A Dual Polarized Quasi-Optical SIS Mixer at 550-GHz

Goutam Chattopadhyay, *Member, IEEE*, David Miller, Henry G. LeDuc, and Jonas Zmuidzinas, *Member, IEEE*

Abstract— **We describe the design, fabrication, and the performance of a low-noise dual-polarized quasi-optical superconductor insulator superconductor (SIS) mixer at 550 GHz. The mixer utilizes a novel cross-slot antenna on a hyperhemispherical substrate lens, two junction tuning circuits, niobium trilayer junctions, and an IF circuit containing a lumped element 180° hybrid. The antenna consists of an orthogonal pair of twin-slot antennas, and has four feed points, two for each polarization. Each feed point is coupled to a two-junction SIS mixer. The 180° IF hybrid is implemented using a lumped element/microstrip circuit located inside the mixer block. Fourier transform spectrometer (FTS) measurements of the mixer frequency response show good agreement with computer simulations. The measured co-polarized and cross-polarized patterns for both polarizations also agree with the theoretical predictions. The noise performance of the dual-polarized mixer is excellent, giving uncorrected receiver noise temperature of better than 115 K (DSB) at 528 GHz for both the polarizations.**

I. Introduction

DRAMATIC advances in millimeter and submillimeter wave receivers in recent years have resulted from the development of sensitive superconductor insulator superconductor (SIS) mixers, which now offer unsurpassed performance from 70 GHz to 1 THz. In principle, the sensitivity of SIS mixers is limited only by the zero-point quantum fluctuations of the electromagnetic field. In terms of the single-sideband (SSB) noise temperature, this limit is $h\nu/k_{\rm B} \approx 0.05$ K/GHz. In practice, the SSB noise temperatures of the best SIS receivers now fall below 0.5 K/GHz over the 100–700 GHz band, dropping as low as 0.2 K/GHz in some cases.

For radio astronomy applications, one way to increase the sensitivity of SIS receivers further is to use a dual polarized receiver. When both polarizations are received simultaneously, there is a $\sqrt{2}$ improvement in signal to noise (S/N), or a factor of two reduction in observing time. Dual polarization operation can be achieved by using a wire-grid polarizer to split the telescope beam into two polarizations. The local oscillator (LO) can be injected using a beamsplitter, either after the polarizer, in which case two beamsplitters are necessary; or before the polarizer, necessitating a single, correctly oriented beamsplitter. Either approach tends to lead to fairly complicated optical designs, especially for receivers with multiple bands, or multiple spatial pixels. A much more elegant and compact solution is to directly construct a dual-polarization mixer. This is reasonably straightforward for quasi-optical designs, since the receiving antenna is lithographically fabricated, and can be designed to receive both polarizations simultaneously. The slot-ring mixer is one such example where a single annular (circular or square-shaped) slot is used, which is fed at two points which are 90° apart, and which has been shown to provide good results at 94 GHz [1]. A slot-ring antenna could easily be adapted for use in a SIS mixer. One drawback for this antenna is that it has a broader radiation pattern (in angle) than the twin-slot antenna [2]. This is simply due to the fact that at any given frequency, the transverse dimensions of a slot-ring are smaller than those of a twin-slot. This broader pattern of the slot-ring will be somewhat more difficult to couple to, so the efficiency will be a bit lower than for a twin-slot. However, we adapted the twin-slot antenna for dual-polarization simply by crossing two sets of slots at 90°, as shown in Fig. 1. In this case,

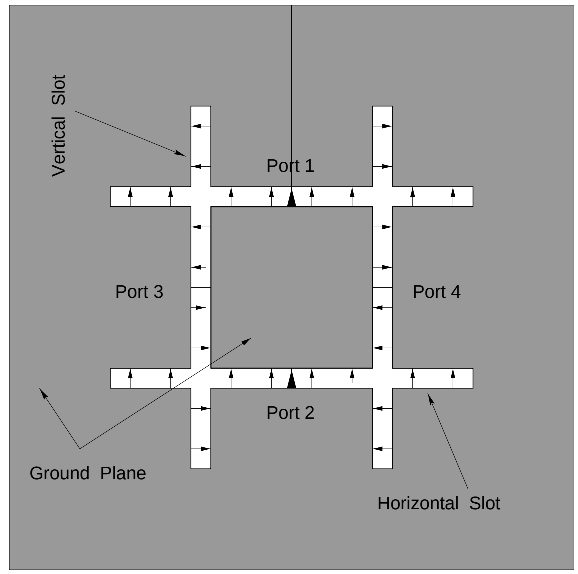

Fig. 1. Cross-slot antenna structure showing the field distribution in the slots when the two horizontal slots are excited symmetrically.

