A Planar Quasi-Optical SIS Receiver

Philip A. Stimson, Robert J. Dengler, Henry G. LeDuc, Scott R. Cypher and Peter H. Siegel

***Abstract*—A novel planar, quasi-optical SIS receiver operating at 230 GHz is described. The receiver consists of a 2×5 array of half wave dipole antennas with niobium-aluminum oxide-niobium SIS junctions on a quartz dielectric-filled parabola. The 1.4 GHz intermediate frequency is coupled from the mixer via coplanar strip transmission lines and 4:1 balun transformers. The receiver is operated at 4.2 K in a liquid helium immersion cryostat. We report here accurate measurements of the performance of single untuned array receiver elements. A mixer noise temperature of 89 K DSB, receiver noise temperature of 156 K DSB and conversion loss of 8 dB into a matched load have been obtained. This mixer noise temperature is approximately a factor of two larger than that of current state of the art waveguide mixers using untuned single junctions at the same frequency.**

I. Introduction

The QUASIPARTICLE superconductor-insulator-superconductor (SIS) mixer is the most sensitive detector in the millimeter-wave region and forms the basis of most high quality receivers for millimeter-wave astronomy [1]. The quantum limit for noise temperature ($1/2 \cdot h\nu/k$ in a SSB mixer) has essentially been reached at 100 GHz [2], [6], but at higher frequencies the performance is poorer, with 10 times the quantum limit being a more realistic goal. This figure has recently been reported from the best waveguide mixers around 200 GHz [3], [4], [5], [18]. The major cause of the performance reduction at high frequency is the SIS junction capacitance, which presents a smaller parallel reactance and shunts the quasiparticle response. Tuning structures can, in principle, alleviate this limitation but are not yet well developed at higher frequencies [8]. The approach most often used, and that used here, is to fabricate high current density junctions with small areas ($<1\ \mu m^2$) to reduce the capacitance. Another serious problem is control of Josephson currents in the junction. Noise temperatures obtained with broadband hot and cold loads be highly inaccurate in the presence of Josephson currents. These effects become more important as the frequency and/or RF bandwidth is increased. Other problems include losses in conductors and dielectrics, the fabrication of small waveguide components and difficulties in obtaining convenient local oscillators.

Quasi-optical receivers with planar circuit mixers are an attractive approach for systems at frequencies in the neighborhood of 1 THz [7]–[9]. They suffer the disadvantage of being fixed tuned but provide the advantage of convenient monolithic fabrication; small waveguide components are not required. Planar configurations are also a desirable approach to realizing array receivers.

In this paper, we report accurate measurements on a quasi-optical receiver at 230 GHz. Our configuration is designed as a 10 element array receiver. However, we report here the best performance of single array elements using two different junction areas. This is because initially poor junction yield (~50%) prevented us from obtaining wafers in which all ten SIS junction elements worked. We have now obtained wafers in which all ten elements work and will report on complete array performance in the near future. The junctions used for these experiments were nominally identical to those used in recent waveguide receivers [3], [4], with which our results may be compared.

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II. Mixer Block

The mixer block, shown in Fig. 1, consists of the junction/antenna wafer, a quartz filled reflector, and IF baluns and connectors mounted in a brass housing. The wafer is clamped on the flat face of the quartz parabolic lens, whose rear surface is metalized. Incoming radiation passes through the quartz, is reflected by the metal surface and focussed onto the antenna elements at the center of the wafer. The configuration, called a Dielectric-Filled Parabola (DFP), is similar to a conventional parabolic dish antenna. The effect of the dielectric substrate is to greatly concentrate the fields radiated into the quartz at the expense of those radiated into the air [19], simulating a conventional feed. The IF signals are coupled from the wafer via coplanar strip transmission lines. Monolithic IF baluns transform the 200 Ω characteristic impedance of the coplanar strips to that of 50 Ω coaxial transmission line. A schematic diagram is shown in Fig. 2. Details of this design are described by Siegel *et al.* [10], [16].

