Design of SIS finline mixers with ultra-wide IF bands

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***Abstract*— We present the design of a 230 GHz finline SIS mixer with a 2-20 GHz IF bandwidth. The mixer is intended for use in a prototype high brightness sensitivity, low spatial resolution heterodyne interferometer currently under construction at Oxford[1]. The sensitivity of the instrument will be sufficient for measuring the spectrum of the Sunyaev-Zel'dovich effect in the brightest galaxy clusters.**

The mixer design is based on a previously reported 230 GHz finline mixer design[2], with a number of improvements and features added to achieve the very demanding IF bandwidth requirements. An RF bandpass filter is included on the chip to isolate the IF signals from the finline transition, and the mixer tuning circuits, RF choke and IF connections have been carefully designed to exhibit very low parasitic reactances in the IF band.

The first two batches of these mixers were recently fabricated at Cologne University, and are currently being tested.

I. Introduction

SIS mixers now routinely achieve noise temperatures of a few times the quantum limit in the mm-wave band. It is therefore difficult to make significant improvements in SIS millimetre receiver sensitivity by improving the noise temperature. However, the performance of SIS receivers can be improved in a number of other ways, such as the use of sideband separation, improvements in stability and the construction of large arrays of mixers.

For observations of continuum sources, the sensitivity of a receiver does not depend on the raw noise performance only, but also on the available instantaneous bandwidth over which detected power is integrated. The instantaneous bandwidth of heterodyne receivers is defined by their IF bandwidth. Increasing the IF bandwidth may also be useful for spectroscopic observations, as it allows the simultaneous observation of several spectral lines and with a wider range of Doppler shifts. Wider IF bands can also provide more data for determining baseline signal levels.

SIS mixers have traditionally had relatively small IF bandwidths (e.g. 4.2-5.8 GHz for SIS receivers on the JCMT) although wider IF bandwidths are now being used on newer instruments (e.g. 4-8 GHz for the HIFI instrument on Herschel and 4-12 GHz for ALMA). This is because a number of key problems have to be solved in designing mixers with very wide IF bandwidths.

Each of the sidebands have bandwidths equal to the IF bandwidth, and so the RF signals must be well coupled to the mixer over a relatively large frequency range. The SIS junction must see a reasonably constant embedding impedance throughout the IF band, and IF signals can not be allowed to leak into the RF feed when the IF frequency becomes a significant fraction of the RF. The IF signals must be efficiently coupled from the mixer chip to an IF amplifier with good performance over a large fractional bandwidth. Other IF components, such as bias tees, must also have good performance over large fractional bandwidths. Finally it is necessary that the backend electronics can handle the large bandwidth signals output by the receiver.

We have designed a finline SIS mixer with an RF bandwidth of 185-275 GHz and a target IF bandwidth of 2-20 GHz. This mixer will be used in our prototype interferometer GUBBINS, described in these proceedings [1].

II. Mixer Design

The mixer chip described in this paper is based on a design that has been described previously [2], with the following significant modifications to allow the ultra-wide IF bandwidth:

(i) An RF bandpass filter has been added to block the IF signal from the finline taper. This is necessary because the top end of the IF band is higher than the cutoff frequency of parts of the finline taper. (ii) The IF connection has been optimised to minimise the reactance of the IF bondwires, and (iii) a multi-stage microstrip IF transformer is used to match the IF output of the mixer to the input of the IF amplifier.

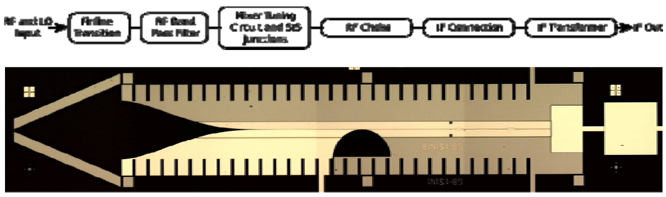

Fig. 11. (Top) circuit components making up the ultra-wide IF band finline SIS mixer. (Bottom) photo of an ultra-wide IF band finline SIS mixer chip prior to dicing and mounting in the mixer block. Apart from the finline taper, left, and the IF bond pads, right, the circuit components are too narrow to be seen in the photo.