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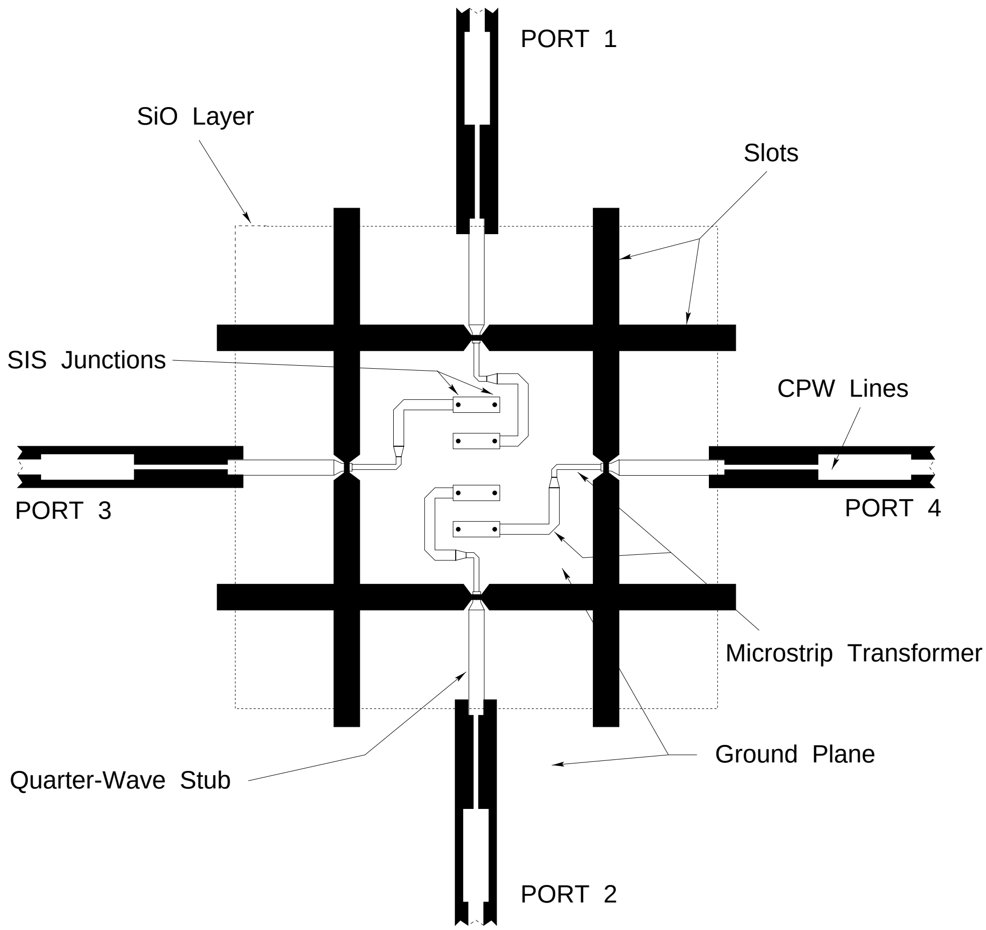


Fig. 2. Details of the mixer layout. CPW lines carry the IF output to the 180° hybrid. The junctions are placed as shown to allow suppression of the Josephson effect with a single magnet.

there are four feed points as can be seen in the figure. The field distribution in the slots can be intuitively obtained from symmetry considerations. In particular, the field distributions in the vertical slots must be antisymmetric and, therefore, the voltage at the orthogonal ports (3,4) must vanish. The characteristics of the cross-slot antenna have been calculated using the method of moments (MoM), and this design was found to have an excellent radiation pattern with fairly symmetric E-plane and H-plane beams, low impedance ($\approx 30\,\Omega$), wide bandwidth (the 1–dB impedance bandwidth for matching to a 30–Ω resistive load is about 40%), low cross polarization, and high coupling efficiency ($\approx 88\%$ for the co-polarized beam) [3].