The dielectric filled parabola configuration is conceptually similar to the hyperhemispherical or elliptical lens conventionally used in quasi-optical millimeter-wave receiver systems. The advantages of the DFP include well known off-axis aberrations which are smaller than those of the hyperhemisphere, a crucial factor for an array receiver, the ability to avoid a diplexer for LO coupling, less dielectric loss due to the thinner substrate and a flat front surface which can make realizing antireflection coatings and Schmidt plates easier. The disadvantages include the requirement to numerically mill the reflector and grind the parabolic lens and the inability to use slot antennas.

The antenna configuration used for the experiments described here was a 2×5 array of resonant dipoles, shown in Fig. 3. The antenna lengths and widths are 407 μm and

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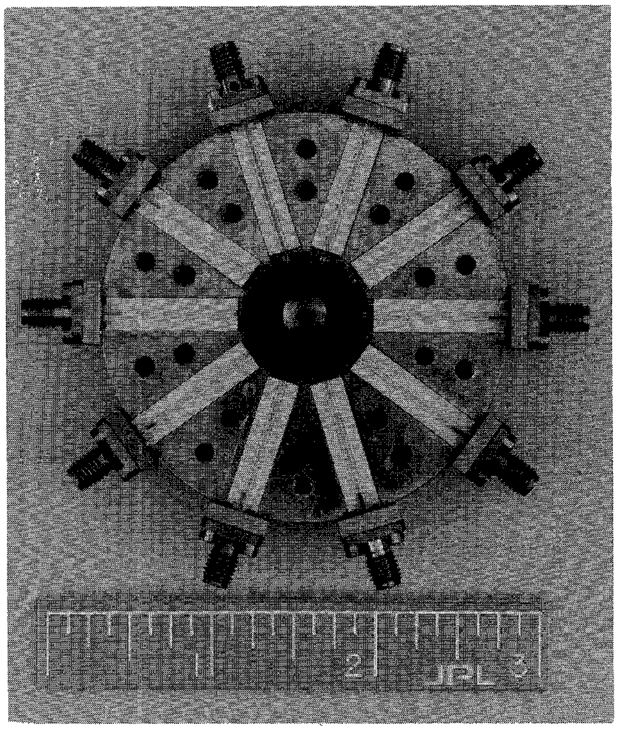

Fig. 1. The mixer block with the upper half removed. The central dielectric-filled parabola (dark), containing the antenna and mixer elements, is surrounded by 10 IF baluns (light) and SSMA connectors at the edge of the block. (Scale in inches.)

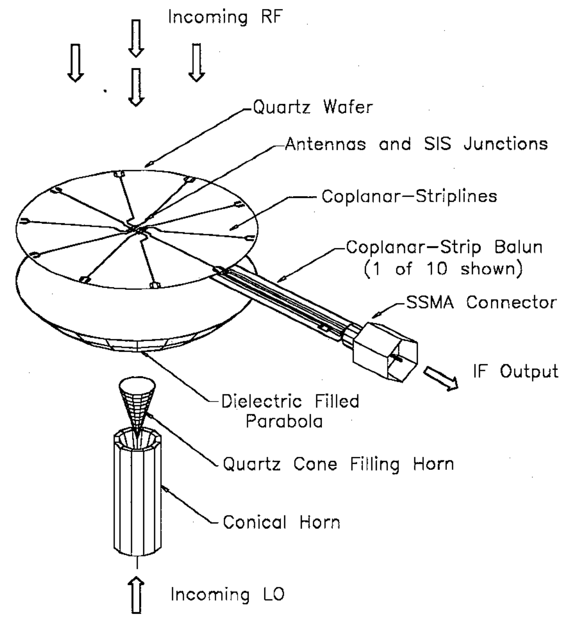

Fig. 2. An exploded schematic diagram of the planar receiver. The IF signal from each of the ten antennas is coupled out via a coplanar strip balun and SSMA connector, only one of which is shown.

