A 230 GHz Finline SIS Receiver with Wide IF Bandwidth

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Abstract— **We have developed anSIS receiver with a wide intermediate-frequency (IF) bandwidth.This is important for reducing image integration time and simultaneously measuring multiple spectral lines. The receiver is a finline mixer-based design, which allows for ultra-wide radio-frequency (RF) bandwidth and has lower mechanical requirements compared to radial stub designs. Simulations of this receiver showed quantum limited noise in the RF frequency range of 140 to 260 GHzand from DC to 10GHz in the IF spectrum.We measured the noise temperature by comparing the receiver's response to hot and cold loads. The best noise temperature was 37.9 K at 231.0 GHz, and all of the results were below 100 K from 213 to 257 GHz (the bandwidth of our local-oscillator). We measured the IF bandwidth using a spectrum analyser, and found good results from around 3-10 GHz. The lower frequency was restricted by our IF amplifier's bandwidth but the higher frequency limit was lower than we expected from simulations. We believe that this discrepancywas due to the inductance of the bondwires that we used to connect the mixer chip to the IF board. We are currently investigating techniques to reduce and compensate for this inductance.**

INTRODUCTION

Observations of millimetre-wave spectral lines are crucial for understanding the chemical and physical properties of star forming regions.However, large detailed surveys of the Milky Way and neighbouring galaxies areslow with the current technology. This is especially true for large interferometers, which have inherently small fields of view.

In order to decrease the time required to form an image, different techniques can be applied. Firstly, the sensitivity of the receivers can be improved. For a given signal-to-noise ratio (SNR), the integration time ($\Delta\tau$) is proportional to the noise temperature (T_N) squared.While improving the sensitivity could greatly reduce the integration time, modern superconductor-insulator-superconductor (SIS) receiversare approaching the quantum limit of sensitivity. It is now very difficult to lower the noise temperature by any significant fraction, hence other techniques must be considered. An alternative way to increase the receiver sensitivity is to increase the number of detectors (mixers) in the focal plane of the dish. If the mixers are operating independently, the imaging time is inversely proportional to the number of mixers. This involves creating a focal-plane array, which has its own challenges (e.g., [1]). Athird technique is to increase the intermediate-frequency bandwidth (IFBW) of the receivers. For a continuum source and a given SNR, integration time is inversely proportional to the IFBW. A large IFBW also has the added benefit that multiple spectral lines can be observed simultaneously, again helping to reduce imaging time. For most modern receivers, the IFBW is approximately 8 GHz and there are many efforts to raise this even further (e.g., [2-5]).

The IFBW of the SIS devices is typically limited due to (a) the intrinsic capacitance of the junction, and (b) RLC resonances forming within the planar circuit of the receivers [3]. Both of these issuescan result in the output impedance of the receiver dropping to zero for extended regions of the IF spectrum, which makes it impossible to match the receiver to the IF circuitry. Issue (a) can be addressed by making the junctions as small as possible(to reduce the intrinsic capacitance), by using multiple distributed junctions [5], and/or by tuning out the junction's capacitance with IF tuning boards. Likewise, issue (b) can be addressed by carefully designing the planar circuit to shift the resonance outside the desired IF spectrum. This mostly involves reducing the surface area of the wiring layer of the planar circuit to reduce the capacitance seen by the IF circuit.We shall address these issues in detail for the receiver presented in this paper.

RECEIVER DESIGN

The receiver we created is a single-ended, dual sideband, single-junction SIS mixer (Fig. 1). We designed it to operate from 150 to 250 GHz with a large instantaneous IFBW from 0 to 15GHz. Full details of the design, simulation and fabrication can be found in a previous publication [4].

