fig.7. In the upper frame of Fig.8, we have plotted the IF output under the hot and cold radiation with LO injection at 208.8 GHz, as a function of DC bias voltage, used to calculate the Y-factor and the noise temperature. In the lower frame, we have show the corresponding pumped and unpumped IV curves. The measured IF noise temperature contribution is approximately 9K, slightly higher than expected from the

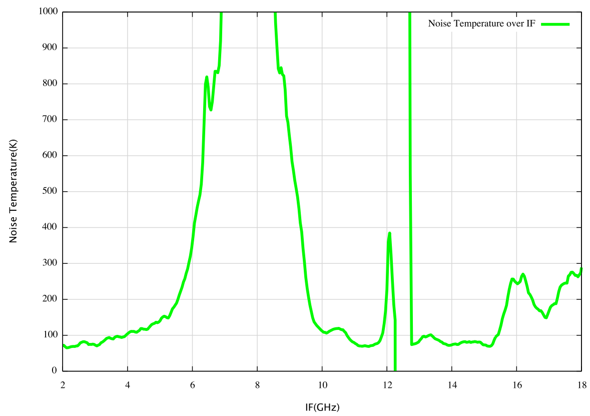

Fig. 10. The measured noise temperature of the SIS mixer, with LO injection at 208.8 GHz, as a function of IF frequency, measured using a spectrum analyzer.

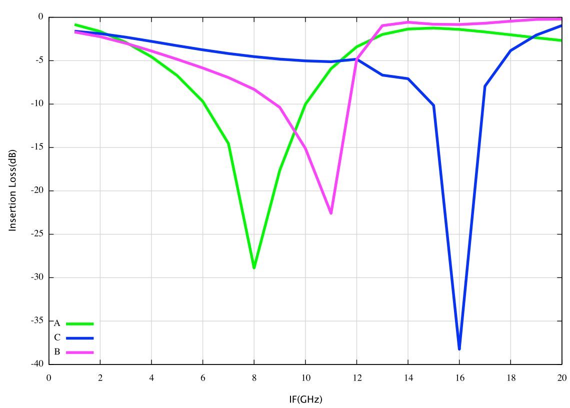

Fig. 11. The insertion loss of the full SIS mixer, simulated by HFSS, across the IF band. The letters denote various stub designs: (A) 90° microstrip stub with a 90° slotline stub with unchanged radius, (B) 60° microstrip stub and 60° slotline stub with unchanged radius, (C) 60° microstrip microstrip stub and 60° slotline stub with the radius cut by 40%.

manufacturer's supplied data for the LNA, shown in Fig.9. The noise temperatures measured are above the state-of-art performance for SIS mixer operating around 230 GHz. We suspect that the noise performance above 240 GHz is being degraded by noise added by unwanted sidebands being generated in our $\times 18$ LO source. Another reason for the elevated noise temperatures is the presence of an IF resonance at 8 GHz, which leads to the noise temperature being elevated in part of the band (5.5–6 GHz) defined by our IF bandpass filter (see below and Fig.10).

All the noise temperature and gain measurements presented above were obtained using a bandpass filter to constrain the IF detection bandwidth to 4-6 GHz. The noise temperature was also measured as a function of IF frequency, without a bandpass filter, using a spectrum analyser (Fig. 10). The noise temperature deteriorates severely in a 4 GHz wide region, centred around 8 GHz. The HFSS simulation reveals that the IF return loss at 8 GHz becomes 0dB for the SIS mixer. This is caused by an IF resonance being formed by a combination of