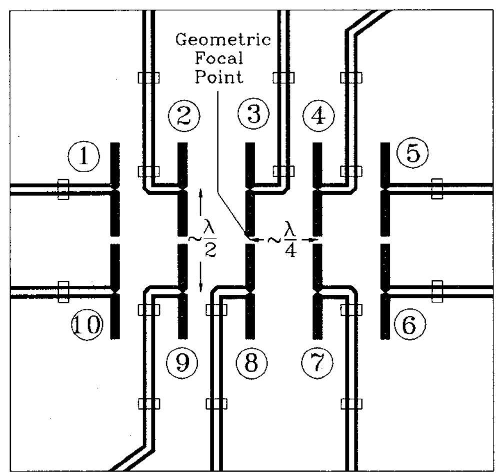

Fig. 3. The ten resonant dipole antennas at the wafer center are spaced $0.53\lambda_e$ and $0.35\lambda_e$ apart in the E and H-planes respectively and fed by 200 Ω coplanar strips. The rectangles on the transmission lines are RF blocking capacitors.

38 μm respectively and the spacings in the E and H-plane are 445 μm and 292 μm. This represents an E and H-plane spacing of $0.53\lambda_e$ and $0.35\lambda_e$ respectively at 230 GHz. The wavelength λ_e is based upon the effective dielectric constant seen by the antennas on the quartz-air interface ($\epsilon_e = 2.4$). Dipoles were chosen because the calculated dipole terminal impedance of approximately 50 Ω provides a good match to the expected RF impedance of the SIS junctions, and because they are conveniently fed by 200 Ω coplanar strips which match the expected junction IF impedance. Two RF blocking capacitors are located one quarter and three quarter wavelengths away from the antenna terminals down the coplanar strips. The routing of the coplanar strips near the antennas was optimized experimentally on a 20 GHz model to produce minimum distortion to the antenna patterns. The antennas, SIS junctions, coplanar strips and capacitors were all fabricated monolithically, directly on a single wafer. No post-processing was performed after the wafer was fabricated other than bonding the pads at the ends of the coplanar strips to the balun transformers.

Principal plane antenna patterns for a single, central antenna at the geometric focal point of the parabola (not one of the antennas shown in Fig. 3) and an edge element (such as antenna 1 in Fig. 3) performed on a 20 GHz scale model of the mixer block, are shown in Figs. 4 and 5. For the off axis element, the E-plane scan was taken at the H-plane angle corresponding to maximum received power, and vice versa. Two dimensional antenna patterns were also performed, and the beam parameters given in Table I extracted. The actual millimeter-wave quartz parabola has a diameter of 20 mm (~30 wavelengths at 230 GHz) and an f/D ratio of 0.25, and produces a narrow beam designed to couple to that of an f/10 millimeter-wave telescope with 3-dB beamwidths of approximately 6° in both the E and H-planes for all elements. The first side-lobe (coma lobe) rises from −22 dB for the central antenna to −12 dB for the edge element (worst case). The cross polarized radiation is maximum out of the principal planes. (The parameters in Table I are from the 2-D patterns.) Its value is quite high because a wide dipole ($l/w \sim 10$) has been used to increase the bandwidth. The parabolic reflector is considerably under-illuminated by the feed antennas which leads to a low system efficiency for coupling to a plane wave incident on the entire reflector area. We point out however, that minimizing the reflector diameter was not an important design criterion in this device.