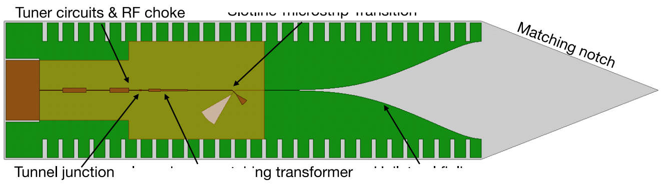

Fig. 1 Layout of the 230 GHz SIS receivers. This device is mounted in the E-plane of the waveguide.

Each component of the receiver was simulated using Ansys'sHigh-Frequency Structural Simulator (HFSS) and then imported intoCalTech's SuperMix package [6,7]. The simulation results show quantum limited performance for an RF bandwidth from 140 to 260 GHz, and an IF bandwidth from DC to 25 GHz.

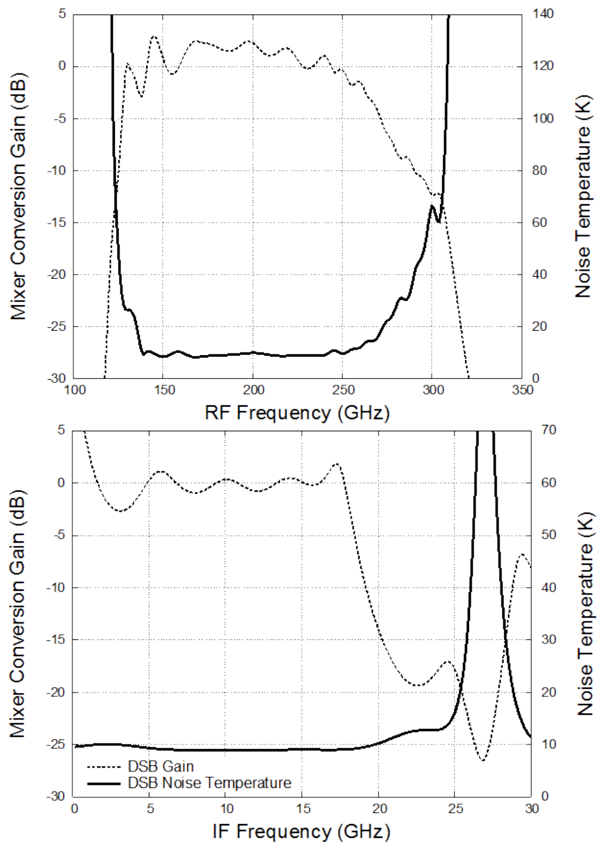

Fig. 2 RF and IF simulation results of the 230 GHz receiver using Ansys's HFSS and CalTech's SuperMix package.

FABRICATION

The mixer chip was fabricated by the Paris Observatory's clean room facility, on a 2 inch quartz wafer, using photolithography techniques [4]. The materials and layer thicknesses are listed in Table 1, and a subsection of a 2" wafer is shown in Figure 3.The junctions are circular, 1.5 μm^{2}Nb/AlO$_x$/Nb SIS tunnel junctions. Based on the materials and dimensions, this gives an estimated normal resistance of 14 Ω, a capacitance of 120 fF, andanωRC product of approximately 2.4.

TABLE I
DEVICE LAYERS.

Layer	Thickness	Material
Wiring	400 nm	Niobium
Dielectric	490 nm	Silicon Oxide
Ground	250 nm	Niobium
Substrate	100 um	Quartz

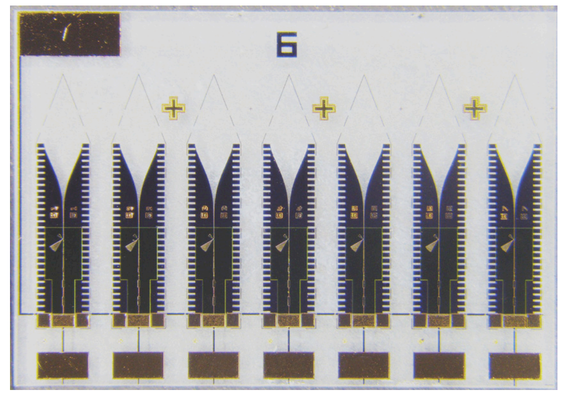

Fig. 3A subsection of a 2" wafer showing 7 completed receivers.

