An SIS unilateral finline mixer with an ultra-wide IF bandwidth

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***Abstract*—In this paper, we will present the design and the simulation of a 230GHz finline Ultra-wide IF Bandwidth SIS mixer. This mixer will be used in a novel millimeter-wave heterodyne interferometer: GUBBINS. GUBBINS is designed to demonstrate high surface brightness mm-wave interferometry at modest spatial and spectrum resolution. Its observational targets are the spectrum of the Sunyaev-Zel'dovich effect in the brightness galaxy cluster[3]. The archetype of the mixer design described here is an antipodal finline SIS mixer designed by Paul Grimes in Oxford Experimental Cosmology group in 2008[1]. Here several improvement and modification are made to simplify the design and fabrication, and also enhance the IF bandwidth. An unilateral finline replaces the complicated antipodal finline. No RF bandpass filter is needed after finline. The tuning circuit design presented here aims to achieve wider RF coupling bandwidth, even though only a single junction is used. A multi-stage IF transformer follows the IF bonding pad matching the IF output of the mixer to the input of the IF amplifier, as well as reducing the impact of the parasitical capacitance introduced by the RF finline and RF radial stub.**

I. Introduction

In recent years, considerable astronomical research has been focused in the millimeter and submillimeter band. The increasing sensitivity of the millimeter and submillimeter receiver enables the observation of fainter astronomical target, e.g the cosmic microwave background radiation. A novel heterodyne interferometer telescope- GUBBINS (220GHz Ultra-BroadBand INterferometer for S-Z) is under construction in Oxford, with the aim of observing galaxy clusters via the Sunyaev-Zel'dovich effect and demonstrating high surface brightness mm-wave interferometer at modest spatial and spectral resolutions.

The observation of the continuous source,like cosmic microwave background, requires extremely high brightness sensitivity. The sensitivity of a receiver does not only depend on the noise performance , but also on the available instantaneous bandwidth over which detected power is integrated. In a heterodyne receiver, the instantaneous bandwidth is determined by the IF bandwidth. Also, wide IF bandwidth mixers allow spectroscopic observations to detect several spectral lines simultaneously. But wide IF bandwidth SIS mixers are still rare currently because several key design challenges are waiting be solved. Wide RF bandwidth signal has to be coupled into SIS junction efficiently, while the IF signal generated in the SIS junction should not leak into the RF circuit of the mixer. The SIS junction must see a reasonably constant embedding impedance throughout the IF bandwidth. This enables the IF signal to be well coupled from the junction to the input of cold IF amplifier over a wide IF bandwidth.

The finline mixer chip introduced here is not sensitive to mixer block fabrication tolerance, hence ease the requirement for the precision of the mixer block.The large chip area also allows elegant integration of complicated planar circuit onto a single chip.The SIS finline mixer design presented below is an improved unilateral finline design based on a direct transition from slotline to microstrip, mounted on a 60μm silicon substrate. The silicon substrate reduces the impedance difference between finline slot and microstrip transmission line, which acts to improve the scattering parameter performance. The designed includes the following components:

- A silicon substrate with 2-stage rectangular notch at the front end, used to transfer the signal from unloaded waveguide to loaded waveguide. The mixer chip is mounted in the E-plane split mixer block, supported by grooves in the waveguide wall.
- A unilateral finline transition to couple the signal from loaded waveguide to microstrip transmission line, where the SIS junction is fabricated. Quarter wavelength serrations are added to each side of the finline to prevent RF power propagating in the grooves.
- A multi-stage microstrip tuning circuit around the SIS junction to tune out the parasitical capacitance of the SIS junction over a very wide RF bandwidth. A 5-stage RF choke is integrated in the tuning circuit to prevent RF signal leaking into the IF output port.
- At the rear of the chip, the IF bonding pad is used to transmit the IF signals from the mixer to the IF transformer using several aluminium bond wires. It is carefully simulated in HFSS to present inductance as low as possible and good transmission performance over a wide IF bandwidth.
- A five-stage quarter-wave microstrip transformer is incorporated onto the IF connection bonding pad to match the mixer output to the 50ohms SMA connector and IF amplifier input over the 2-20 GHz IF band.