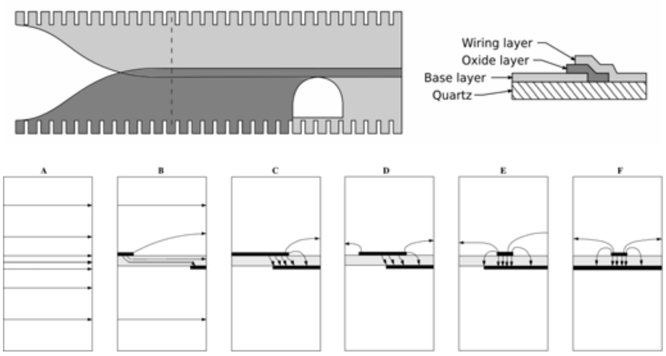

Fig. 12. (Top) Schematic of the modified antipodal finline taper used on these mixers. (Bottom) Cross-sections through an antipodal finline transition, showing E-field lines. **A** Loaded waveguide. **B** Unilateral finline section. **C** Antipodal finline section. **D** 1st half of circular finline to microstrip transition. **E** 2nd half of circular finline to microstrip transition. **F** Output microstrip.

The mixer is fabricated on 225 µm thick Infrasil fused quartz and uses a 200/10/100 nm thick Nb-AlO$_x$-Nb trilayer, a 425 nm thick SiO dielectric evaporated in two layers with a dielectric constant $\varepsilon_r = 5.8$ and 400 nm thick Nb wiring layer.

A schematic of the components on the completed mixer chip are shown in Fig. 11. In the rest of this section we shall describe the details of the mixer components.

A. Finline transition

An modified antipodal finline transition [3] is used to couple RF power into the mixer chip. The antipodal finline taper transforms the waveguide mode into the TEM microstrip mode using overlapping superconducting niobium films, separated by 425 nm of silicon monoxide. The taper is deposited on a 180 µm quartz substrate which supports the structure in the E-plane of a rectangular waveguide. Before the fins overlap, the taper acts as a unilateral finline since the oxide is much thinner than the quartz substrate. When the fins start to overlap it behaves like an antipodal finline, and when the overlap becomes larger than the oxide thickness the transition to microstrip is performed using a semicircular taper. A schematic of the tapering is shown in Fig. 12.

The mixer chip is mounted in the E-plane split mixer block, supported by grooves in the waveguide wall. Quarter wavelength serrations are added to each side of the finline to prevent RF power propagating in the grooves. These serrations provide a virtual RF short for finline at the waveguide wall, while allowing the mixer chip to remain DC isolated from the mixer block.

The finline taper is designed in several sections. The approximately unilateral section (before the fins overlap) was designed using the transverse resonance technique in conjunction with an optimum taper method, as described in [4].

The overlapping fin section is designed using HFSS simulations to calculate the wave impedance as a function of fin overlap and then using an impedance tapering method to synthesize the taper. A similar technique is used to taper the fin overlap and microstrip width in the semicircular transition from antipodal finline to microstrip.

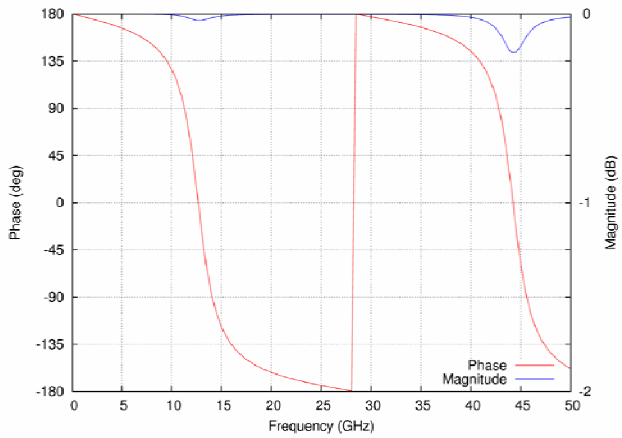

Fig. 13. Phase and magnitude of the reflection back from the finline taper towards the SIS junction in the IF band, as calculated by HFSS.

The profiles generated by each of the methods are combined by overlapping the sections, and matching the impedances, fin widths and gradients of each section at the join.

This rigorous design method generates finline tapers that are significantly shorter than those previously used, and allows the scattering parameters of the full transition to be calculated in the RF band. The resulting design of both the tapers and serrations has been validated by both scale model measurements at 15 GHz and by HFSS simulations of the complete tapers.

Ansoft HFSS was used to calculate the scattering parameters of the finline transition in the IF band of the mixer. The cut-off frequency varies smoothly along the finline transition, from zero in the microstrip output to the waveguide cut-off frequency at the front of the chip. This means that although all of the IF power is reflected from the finline, the point at which it is reflected varies with frequency, giving a large variation in the phase of the reflected signal across the IF band. This would limit the IF bandwidth of our mixer to around 10-12 GHz if IF signals were allowed to leak into the finline taper.

B. RF band-pass filter

To prevent the IF signal from leaking into the finline transition, we place an RF band-pass filter between the finline transition and the mixer tuning circuit. This filter transmits fully the RF signals, but reflects the IF signals from a fixed point, close to the mixer tuning circuit. The RF filter is made up of three sections of microstrip line and two parallel plate capacitors in series. The design was initially modelled and optimised as a lumped element and ideal transmission line circuit in the Ansoft Designer, before being verified in Sonnet *em* Suite. The final design and simulated performance are shown in Fig. 14.