II. Mixer Design and Fabrication

To design an SIS mixer using the crossed-slot antenna, the easiest method would be to couple a separate tuned SIS circuit to each of the four antenna ports. One possible concern in this approach would be that the resonant frequencies of the four SIS circuits might not all be the same, which would lead to degraded cross-polarization, and inferior performance overall. To minimize this effect, we decided to use tuning circuits in which the junction *separation* dictates the tuning inductance [4]. For two-junction tuning circuits, since both junctions are defined in the same lithography step, the tuning inductance is nearly immune to registration errors between layers. The four SIS circuits are combined into the two horizontal and vertical polarization outputs simply by biasing them in series from IF port 1 to 2, and from 3 to 4. This also eliminates the necessity of attaching an electrical connection to the isolated ground plane at the center of the cross-slot with the ground plane outside the slots. Fig. 2 shows the details of the mixer layout. The two section microstrip transformer, shown in Fig. 2, allows a good impedance match between the antenna ($\approx 30\ \Omega$) and the tunnel junctions ($R_n/2 \approx 7\ \Omega$). The relatively low antenna impedance promotes good matching to even low resistance tunnel junctions. We used a simulation program, developed in house [5], to simulate and optimize the RF device performance.

We used JPL's all optical-lithography junction fabrication process to fabricate junctions with three different junction areas $1.44\,\mu\mathrm{m}^2$, $1.69\,\mu\mathrm{m}^2$, and $1.96\,\mu\mathrm{m}^2$. Though the design was optimized for $1.69\,\mu\mathrm{m}^2$ area junctions, we decided to fabricate three different junction area devices to allow for process variations. We used a three mask level Nb/Al-Oxide/Nb junction fabrication with a 2000 Å thick

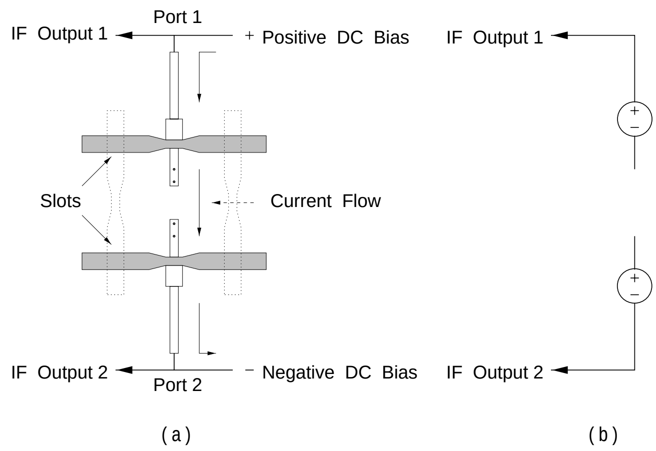


Fig. 3. Schematic showing how the two IF outputs for a given polarization are 180° out of phase: (a) shows the current flow for biasing the junctions in series and (b) shows the equivalent circuit.

niobium ground plane, 2500 Å thick niobium wiring layer and a single layer of 2000 Å thick SiO, which is used as the dielectric for the superconducting microstrip line. The SIS mixer chip is placed on a hyperhemispherical silicon substrate lens. It can be seen from Fig. 2 that for each polarization there are two IF outputs and four SIS junctions, for a total of eight junctions on the chip. In principle, single junction mixers could also be used, which would require only four junctions per chip.

Due to the mixer structure and the series bias of the junction pairs, it turns out that the two IF outputs for a given polarization are 180° out of phase. This can be easily explained. For a given polarization (we choose the horizontal pair of slots, as shown in Fig. 3(a)), the LO and RF will have the same relative phase at either port (1 or 2), so we would expect the IF currents to be in phase. However, due to the series biasing of the junctions, one junction pair is "forward" biased while the other is "reverse" biased. As shown in the equivalent circuit in Fig. 3(b), the two IF outputs are 180° out of phase, and thus a 180° hybrid is necessary to combine the two IF outputs for a given polarization. The hybrid circuit is designed using a first order lowpass-highpass filter combination, whose 1–dB bandwidth at 1.5 GHz center frequency is more than 500 MHz. The hybrid is implemented using a combination lumped element/microstrip circuit and is located inside the mixer block. The circuit was optimized using Hewlett Packard's microwave design system (MDS) [6] to deliver maximum power to a 50 Ω load (the LNA input) from two 180° out of phase 30 Ω generators (the SIS IF outputs). The input reflection coefficient (S_{11}) of the lumped hybrid IF circuit was measured at cryogenic temperatures to evaluate its performance and to verify the design.