RF RESULTS

The noise temperature and gain weremeasuredusing hot and cold loads(room-temperature Eccosorb and liquid nitrogen, respectively) and measuring the IF current with a detector diode (Fig. 4). Our existing LO (frequency range: 213-257 GHz) was used to pump the the mixer. In the IF chain, we used a 4-6 GHz bandpass filter. We have not correctedthis data to account for the beam splitter loss, the vacuum window loss, or any other optical losses.The best noise temperature was 37.9 K at 231.0 GHz, and all of results were below 100 K from 213 to 257 GHz. Using the methods described in [8] and [9], weestimated theIF noise to be 11-14 K and theRF noise to be16-19 K.

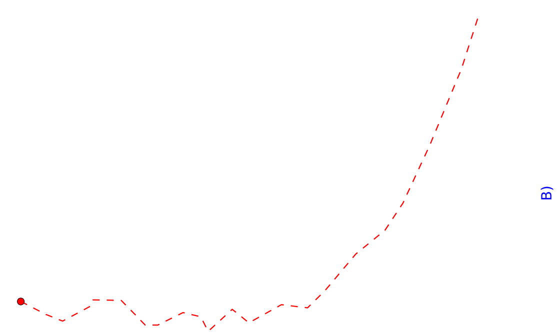

Fig. 4 Noise temperature and gain results for the 230 GHz receivers. This was measured using hot and cold loads with the current measured by a detector diode.

IF RESULTS AND DISCUSSION

The IF spectrum was measured usinga spectrum analyser (Fig.5). Ringing was present below 4 GHz, but this was due to reflections from the low-noise amplifier (LNA, bandwidth: 4-12 GHz).We could have used an isolator to prevent this, but they are typically very narrowband.The peak around 6 GHz was due to a standing wave in the IF chain and wasn't present in every measurement. On the high frequency side, the resultsare much higher than what was simulated by SuperMix (i.e., compared to Fig. 2). We tested 2 other devices as well and they both provided similar results.

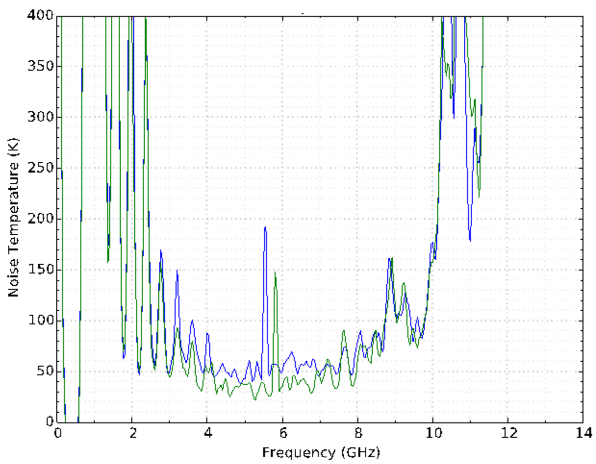

Fig. 5 IF spectrum at 220 GHz (blue line) and 230 GHz (green line).

To help understand the IFBW results, we measured the IF output impedance by using the technique described in [10] (Fig. 6). This technique uses a vector network analyser (VNA) to measure the reflection from the receiver, which can then be used to determine the output impedance. The system was calibrated by biasing the junction to create artificial open, short and matched load calibrations. In Fig. 6, the impedance appears to drop to zero around 9 GHz, but this is an artefact of the calibration method not working as well at these frequencies (i.e., strong reflections from the IF side of the junction cause a loss of sensitivity). This suggests that poor matching is occurring above 9 GHz, which is consistent with the spectrum analyser measurements.