A. Mixer design

The mixer is fed by a waveguide diagonal horn which couples into a unilateral finline taper, the taper then couples the signal into a microstrip line which contains the superconducting tunnel junction[4]. The device is fed by a miniature microstrip line, the field of which does not interact

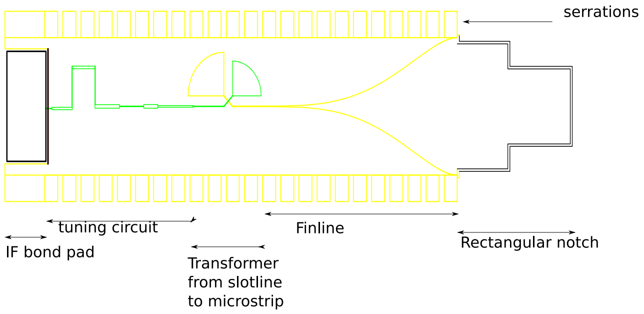


Fig. 1. AutoCAD photo of an ultra-wide IF bandwidth finline SIS mixer chip. The RF signal is coupled from free space from the right and the IF signal signal leaves from the IF bond pad, on the right.

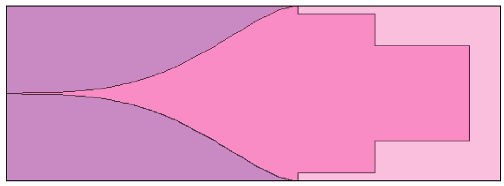
with the waveguide mode, thus neither back-short or E-plane tuner is needed. The mixer chip will be fabricated on 60μm silicon substrate and uses a 200/10/100 nm thick NB-AlOx-Nb trilayer, a 490 nm thick SiO dielectric evaporated separately in two layers, 240nm and 250nm, with a dielectric constant of 5.8 and 400nm thick Nb wiring layer.

A schematic of diagram of the mixer chip in shown in Fig.1. In the following section , we will introduce the detail of each Mixer component.

1) Transmission line: The finline mixer is deposited on a 60μm silicon substrate which supports the structure in the E-plane of a rectangular waveguide. The wafer is supported in a groove which runs along the sides of the waveguide. Waveguide dimension is standard WR-4 , 550μm $\times$1100 μm. Impedance matching between the loaded waveguide and free space is achieved by a 2-step binomial multisection notch shown in Fig. 1. The length of each step is approximately one quarter of the guide wavelength at that section and the impedance of each step can be determined by the binomial formulars(eqn. 1) given the impedance of waveguide $Z_0$and microstrip Z_L [2]. The widths of each step are optimized in the HFSS software.

$$[tp] \ln \frac{Z_{n+1}}{Z_n} = 2^{-N} C_n^N \ln \frac{Z_L}{Z_0} \tag{1}$$

As stated in the previous paper[1], a lot of care has to be taken in the fabrication of antipodal finline to avoid the narrow spikes that can potentially AC-short the chip , especially at the stage when the fins start to overlap with each other. To overcome this difficulty, A newly developed unilateral finline transition is used to couple the RF power into the mixer chip[5][6][7]. An important advantage of this design is that it provides an extremely wide bandwidth transition from the waveguide impedance to a low microstrip impedance.For Nb film with 500nm thickness deposited on 60μm silicon substrate, an impedance of approximately 36Ω is obtained with a finline gap of 2.5 μm. A microstrip bridge with a width of 2.2μm is deposited across the slotline on a 490nm thick layer of SiO and terminated by a shorted quarter-wave radial stub. The finline itself is also terminated by a quarter-wave radial stub which forms a RF short. The quarter-wave radial stub of finline shorts the signals to the microstrip bridge, and then the radial stub of the microstrip shorts the signal again and then directs the signals to the 2.2μm microstrip line.



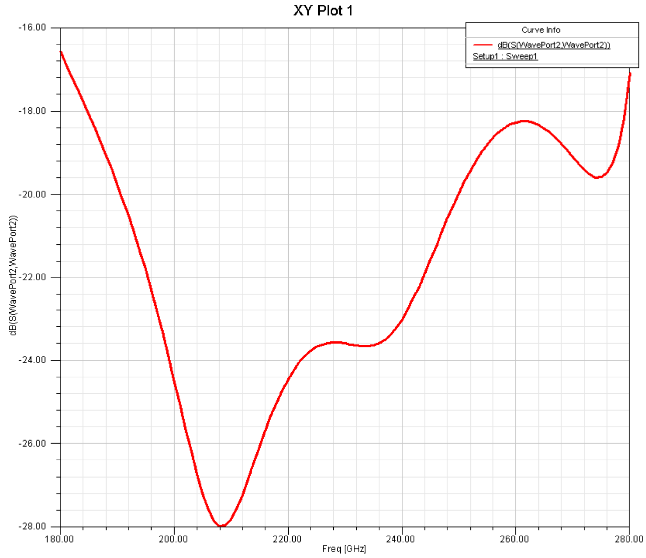


Fig. 2. (Top)HFSS model of the unilateral finline.(Bottom)The scattering parameter of such unilateral finline across RF bandwidth.