The parallel plate capacitors are fabricated by depositing the lower plates as part of the first niobium wiring layer, before anodising the plates to form niobium oxide. The second wiring layer is then deposited to form the two top plates and the central microstrip of the band-pass filter.

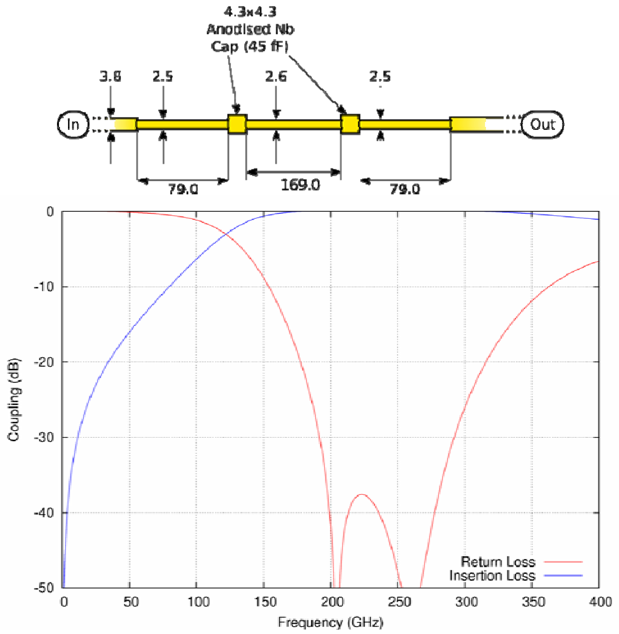

Fig. 14. (Top) Diagram of the RF band-pass filter. Dimensions are in microns. (Bottom) Calculated scattering parameters of the RF band-pass filter.

One potential problem with this design is that the dielectric constant of niobium oxide depends somewhat on the degree of oxidation which in turn affects the capacitance of the parallel plate capacitors. The wet anodisation process used to produce the niobium oxide gives us good control of the oxide thickness, so it should be possible to adjust this process to give the correct capacitances.

C. Tuning circuits

We have designed two tuning circuits for these mixers, both of which use identical 16.5 Ω, 1.25 µm diameter (area 1.21 μm^2) SIS junctions with a critical current density of 14 kA/cm^2 and a specific capacitance of 75 $fF/\mu m^2$. The first design uses a single SIS junction tuned by a single microstrip stub terminated by the RF choke (Fig. 15). This design gives relatively narrow band tuning, but is reliable and relatively simple to design and analyse.

The second design uses two SIS junctions in a single-ended dual-junction tuning circuit [5], with the IF output end terminated by a microstrip stub and stepped microstrip line RF choke (Fig. 16). This design gives very wide RF bandwidth, but is somewhat more difficult to integrate, as it relies on the successful fabrication of two identical SIS junctions on the chip.

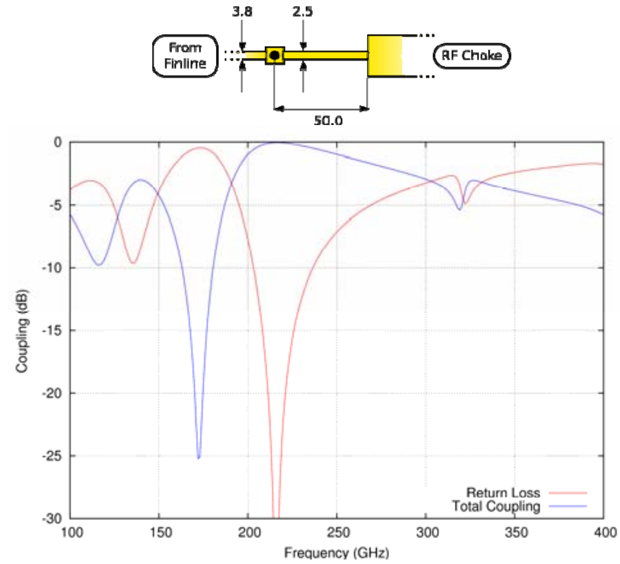

Fig. 15. (Top) Diagram of the single junction tuning circuit. Dimensions are in microns and the SIS junction is shown as a black circle. (Bottom) SuperMix calculated scattering parameters for the single-junction tuning circuit.