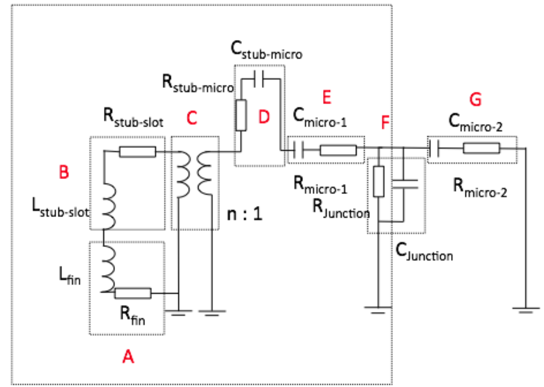

Fig. 12. RLC equivalent circuit representing the SIS mixer in the IF band. The circuit components outlined correspond to the following elements of the mixer chip's planar circuit (A) the unilateral finline, (B) the radial slotline stub, (C) the slotline-to-microstrip transition, (D) the radial microstrip stub, (E) 'Chebyshev transformer' and 'Tuner 1', referred to Fig.2, (F) the SIS tunnel junction, (G) 'RF choke' and 'Tuner 2', again referred to Fig.2

the unilateral finline, the slotline-to-microstrip transition, part of the RF tuning circuit and the SIS junction. In the IF band, the wavelength is much longer than the physical dimensions of the planar circuit, which allows us to treat these planar circuits as simple lumped elements. The LRC equivalent circuit, illustrating the resonant circuit is shown in Fig.12. The planar circuits enclosed in the large dotted frame constitute the resonant circuit. The SIS junction shares the same ground with the unilateral finline, so a closed loop is formed between the finline and the SIS junction, whose resonant frequency accidentally falling between 3-13 GHz. The planar circuit after the SIS junction and the capacitance of the SIS junction do not form part of the resonant circuit. The capacitance is contributed by all the microstrip transmission lines, mainly the large-area of the 90° radial stub. The inductance arises from the slotline structures, e.g. the unilateral finline and the slotline radial stub. The resonant frequency is given by,

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where, referring to Fig.12,

$$L = L_{stub-slot} + L_{fin} \quad (2)$$

$$C = C_{stub-micro} + C_{micro-1}. \quad (3)$$

We can thus conclude that the large area of the 90° microstrip stub and the 90° slotline stub is mainly responsible for the 8 GHz resonance. It shorts out the IF signal generated by the SIS junction at 8 GHz, resulting the IF output resistance at 8 GHz approaching zero, which cannot be matched by the IF transformer.

IV. Design Modification

Given the problems of the IF resonance described in the last section, the design was modified aiming to shift the 8 GHz

IF resonance to a higher frequency. According to Eq.1, this can be easily achieved by decreasing L and C. However, the RF coupling in the slotline-to-microstrip transition is a strong function of the radius of the stubs, which provide the best coupling with a radius of $\lambda_g/4$. So, while carefully balancing both the IF and RF performance, the radii of the stubs were reduced by 40% and the angles were reduced to 60°. The total area and hence capacitance of the microstrip and slotline stubs were thus reduced by 76%. From Eq.1, the resonant frequency will thus be doubled to around 16 GHz.

Our expected shift in the IF resonant frequency was confirmed by a full HFSS simulation, shown by the blue curve in Fig.11. The IF resonant frequency is seen to be shifted to 16 GHz, as expected. Minor changes were made to the tuning circuit and the Chebyshev transformers, to improve the matching to the modified slotline-to-microstrip transition. The SIS mixer was re-simulated in HFSS in both the IF and RF band, and the results are shown in Fig.13. The IF performance in Fig.13 was calculated, combining the SIS mixer with the 6-stage IF transformer board, used to matching the dynamic output impedance from the mixer chip to the LNA.