In the calculation of the unilateral finline taper, the Optimum Taper Method is used[5], which takes a maximum allowed returned loss for the taper (e.g. -30dB), and then calculates the corresponding cutoff frequency profile along its length. Transverse resonance method is used to give the relationship between the cutoff frequency , the slot width and the propagation constant. Because the cutoff frequency of unilateral finline is right above the IF frequency range, no RF bandpass filter is needed after the finline, which reduces the length of the chip, hence the loss. Figure 2 shows the computed scattering parameter of an unilateral finline taper deposited on a 60μm silicon substrate using HFSS software. We found that the bandwidth of the finline taper is restricted by the 2-stage rectangular notch , rather than the finline taper itself.

2) Tuning circuit: The RF choke is integrated in the tuning circuit design. We have designed three tuning circuits of different sizes, using the same design method and roughly the same performance, but with various dimensions . Here only one designed will be illustrated and introduced in detail.The schematic diagram of the tuning circuit is shown in Figure 3, with 20Ω ,1μm^2 SIS junction with a critical current density of 14 KA/cm^2 and a specific capacitance of 75fF/μm^2 . It is a single junction tuned out by two series microstrip stub located before and after the junction, each tuned at two different frequency, giving a wide RF coupling. The 2.5 μm wide microstrip transmission line deposited on 490 nm thickness SiO dielectric layer presents an impedance of roughly 20 Ω, ideal for the the coupling to the 20 Ω SIS junction. Before

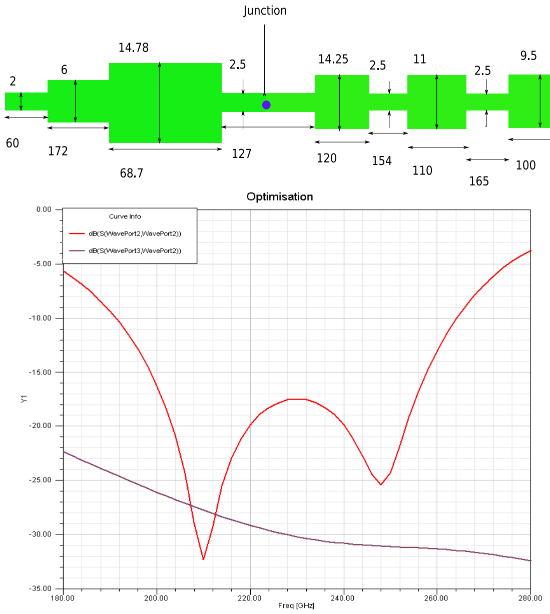


Fig. 3. (Top)Diagram of the tuning circuit with the integrated RF choke. Dimensions are in μm and the SIS junction is shown as a purple dot. The 7-step stubs after the junction are the RF choke. (Bottom) HFSS calculated scattering parameter of the tuning circuit. The red line represents the return loss while the purple line represent the insertion loss.

the SIS junction, a 3-stage Chebyshev transformers is used to realize impedance matching between 2.2μm^2 microstrip line and the SIS junction.

After the SIS junction, 6-stepped width section RF chokes are added to block the unnecessary RF signals leaking into the IF port. The first section of the RF choke also acts as the microstrip stub termination in the tuning circuit.

3) IF connection and transformer: The IF signal generated in the SIS junction is transmitted to the wiring layer bond pad at the rear of the chip. This bond pad is connected to the IF transformer through three 50 μm diameter aluminium bond wires. The 5-step IF transformer is fabricated on 254 μm thick Roger's Duroid 6010 substrate. The bonds are kept as short as possible to minimize the inductance of the bond wires. At each side of the chip, there are two bond wire providing a ground connection to the mixer block. The gap between the wiring layer and the ground layer is optimized in HFSS to achieve good performance in the IF coupling(Figure 4).

A five step quarter-wave microstrip transformer is designed following the IF bond pad connection to match the mixer output to the 50 Ω SMA connector over 2- 20GHz IF band. The finline and large area stub on the chip will introduce considerable parasitical capacitance. Thus the width and length of the first section of the IF transformer is optimized in Ansoft Designer to enable a good match between the complex output impedance of the SIS mixer chip and the 50 Ω IF amplifier(Figure 5).