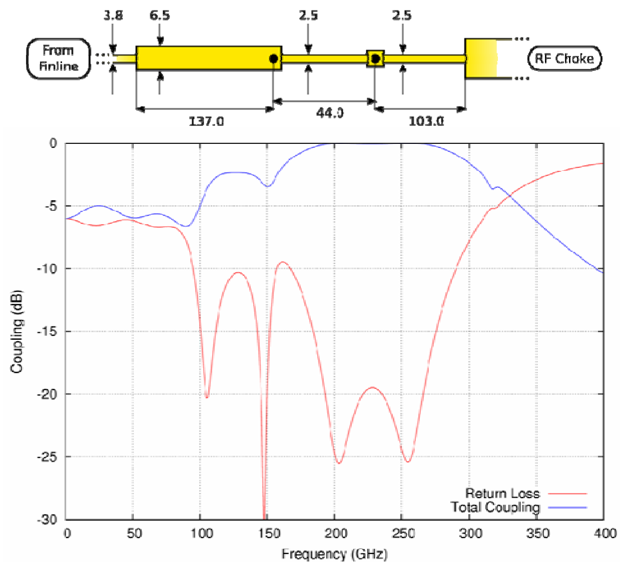

Fig. 16. (Top) Diagram of the dual junction tuning circuit. Dimensions are in microns and the SIS junctions are shown as black circles. (Bottom) SuperMix calculated scattering parameters for the dual-junction tuning circuit.

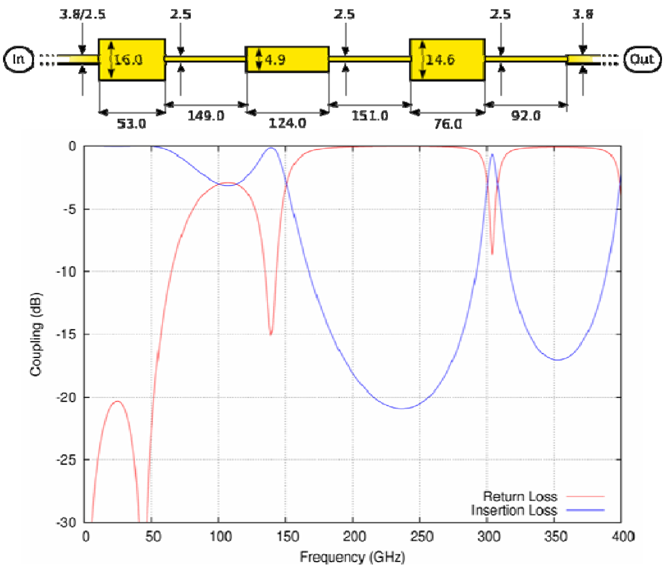

Fig. 17. (Top) Diagram of the stepped width microstrip RF choke. Dimensions are in microns. (Bottom) Sonnet *em* calculated performance of the RF choke.

D. RF choke

The RF choke is made up of six stepped width sections of microstrip in series (Fig. 17). The lengths and widths of these sections were optimised in Ansoft Designer and Sonnet *em* Suite to give the best possible transmission in the IF band, while still blocking the RF signal at a relatively high level. Some RF performance was sacrificed in order to obtain very wide IF bandwidth. The RF choke also acts as the microstrip stub termination in both of the tuning circuits.

This stepped microstrip line design was found to give significantly better IF bandwidth than the radial stub chokes used in previous finline mixers.

E. IF connection and transformer

IF signals from the mixer are transmitted through the RF choke to the wiring layer bond pad at the rear of the chip. This bond pad is connected to an IF connection circuit fabricated from 17 μm thick copper microstrip on 0.254 mm thick Rogers' Duroid 6010LM by three 50 μm diameter aluminium bond wires (Fig. 18). In order to minimise the inductance of the bond wires, the bonds are kept as short and low as possible. Two bond wires on each side of the chip provide the ground connection to the mixer block.

The IF connection has been carefully modelled in HFSS and various aspects tuned to achieve good performance at high IF frequencies. In particular, the width of the bond pad was increased, and the gap between the wiring layer bond pad and ground layer was reduced. This appears to reduce the mismatch between the 16.5 Ω microstrip output of the RF choke and the bond pad.