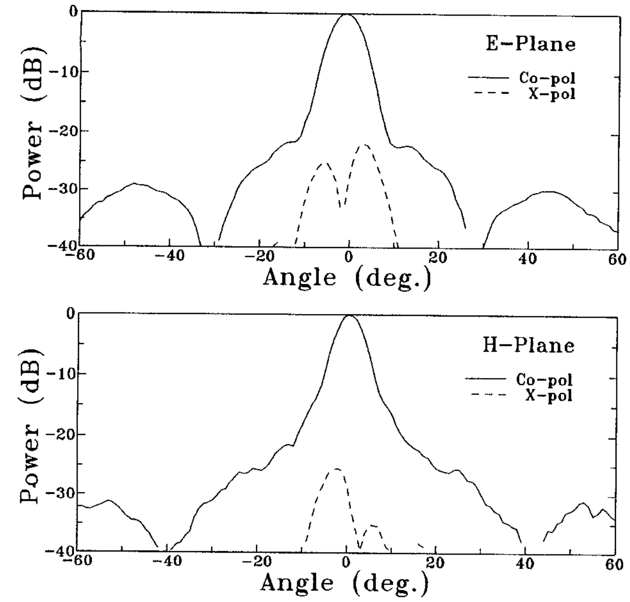

Fig. 4. Antenna patterns of a single antenna element at the geometric focus of the parabola measured on a 20 GHz model of the mixer block.

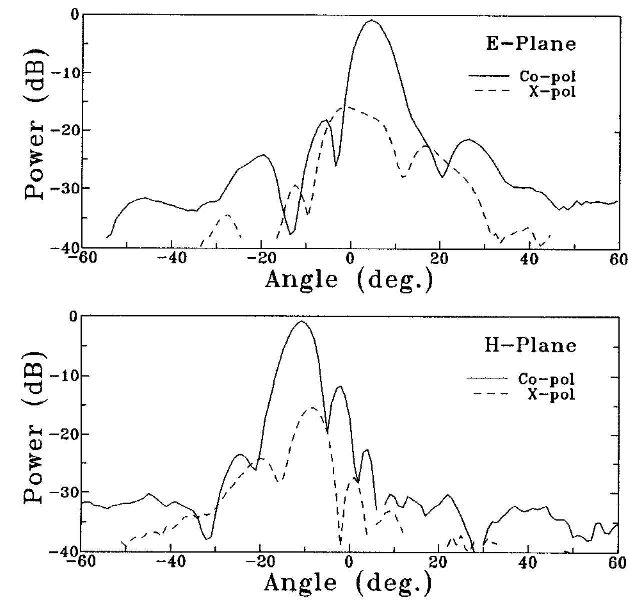

Fig. 5. Antenna patterns of an edge antenna element measured on a 20 GHz model of the mixer block.

III. SIS Junction Fabrication

The SIS junctions used in the receiver were fabricated using a self aligned lift-off trilayer process [20]. The niobium-aluminum oxide-niobium trilayer was sputtered onto the 0.25 mm thick, 20 m diameter quartz substrate through a photoresist stencil. The trilayer remaining after lift-off formed half of each antenna and the ten coplanar strip transmission lines used for the IF. The junction mesa was patterned using electron beam lithography on 1200 Å thick PMMA over a 4000 Å thick polyimide layer, followed by evaporation of 500 Å of chromium metal and lift-off. The contact regions were protected with a resist stencil and transferred to the polyimide underlayer by reactive ion etching in an oxygen plasma. The chromium/polyimide mask was then used to etch the junction. Evaporated SiO was deposited using the same stencil to provide electrical isolation of the base electrode and to provide dielectric for the two capacitors. The polyimide was then removed with dichloromethane. The second half of the antennas was made by deposition of niobium and reactive ion etching. Junction areas of 0.5 μm^2 and 0.2 μm^2 were used for the experiments described here.