III. Receiver Configuration

A general view of the receiver configuration is shown in Fig. 4. The LO used is a tunable Gunn oscillator with a varactor multiplier [7], [8]. The RF and the LO signals pass through a 10 μm thick mylar beamsplitter and the combined signals travel into the cryostat through a 3.8 mm thick crystal quartz pressure window at room temperature, followed by a 0.1 mm thick Zitex [9] IR filter at 77 K. Inside the cryostat the well-collimated ($\approx F/17$) beam is matched to the broad beam pattern of the cross-slot antenna with a polyethylene lens and a silicon hyperhemispherical lens with anti-reflection (AR) coating of alumina-loaded epoxy [10], [11]. The quartz pressure window is AR coated with Teflon.

For the dual-polarization mixer, we used our existing single polarization mixer block, described in detail by Gaidis *et al.* [12], with some minor modifications, such as a second SMA connector to bring out two IF outputs for the two polarizations. Fig. 5 presents a detailed view of the mixer block and the associated circuitry. Fig. 5(a) shows a disassembled block with the mixer chip at the center. Fig. 5(b) shows the hardware details for the mixer block and Fig. 5(c) shows the bias and IF circuitry. The back side of the SIS mixer chip is glued [13] to one side of a silicon support disk, and the silicon hyperhemisphere is glued [13] to the opposite side of the disk. The SIS devices are fabricated on a 0.25 mm thick, 50 mm diameter silicon wafer, which is then diced into 2.0 x 2.0 mm individual chips. The high resistivity (> 1000 Ω–cm) silicon support disk is 2.5 cm in diameter and 1.0 mm thick. The silicon hyperhemisphere is similar to the one described by Gaidis *et al.* [12].

DC bias supply and readout leads enter from the multi-pin connector on the right, and the mixer IF outputs, after being combined by the 180° hybrids, are carried on two different microstrip lines to SMA connectors on the left of the block. The schematic in Fig. 5(c) details the circuitry on the printed circuit board. The IF-blocking spiral inductors (17 nH) at liquid helium temperature (4.2 K) add $\ll 1\ \Omega$ series resistance. The SIS mixer chip sits within a through hole at the center of the board, allowing straight forward wire-bonding of the mixer chip to the biasing network and to the 180° hybrid circuits.

The picture in Fig. 5(d) shows the assembled mixer

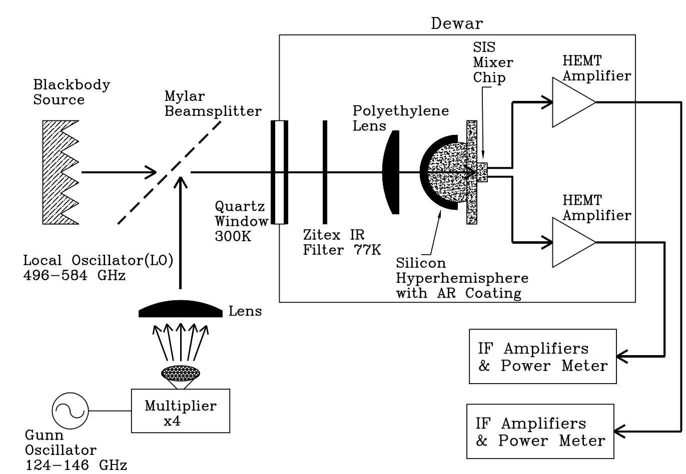
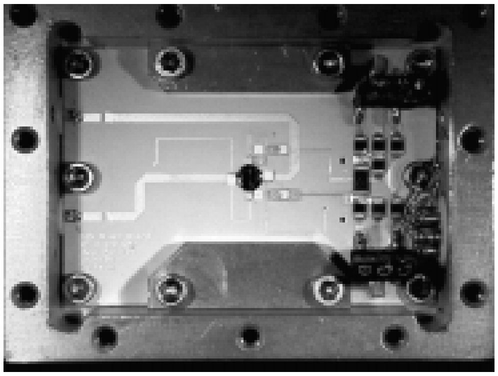
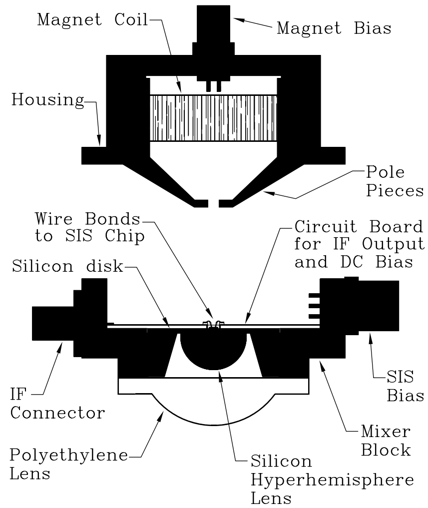