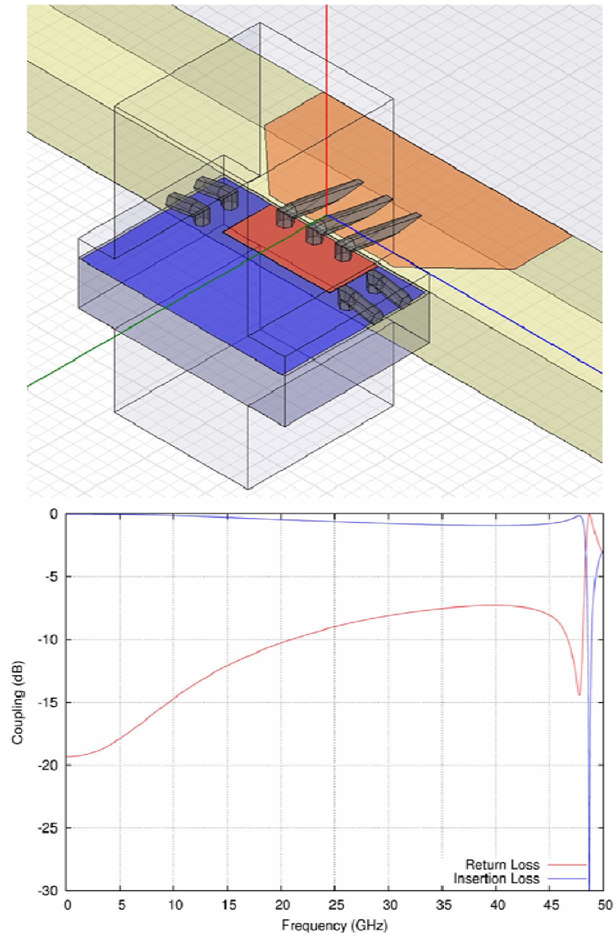

Fig. 18. (Top) HFSS model of the IF bond pads (blue and red), bond wires (grey) and IF output microstrip (pink). Three bond wires connect the mixer wiring to the IF output, while two wires are used on each side to ground the chip to the mixer block. (Bottom) HFSS calculated scattering parameters of the IF connection, normalised to the mixer output impedance of 16.5 Ω.

A five step quarter-wave microstrip transformer is incorporated onto the IF connection board to match the mixer output to the 50 Ω SMA connector and IF amplifier input over the 2-20 GHz IF band (Fig. 19). The first section of this transformer is shortened to cancel some of the inductance due to the bond wires and pad, and the whole transformer design is optimised in Ansoft Designer in conjunction with the HFSS results for the IF connection above. This allows an excellent match to be achieved between the 16.5 Ω SIS junction and the 50 Ω IF amplifier.

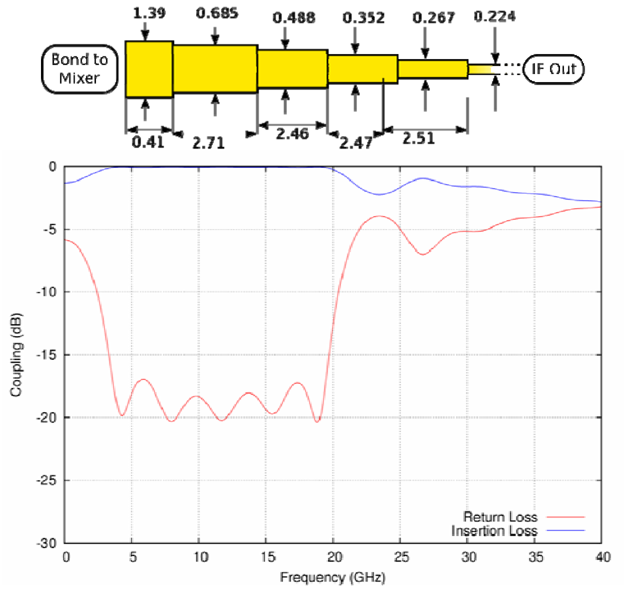

Fig. 19. (Top) Diagram of the IF output transformer, fabricated on 0.254 mm thick Duroid 6010LM. Dimensions are in mm. (Bottom) Combined scattering parameters of the IF connection and output transformer, normalised to 16.5 Ω at the input and 50 Ω at the output.

III. Fabrication

The mixers were fabricated on 225 µm thick Infrasil fused quartz with a 20 nm AlN etch-stop layer using UV photolithography to define all features except the junctions, which are defined by E-beam lithography.

Fabrication takes place in seven fabrication steps:

1. Deposition of 200/10/100 nm thick Nb-AlO_x-Nb trilayer and lift-off to form the lower finline and mixer ground plane.
2. Definition of areas to covered by first SiO dielectric layer (including junction areas to be defined by E-beam), and definition of junctions by E-beam lithography. Reactive ion etching to form junctions.
3. Evaporation of first 200 nm SiO layer followed by lift-off of SiO over junctions.
4. Evaporation of 225 nm second SiO layer and lift-off.
5. Deposition of first 400 nm Nb wiring layer and lift-off
6. Anodisation of wiring layer to form capacitors for RF band-pass filter.
7. Deposition of second 400 nm Nb layer and 25 nm Au protection layer and lift-off to form RF band-pass filter centre section and bond pads.

The junction definition and first SiO layer steps (2 and 3 above) use both UV and E-beam lithography to define the area of the trilayer to be reactive ion etched and covered in SiO. First the outside edge of the area to be etched and covered in SiO is defined by UV lithography, before the junctions are defined by E-beam lithography and reactive ion etching through the top Nb layer. SiO is then evaporated onto the wafer. A chemical mechanical polishing step was used with these wafers to remove the E-beam charge dissipation layer from the junction areas before lifting off the E-beam resist and SiO covering the junctions.