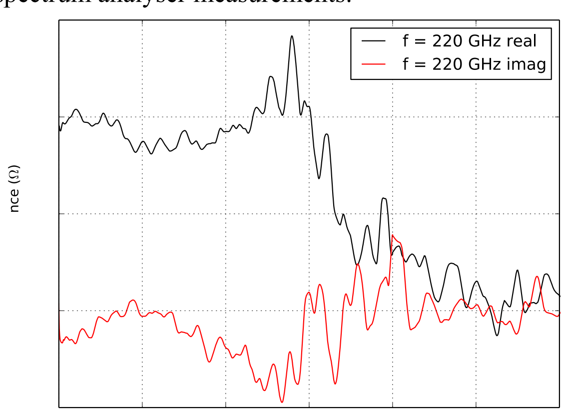

Fig. 6The receiver's IF output impedance for f_{LO} = 220 GHz. This was measured using the technique described in [10]. The results were filtered using a median and moving-average filter (order=3).

We believe that this mismatch is likely due to the inductance of the bondwires. To connect the mixer output to the IF tuning boards (microstrip circuit on aPCB board [11]), we used 25.4 µm diameter aluminium bondwires. A general rule of thumb for bondwires is 1 nHof inductance for every 1 mm. The bondwires for our devices were typically less than 0.5 mm, and usually two wires were used. If we include a series inductance of 2 nH in our SuperMix simulations, the IFBW shrinks dramatically as seen in Fig. 7. To further confirm these results, we tested the receiver with an extremely long bondwire (around 1 mm with a large arc). The IFBW for this device (Fig. 8) was much lower than the previous results (shown in Fig. 5). These results demonstrate that the bondwire inductance must be taken into consideration and that it is limiting the IFBW.

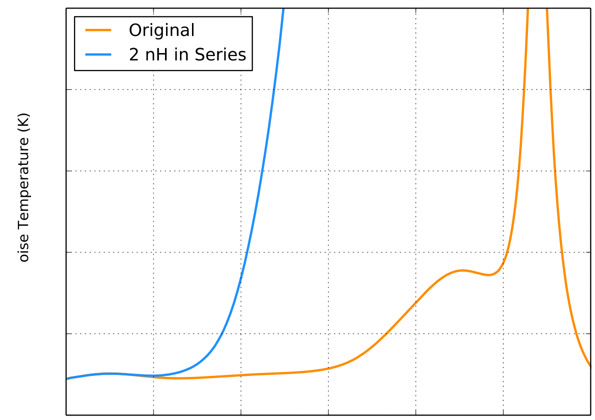

Fig. 7Simulated noise temperature shift due to the bondwires' inductance (assuming 2 nH).

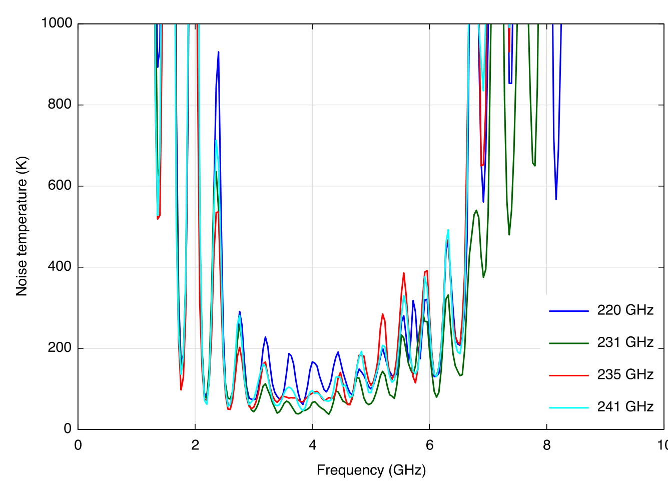

Fig. 8Experimentally measured noise temperature shift due to a long bondwire (1mm long with a large arc). Similar device to Fig. 5.