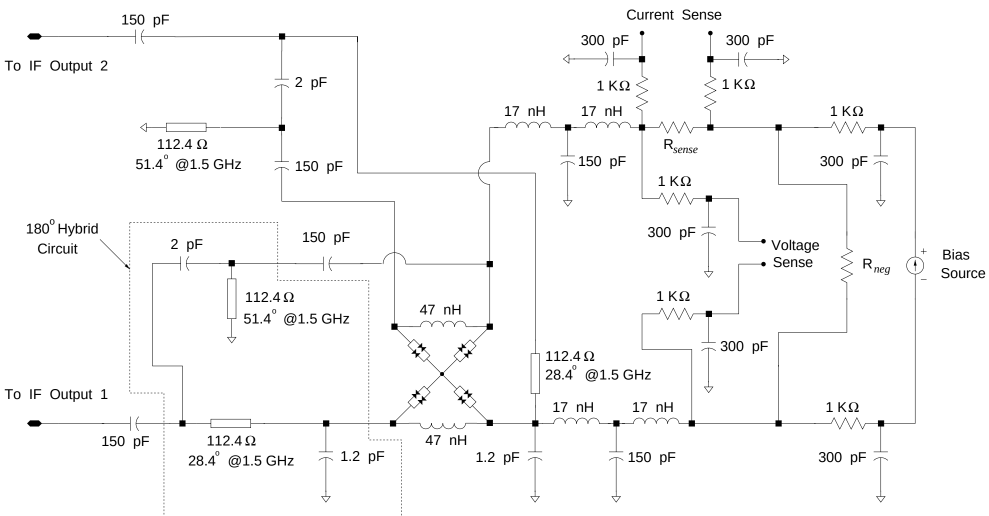
Fig. 4. Simplified receiver layout. The elements within the dewar are mounted on a 4.2 K cold plate.



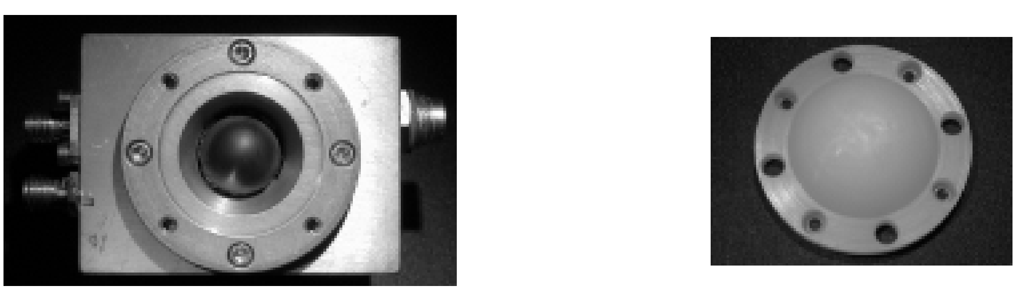
(a)



(b)



(c)



(d)

Fig. 5. Details of the mixer block and associated circuitry: (a) shows the block revealing the internal components, (b) provides a key to the hardware used within the block, (c) shows the details of biasing and IF circuits on the printed circuit board, (d) shows actual picture of an assembled block, with the polyethylene lens removed to show the AR coated silicon hyperhemisphere.

block, with the polyethylene lens removed to reveal the silicon hyperhemispherical lens. Semi-rigid coaxial cables connect the SMA IF output ports with HEMT low noise amplifiers (LNAs). The measurements presented below were obtained using a 1.0–2.0 GHz LNA with measured noise temperatures of 5 K [15]. The LNA outputs are sent to room temperature amplifiers and diode detectors which measure the total power in a 500 MHz IF bandwidth.