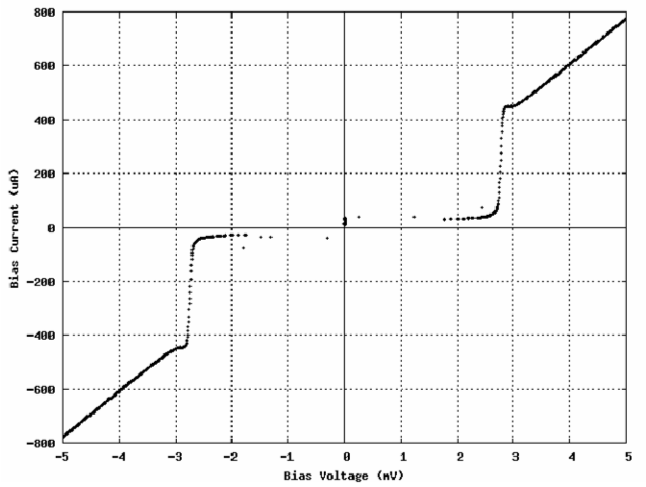

Fig. 20. Measured I-V curves for a dual-junction mixer from the first fabrication batch.

The niobium oxide insulating layers in the capacitors in the RF band-pass filter are anodised in $C_2H_2O_6/NH_4B_{10}O_{16}$ solution under a constant current until the anodisation voltage indicates that the required thickness has been achieved.

Two batches of 18 devices were fabricated in the first fabrication run at KOSMA, Cologne in December 2007. The second batch used an alternative wiring layer mask that does not have the RF band-pass filters, so that the RF coupling with and without this component can be compared.

The yields from the two batches were excellent, and apart from some problems with the wiring layer photoresist in the second batch, all fabricated devices showed excellent I-V characteristics (Fig. 20) and consistent normal resistances and Fiske resonances across the wafers.

IV. Simulated Mixer Performance

The mixer designs have been extensively simulated throughout the design process with software based on Caltech's SuperMix simulation library[6]. In this section we present simulation results for both single and dual junction mixer designs.

The simulations include all of the components on the chip as well as the IF connection and IF transformer board, and the 4 K input noise of the IF amplifier. Other receiver components such as the cryostat window, IR shields and LO injection beamsplitter are not included. Additionally, RF losses in the finline are not included, although these are expected to be small at frequencies below the energy gap of niobium.

In both cases the unpumped junction I-V curve is taken from a 700 GHz finline mixer fabricated in the KOSMA facility in December 2002, using a similar process to these mixers, apart from the junction definition, which used UV lithography. This junction should give a very similar I-V curve to these new devices.

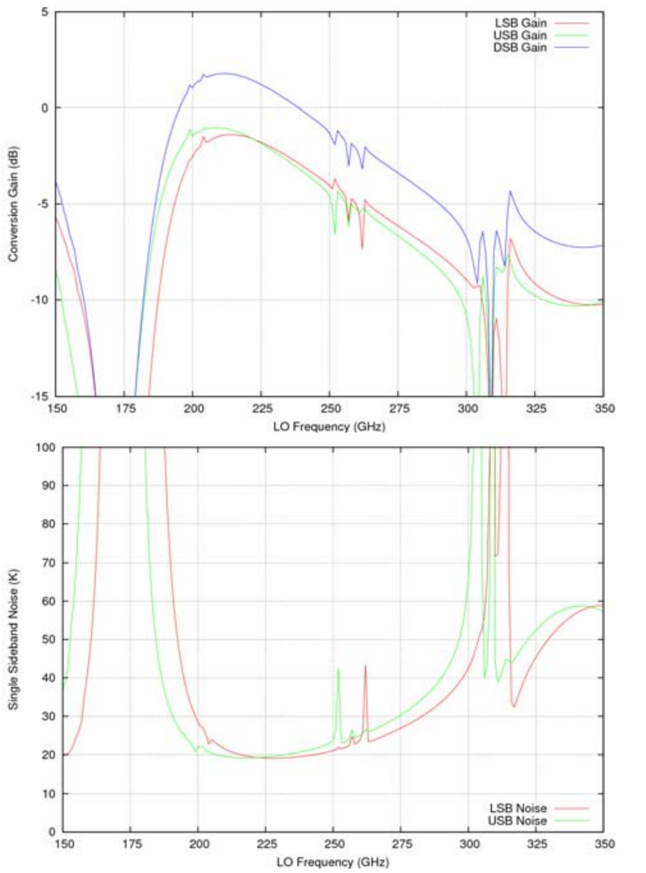

Fig. 21. SuperMix calculated mixer conversion gain (top) and noise temperature (bottom) against LO frequency for the complete single-junction mixer. The mixer is biased at a fixed bias voltage of 2.2 mV, and pumped with a fixed LO power of 50 nW. The IF frequency is 5 GHz. The narrow spikes in the performance just above 250 GHz and 300 GHz are artefacts caused by running the simulation at a fixed bias voltage and LO power.