TABLE I
Antenna Pattern Parameters for a Central Antenna Element and an Edge Element Measured on a 20 GHz Model

	Central Elt.	Edge Elt.
Beam Direction (E, H-plane)	0°, 0°	3.5°, 11°
E-Plane Beamwidth (3 dB)	6.7°	6.5°
H-Plane Beamwidth (3 dB)	5.9°	6.1°
Directivity	28.0 dB	27.6 dB
Main Beam Efficiency	80%	77%
Max. Side Lobe	-22 dB	-12 dB
Max. Cross Pol.	-16 dB	-10 dB
Total Cross Pol. Power	9%	12%

IV. Receiver Design

The IF system shown in Fig. 6, consists of ten IF cables routed through two 6-position coaxial switches and one 2-position switch to a single amplifier chain. The remaining two switch positions are used to connect a short and a variable temperature IF load to the amplifier input. The load consists of a resistor terminating a stainless steel coaxial cable on a thermally isolated plate which contains a heater resistor and temperature sensor. The structure is enclosed in an indium sealed can. This permits accurate calibration of the IF system and accurate mixer measurements [11]. An isolator is used to reduce the SWR at the amplifier input and a directional coupler with cooled attenuators allows signals to be injected into the IF system to measure the mixer reflection coefficient. After removal from the cryostat the IF signal is further amplified, passed through a variable center frequency 50 MHz wide filter and fed to a power detector. The IF system noise temperature is approximately 7 K at 1.4 GHz as shown in Fig. 7.

The optical system consists of a chopper mounted directly in front of the mixer, and the hot and cold loads. When the chopper blade is closed the input beam is directed onto a 4 K (cold) load mounted on the receiver plate; when it is open the beam passes through a quartz window to a 77 K (hot) load mounted on the liquid nitrogen shield of the cryostat. The chopper (constructed in our lab) is driven by a motor mounted on top of the cryostat via a vacuum sealed stainless steel tube shaft. Rotation speeds up to a few hertz do not result in excessive agitation of the helium. The loads are pyramidal absorbers manufactured from Eccosorb CR-110, which is known to provide high absorption and low reflection at this frequency. Reflection from a flat plate of CR-110 has been measured at less than -10 dB in this frequency range [12]. The window is exactly five wavelengths (in the quartz)

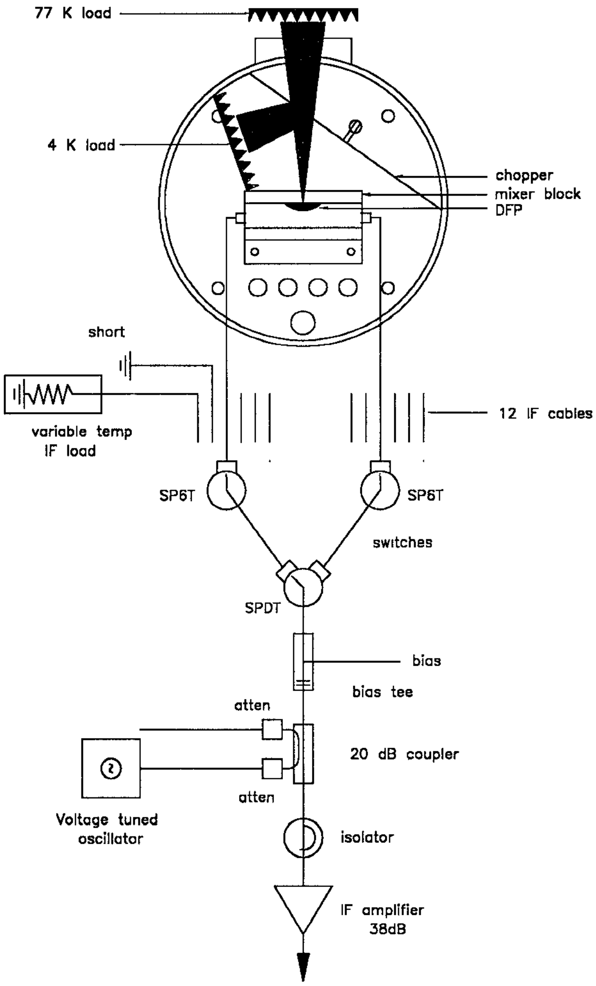

Fig. 6. Schematic diagram of the IF system of the receiver. The antenna elements are switched sequentially into the single filter-amplifier chain.