IV. Measurement and Results

A. Antenna Beam Pattern Measurements

The beam pattern of the dual-polarized antenna was measured with an antenna measurement system which consists of an aperture limited chopped hot-cold load on a x-z linear stage, stepper motors to drive the linear stage, a lock-in amplifier, and a data acquisition system [16]. The IF output of the mixer is detected, amplified, and fed to the lock-in amplifier. The hot-cold load linear stage was placed 24 cm away from the cryostat vacuum window for our beam pattern measurements. The hot-cold load aperture was set at 3.2 mm and the lock-in amplifier time constant was set at 3 seconds, giving signal to noise of about 18 dB for the measurement set-up. The mixer was pumped with a 528 GHz LO source. The hot-cold RF signal and the LO were coupled to the junctions through a 10 μm thick beamsplitter. Fig. 6 shows the co-polarized beam pattern along with E-plane and H-plane cuts for the horizontal pair of slots. The E-plane beam is wider than the H-plane beam (as is expected) for both the polarizations. For the horizontal slots, the E-plane and H-plane FWHM was found to be 4.4 degrees and 3.4 degrees respectively, giving E/H ratio of 1.3, which is higher than our theoretical prediction of 1.14. Similarly, for the vertical slots, the E-plane and H-plane FWHM was found to be 4.3 degrees and 3.1 degrees respectively. The discrepancy between the measured and the calculated beam width ratio may be due to the misalignment of the mixer-chip with respect to the silicon hyperhemispherical lens. It can be seen in Fig. 6(a) that the beam is stretched a bit towards the bottom end of the E-plane. This asymmetry is not expected theoretically and may be indicative of chip/lens misalignment. Initially, we thought that this could be the result of distortion of the shape of the plastic lens at liquid helium temperature (4.2 K). To verify that, we made measurements after rotating the plastic lens to different angles, but we did not notice any significant change in the beam pattern. We are currently developing better methods to align the chip with respect to the silicon lens.

For cross-polarization measurement we used a wire-grid polarizer in front of the cryostat window. The hot-cold load aperture was set at 6.4 mm and the lock-in ampli-

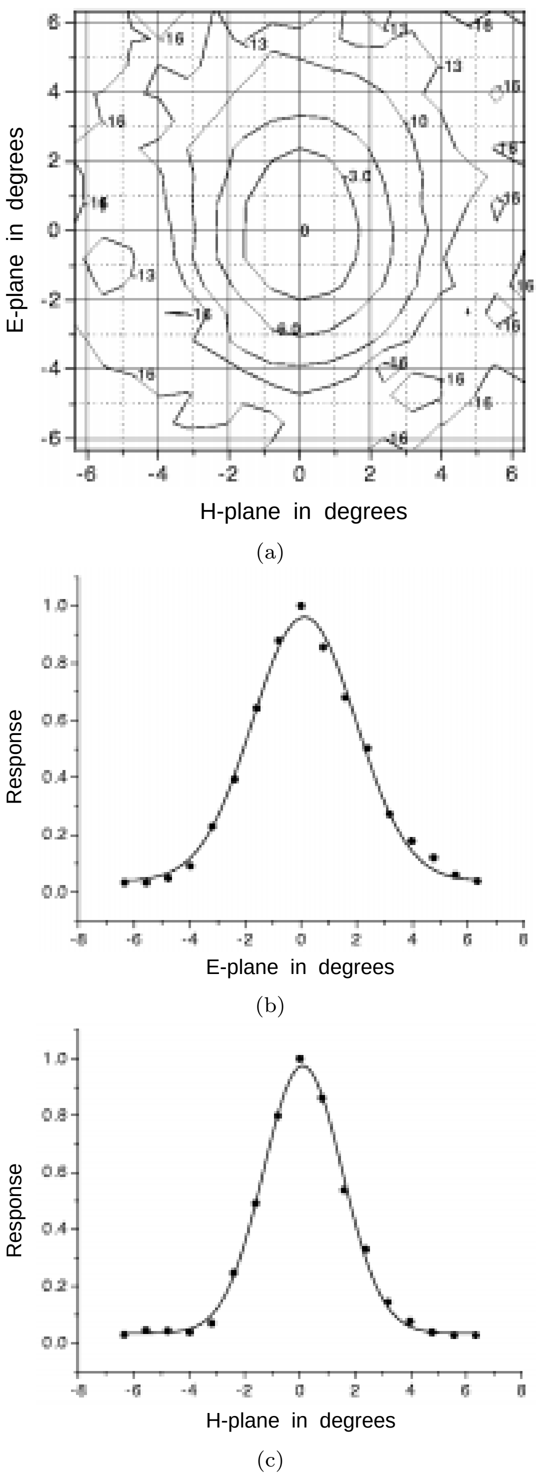


Fig. 6. Antenna beam pattern for the horizontal pair of slots: (a) shows the contour plot, (b) and (c) are the E-plane and H-plane cuts for the beam. The LO frequency for the beam pattern measurement was set at 528 GHz.