F. Single-junction mixer

The mixer performance for the single-junction mixer as a function of LO frequency is shown in Fig. 21. In these plots the mixer is biased at a fixed voltage of 2.2 mV and pumped by a fixed LO power of 50 nW, while the performance calculated at a fixed IF frequency of 5 GHz.

The mixer performance as a function of IF frequency is shown in Fig. 22. The mixer bias voltage and LO power are again 2.2 mV and 50 nW respectively, while the LO frequency is 220 GHz, the centre of the mixer's tuning resonance.

The reduction in the mixer conversion gain (and associated increase in noise temperature) with increasing IF is mainly due to the narrowness of the RF coupling response of the mixer tuning circuit. This reduces the coupling of the sidebands to the mixer as the IF frequency increases, since the sidebands are now further from the centre of the coupling response.

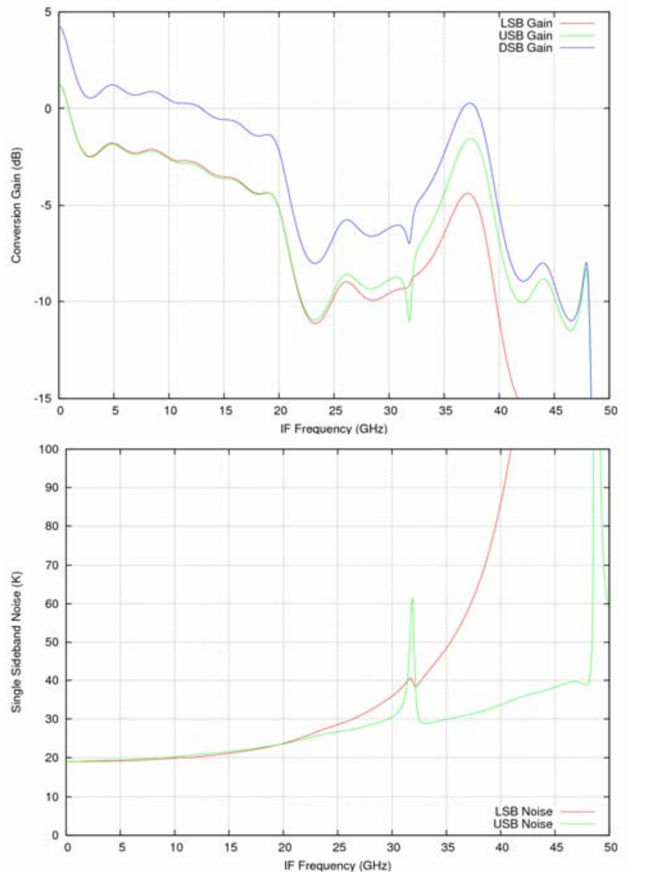

Fig. 22. SuperMix calculated mixer conversion gain (top) and noise temperature (bottom) against IF frequency for the complete single-junction mixer. The mixer is biased at 2.2 mV, and pumped by 50 nW of LO power at a frequency of 220 GHz.

G. Dual-junction mixer

The mixer performance for the dual-junction mixer as a function of LO frequency is shown in Fig. 23. In these plots the mixer is biased at a fixed voltage of 2.2 mV and pumped by a fixed LO power of 100 nW, while the performance calculated at a fixed IF frequency of 5 GHz.

The mixer performance as a function of IF frequency is shown in Fig. 24. The mixer bias voltage and LO power are again 2.2 mV and 100 nW respectively, while the LO frequency is 220 GHz, for comparison with the single-junction mixer above.

In this case the reduction in mixer conversion gain with increasing IF (up to 20 GHz) is due to the mismatch between the two parallel 16.5 Ω junctions and the 16.5 Ω IF output. This leads to a much lower increase in noise temperature than for the RF mismatch in the single-junction case above, as the mixer noise is also mismatched.