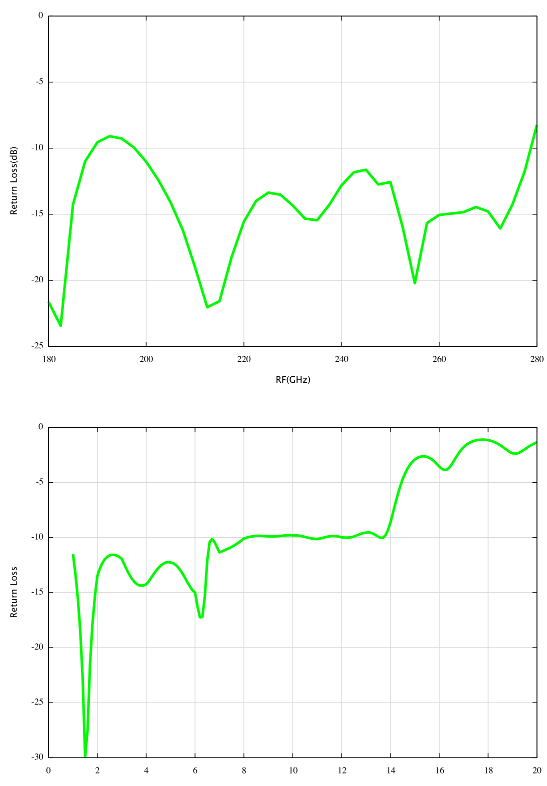

Fig. 13. Top: HFSS calculated S-parameters for the modified SIS mixer in RF band 180-280 GHz. Bottom: HFSS calculated S-parameter for the modified SIS mixer in IF band 0-16 GHz. An 6-stage IF transformer is included here to provide good IF matching between 0-14 GHz.

V. Conclusion

The design and measurement of a unilateral finline SIS mixer, operating around 230 GHz, has been described. The design features a unilateral finline which gives broad RF bandwidth. The passive superconducting components have been rigorously simulated using the 3-D electromagnetic simulator HFSS and planar circuit simulator Designer. The measured noise temperature in the RF band were found to be compatible with these simulations. The noise temperature was found to be degraded by an IF resonance around 8 GHz, caused chiefly by the excessive capacitance of the microstrip/slotine radial stubs. The measured IF performance was found to be consistent with a lumped element simulation of the IF circuitry. The initial design was then improved by reducing the surface area of microstrip/slotline stubs, shifting the IF resonance frequency to 16 GHz away from the centre of the target IF band. We hope to fabricate and test a new batch of mixers using the improved design in the near future.

References

[1] P.K.Grimes, M.J.R. Brock, C.M.Holler, J.John, M.E.Jones, O.G.King, J.Leech,A.C.Taylor, G.Yassin,K.Jacobs and C.Groppi, ”GUBBINS: A novel millimeter-wave heterodyne interferometer”, 20_th *International Symposium on Space Terahertz Technology*, Charlottesville, 20-22 April 2009

[2] M.J.Feldman, ”An Analytic Investigation of the Superconductor Quasiparticle Mixer in the Low Power Limit”, *Accepted IEEE trans, Magn, Univ. of Rochester, Rochester NY 14627*, Charlottesville, 20-22 April 2009

[3] G.Yassin, R.Padman. S.Withington and K.Jacobs ,”A broad band antipodal finline mixer for astronomical imaging arrays”, *Electron Lett.*, vol.33,pp 498-500,1997.

[4] Paul K.Grimes, Ghassan Yassin, Karl Jacobs, and Jamie Leech ,”Design of SIS finline mixers with ultra-wide IF bands”, *Electronics letter*, 3rd July 2008, Vol.44, No.14

[5] Granet C., James G.L., Bolton R. and Moorey G., (2004) “A smooth-walled spline-profile horn as an alternative to the corrugated horn for wide band millimeter-wave applications” IEEE Trans. Antenna Propagat., 52(3), pp. 848-854

[6] G.Yassin, P.K.Grimes, O.G.King and C.E.North ”Waveguide-to-planar circuit transition for millimetre-wave detector”, 17_th *International Symposium on Space Terahertz Technology*, Paris, 10-12 May 2006

[7] C.North, G.Yassin, and P.Grimes, ”Rigorous Analysis and Design of Finline Taper for High Performance Millimeter and Submillimeter Detectors”, 17_th *International Symposium on Space Terahertz Technology*, Paris, 10-12 May 2006

[8] S. Weinreb, Private Communication.