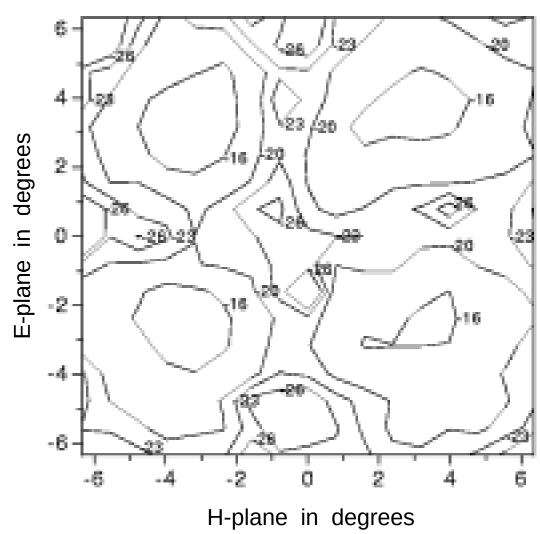


Fig. 7. Cross-polarization beam pattern in dB relative to peak co-polarized power. The LO frequency for the beam pattern measurement was set at 528 GHz.

fier time constant was set at 10 seconds, which improved the signal to noise to about 28 dB. The cross-polarization beam pattern is shown in Fig. 7. One can see from the cross-polarization plot that the four lobes are not identical, and we suspect that this is due to the misalignment of the mixer-chip. To verify this, we mounted another chip on the silicon hyperhemispherical lens, deliberately misaligning the chip with respect to the silicon lens. The resulting cross-polarization pattern indeed showed inferior cross-polarization performance, with the lower two side lobes of Fig. 7 stretching more towards the bottom of the E-plane. That clearly demonstrated that the chip alignment plays a significant role in cross-polarization level of the beam. The integrated cross-polarization level was found to be around -15 dB (compared to the integrated co-polarized beam), which includes the effects of the wire-grid polarizer and the beamsplitter.

B. Fourier Transform Spectroscopy

The receiver response as a function of frequency was measured with an FTS system built in-house using the mixer as a direct detector [17]. Fig. 8 shows the FTS response for two different polarizations of the receiver. The device we used for this measurement had 1.69 μm^2 area junctions and was optimized for 550 GHz frequency band. The FTS response agrees well with our simulation results, as can be seen from Fig. 8, given the non-idealities present in the measurement: strong water absorption lines at 557 GHz and 752 GHz, and Fabry-Perot resonances from the IR filter spaced approximately 50 GHz apart. The FTS response is very similar for both the polarizations, and the peak response was found at 528 GHz, which means that the best noise temperature for these devices would be around this frequency.

C. Heterodyne Measurements

We measured the noise temperature of the receiver, with both the polarizations simultaneously active, using the Y–factor method. The cryostat temperature was 4.2 K for all the measurements. The noise temperatures reported here are referred to the input of the beamsplitter; *no corrections have been made for beamsplitter or any other optical losses.* We mounted the device at 45° angle with respect to the horizontal microstrip line shown in Fig. 5(a). The junctions were biased as shown in Fig. 5(c), where the IF outputs of the two different polarizations are isolated from each other by two 47 nH spiral inductors. A single LO source pumped the junctions for both the polarizations simultaneously. It was very important to check that we indeed were observing dual-polarization operation, and we confirmed that experimentally. We placed a wire-grid polarizer in between the beamsplitter input and a cold load (80 K). As we rotated the grid about the optical axis, the two IF outputs were observed to increase or decrease independently, depending on whether the corresponding mixer could *see* the cold load behind the wire-gird. This clearly demonstrated that the mixer was operating in dual polarization mode.