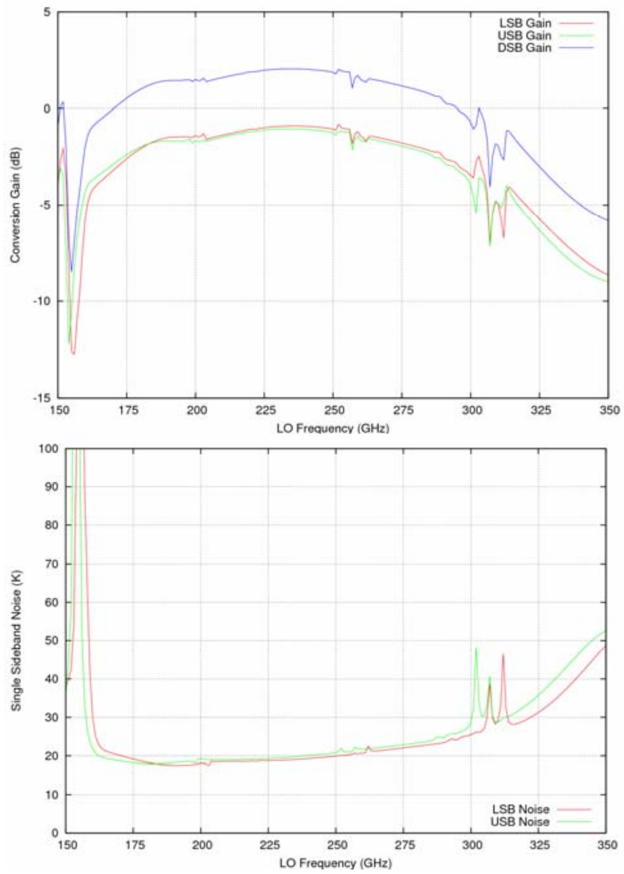

Fig. 23. SuperMix calculated mixer conversion gain (top) and noise temperature (bottom) against LO frequency for the complete single-junction mixer. The mixer is biased at a fixed bias voltage of 2.2 mV, and pumped with a fixed LO power of 100 nW. The IF frequency is 5 GHz. The narrow spikes in the performance just above 250 and 300 GHz are artefacts caused by running the simulation at a fixed bias voltage and LO power.

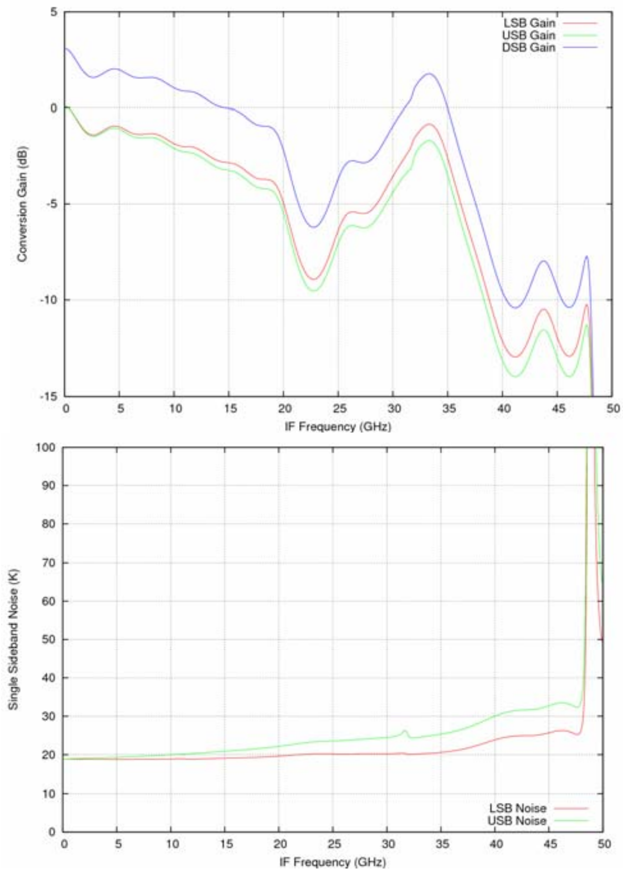

Fig. 24. SuperMix calculated mixer conversion gain (top) and noise temperature (bottom) against IF frequency for the complete single-junction mixer. The mixer is biased at 2.2 mV, and pumped by 100 nW of LO power at a frequency of 220 GHz.

CONCLUSION AND FUTURE WORK

We have presented an SIS mixer design with a very wide IF bandwidth covering the range of 2-20 GHz. The employment of the finline design permitted elegant integration of circuits to allow efficient operation at these high IF frequencies and minimise parasitic reactances. Our RF simulations demonstrate that operation at these high IF frequencies is feasible, while our SuperMix simulations show that both the wideband RF and IF operation can be achieved in conjunction with a high performance mixer.

So far we have only tested the narrow-band devices with a narrow-band IF system in order to set a benchmark for the more complicated wide-band mixers. Preliminary results have confirmed the integrity of our design method.

Testing of the broadband devices will follow after the benchmark tests are completed.

Once these mixers have been characterised, we will develop single chip balanced and image separating mixers with very wide IF bandwidth based on our back-to-back finline layout. These devices will be particularly suitable for use with photonic LOs as they require much less LO power than single-ended designs.

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