NEXT STEPS

To extend the IFBW of this device, we first attempt reducing and compensating for the bondwire inductance. This can be done by using larger bondwires (e.g., ribbon bonding versus wedge bonding), by using multiple bondwires (although space on the receiver is limited), and by compensating for the inductance with a shunt capacitance on the IF tuning board. To measure the entire IFBW of this device, we will also test the receiver with broadband LNAs, which cover the whole spectrum of interest (0-20 GHz). Finally, in the very near future, these devices will be used to populate a new 1x4 pixel array [1].

CONCLUSION

We have designed and tested a new finline-based SIS mixer. Considerable effort was made in the design to extend the IFBW over the existing state of the art. Simulations showed an RF bandwidth from 140-260 GHz and an IFBW from DC to 25 GHz.Experimentalresultsshowed high sensitivities withnoise temperatures down to 37.9 K, and a wideIFBW extending up to around 10 GHz. The IFBW waslower than simulated results due to the bondwires' inductance, which we have confirmed through simulations and experiments using longer bondwires. We are currently investigating solutions to reduce the effects of this inductance which will extend the IFBW.

REFERENCES

[1] J. Leech *et al.*, "An SIS Mixer Based Focal-Plane Array at 230 GHz," in *Proceedings of the Twenty-Sixth International Symposium on Space Terahertz Technology*, Cambridge, MA, 2015.

[2] Y. Zhou *et al.*, "An SIS Unilateral Finline Mixer with an Ultra-Wide IF Bandwidth," in *Proceedings of the Twenty-First International Symposium on Space Terahertz Technology,* Oxford and Didcot, 2010, pp. 204-211.

[3] Y. Zhou *et al.*, "Performance of a 230 GHz Finline SIS Mixer with a Wide IF Bandwidth," in *Proceedings of the Twenty-Third International Symposium on Space Terahertz Technology,* Tokyo, 2012, pp. 111-116.

[4] J. Garrett *et al.*, "A 220 GHz Finline Mixer with Ultra-Wide Instantaneous Bandwidth," in *Proceedings of the Twenty-Sixth International Symposium on Space Terahertz Technology,* Cambridge, MA, 2015.

[5] C.-Y. Tong *et al.*, "A Distributed Lumped-Element SIS Mixer with Very Wide Instantaneous Bandwidth," *IEEE Trans. Appl. Supercond.,* vol. 15, pp. 490-494, 2005.

[6] J. Ward*et al*., "SuperMix: A Flexible Software Library for High-Frequency Circuit Simulation, Including SIS Mixers and Superconducting Elements," in*Proceedings of the Tenth International Symposium on Space Terahertz Technology*, Charlottesville, VA, 1999, pp. 269-281.

[7] F. Rice *et al*., "Fast Harmonic Balance of SIS Mixers with Multiple Junctions and Superconducting Circuits," in *Proceedings of the Tenth International Symposium on Space Terahertz Technology*, Charlottesville, VA, 1999, pp. 282-297.

[8] D. Woody, R. Miller, and M. Wengler, "85—115-GHz Receivers for Radio Astronomy," *IEEE Trans. Microw. Theory Tech.*, vol. 33, pp. 90-95, Feb. 1985.

[9] C.-Y. Tong, A. Hedden, and R. Blundell, "An Empirical Probe to the Operations of SIS Receivers—Revisiting the Technique of Intersecting Lines," in *Proceedings of the Nineteenth International Symposium on Space Terahertz Technology*, Groningen, 2008, pp. 28-30.

[10] P. Serres *et al.*, "The IF Output Impedance of SIS Mixers," *IEEE Trans. THz Sci. Technol.*, vol. 5, pp. 27-36, Jan. 2015.

[11] B.K. Tan, G. Yassin, and P. Grimes, "A Simple Method to Widen the IF Bandwidth of an SIS Mixer," in *Proceedings of the Twenty-fourth International Symposium on Space Terahertz Technology*, 2013.