We adjusted the LO and the magnet current to get a smooth IF output for both the polarizations and then measured the noise temperature. Fig. 9 shows the pumped and the unpumped I–V curves along with the IF outputs in a 500 MHz bandwidth at 528 GHz LO frequency when hot and cold loads (absorber at room temperature and at 80 K respectively) are placed at the receiver input. The pumped I–V curves clearly show the photon step around V $\approx$ 1.4 mV, as expected from a 528 GHz LO source ($h\nu/e \approx$ 2.2 mV). Since the junctions are in series, the gap voltage is at 5.8 mV and the photon step will appear at 5.8 mV - 2 x 2.2 mV = 1.4 mV. We measured nearly identical DSB

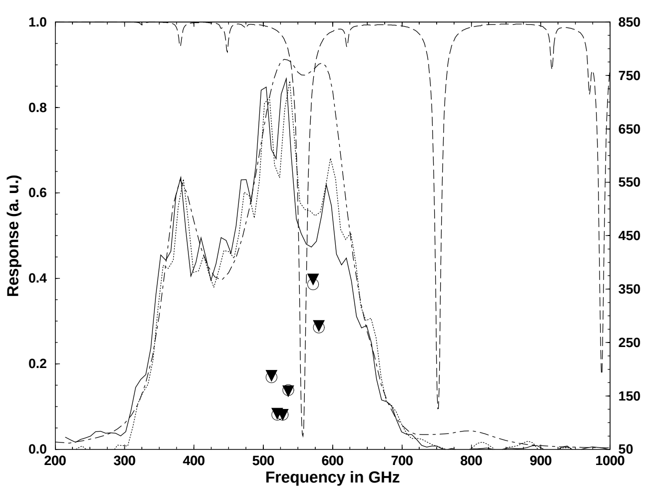


Fig. 8. FTS measured response along with the simulation results. The solid line is for the "horizontal" polarization and the dotted line is for the "vertical" polarization. The dot-dashed line shows the simulated frequency response using nominal device parameters. The long-dashed line shows the transmission of the FTS instrument. Also shown are the mixer noise temperatures as a function of frequency, the circles are for the "horizontal" polarization and the triangles are for the "vertical" polarization.

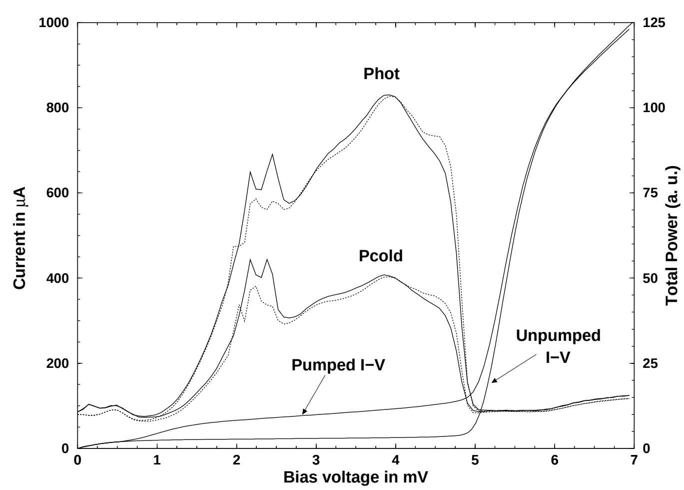


Fig. 9. Current and IF output power versus bias voltage at 4.2 K when we measured both the polarizations simultaneously. The solid lines are for the "horizontal" polarization and the dotted lines are for the "vertical" polarization. The LO frequency for both polarization was 528 GHz and the measured DSB receiver noise temperatures were 115 K. The LO-pumped and unpumped I–V curves actually plotted for both polarizations but are indistinguishable on this scale.

noise temperature of 115 K for both the polarizations at 528 GHz. The mixer noise temperature as a function of frequency was found to be very similar for both the polarizations and is shown in Fig. 8.

V. Conclusion

We have designed, fabricated and measured a dual-polarized quasi-optical SIS receiver at 550 GHz using a cross-slot antenna structure on a anti-reflection coated hyperhemispherical silicon lens which gives excellent noise temperature performance (115 K DSB) for both the polarizations. The measured antenna radiation patterns agree reasonably well with theoretical predictions. We have shown that this receiver has almost identical performance for both the polarizations, and could be very effectively used for submillimeter radio astronomy observations. Wider IF bandwidths are possible through the use of a more sophisticated 180° hybrid design, perhaps integrated on-chip. It is also possible to use this device as a balanced mixer [18].

Acknowledgments

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From 1988 to 1989, he was a postdoctoral fellow at the University of Illinois, where he worked on the design and fabrication of SIS mixers. He is currently an Associate Professor of Physics at the California Institute of Technology, Pasadena, CA. His research interests are in the areas of high-frequency superconducting devices and their application to submillimeter astronomy.