II. Simulated Mixer performance

As well as the HFSS simulations shown above, the mixer designs have been extensively simulated by the software based on Caltech's SuperMix simulation library. In this section , we

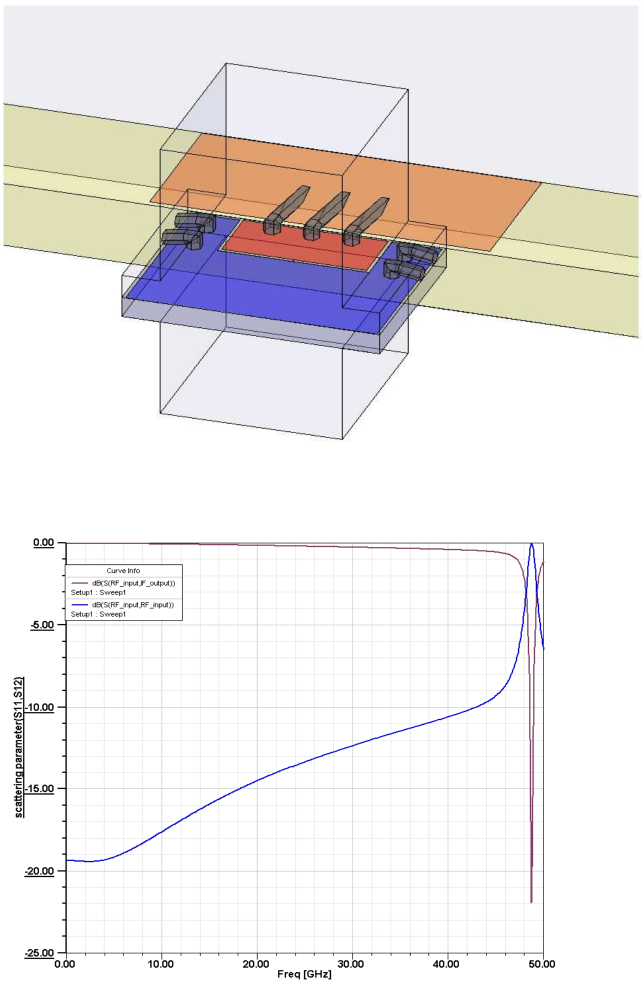


Fig. 4. (Top)HFSS model of the IF bond pad.Bond wires are shown in grey. The blue pad is the ground plane while the red pad is the bonding pad. The orange pad connected to the bonding pad by grey wire is part of the IF transformer.(Bottom)HFSS calculated scattering parameter of the IF connection,normalized to the mixer output impedance of 20 Ω)

will present simulation results for the whole chip, including unilateral finline ,tuning circuit, IF bond pad and IF transformer along RF bandwidth, IF bandwidth and various DC bias point. But other receiver components , like the cryostat window, IR shields and the LO injection beamsplitter are not included. The mixer performance along the RF band for the single junction design is present in Figure 6 and the performance along the IF band for the single junction design is presented in Figure 7. In these RF simulation, the mixer is biased at a fixed voltage 2.2mV and pumped by a fixed LO power of 40nW, while the performance calculated at a fixed IF frequency of 10GHz. In the IF simulation, the voltage bias point and pumped level are the same with the RF while, but the RF frequency is set to be 230GHz.

III. Conclusion

We have designed a novel silicon-substrate unilateral finline mixer which is expected to exhibit wide RF coupling bandwidth and ultra wide IF bandwidth of 2-20GHz. The application of the novel unilateral finline allows wide RF signal

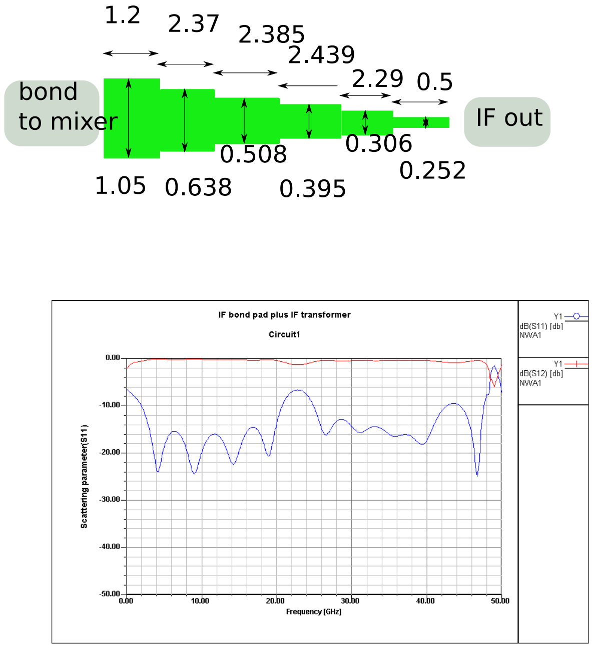


Fig. 5. (Top)Combined scattering parameter of the IF bond pad and the 6-step IF transformer, normalized to 20 Ω at the input end and 50 Ω at the output SMA of amplifier. The dimension shown is in unit of mm. It is calculated by the Ansoft designer. The scattering parameter of IF bond pad is exported from the HFSS simulation.(Bottom) Diagram of the IF output transformer, fabricated on 254μm thick Duroid 6010LM. The unit in the diagram is μm and the left hand side of the IF transformer is connected to the IF bond pad and the right hand side is connect to the output SMA.

coupling , elegant integration of complicated planar circuit as well as minimum parasitical capacitance. The simulation result from SuperMix demonstrates both the wideband RF and IF operation could be achieved by this high performance mixer.

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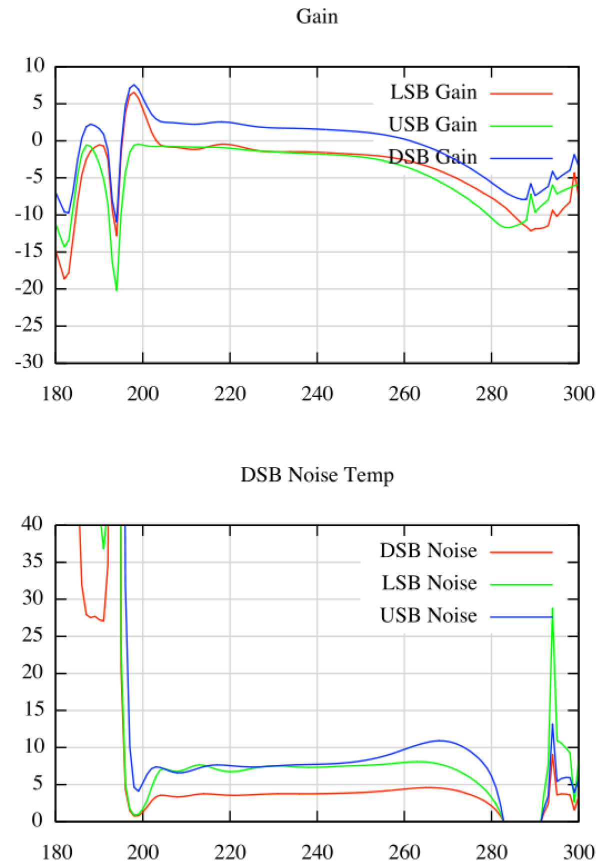
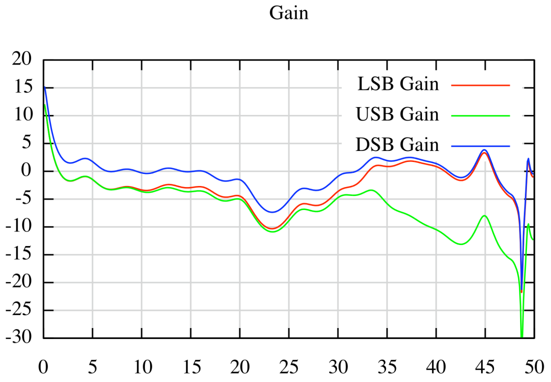


Fig. 6. Supermix calculated mixer conversion gain and noise temperature against the LO frequency the entire mixer chip. The mixer is biased at a fixed bias voltage of 2.2mv and pumped with a fixed LO power of 40nw. The IF frequency is 5GHz.



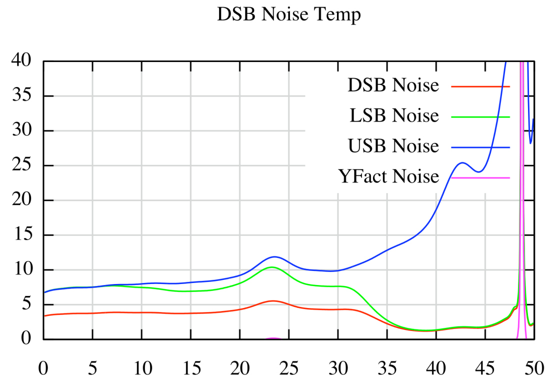


Fig. 7. SuperMix calculated mixer conversion gain (top) and noise temperature (bottom) against IF frequency. The mixer is biased at 2.2mv and pumped by 40nw of LO power at frequency of 230Ghz.