thick and passes almost all the incident 230 GHz radiation. The theoretical transmittance is 0.999 at 4 K (the loss is assumed to be zero at 4 K); we measured a transmittance of over 0.95 at 20 C. Local oscillator radiation is produced by a Gunn diode and Schottky diode doubler and is injected through the back of the mixer block using a quartz filled circular horn tapering from WR-3 waveguide. No diplexer is required. The entire receiver is immersed in liquid helium which eliminates heat sinking problems. The dielectric constant of the helium is 1.048 [15].

V. Measurement Technique

We use a variation of the technique of McGrath *et al*. [11], to obtain mixer gain and noise temperature. First, the IF system is calibrated by plotting the IF output power as a function of the temperature of the IF load. This measures the IF system noise temperature T_{IF}. The receiver noise temperature T_R is measured using the hot and cold loads (T_H and T_C), the ratio of the IF output powers $Y = P_{\mathrm{IF}H}/P_{\mathrm{IF}C}$ and (1).

$$T_R = \frac{T_H - YT_C}{Y-1} \tag{1}$$

$$T_M = T_R - \frac{(T_{\mathrm{IF}} + T_S\Gamma^2)}{(1-\Gamma^2)} L_M \tag{2}$$

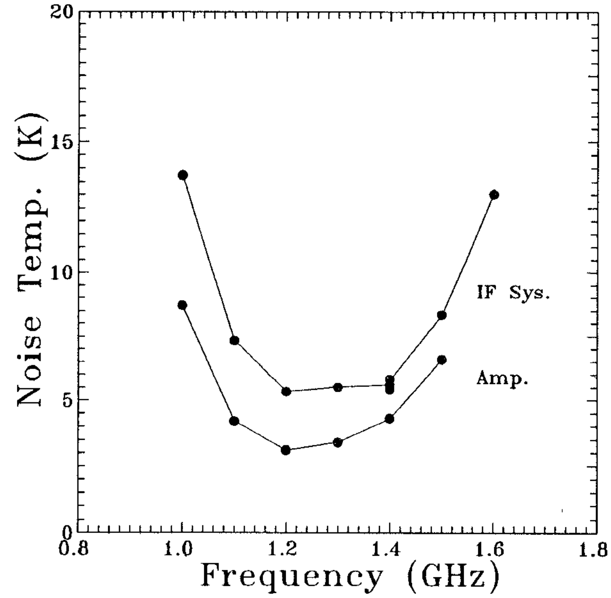

Fig. 7. IF system noise temperature and amplifier noise temperature as a function of IF frequency.

$$\frac{1}{L_M} = \left(\frac{T_{\mathrm{IF}H} - T_{\mathrm{IF}C}}{T_H - T_C}\right)\left(\frac{1}{1-\Gamma^2}\right) \tag{3}$$

Next, the temperatures of the IF load, $T_{\mathrm{IF}H}$ and $T_{\mathrm{IF}C}$, which produce output powers $P_{\mathrm{IF}H}$ and $P_{\mathrm{IF}C}$ are calculated from the calibration, and the effective bath temperature T_S determined by measuring the power output from the IF system with a shorted input. The IF reflection coefficient of the mixer Γ is measured by injecting a signal from a voltage tuned oscillator through the coupler and recording the difference in reflection between the mixer and the short. The loss into a matched load and noise temperature are then calculated from (2) and (3).

VI. Results

Typical pumped and unpumped IV characteristics are shown in Fig. 8, and IF output power as a function of bias voltage for hot and cold load inputs is shown in Fig. 9. A superconducting magnetic field coil mounted on the mixer block was used to suppress Josephson currents in the junctions. The IF curve exhibits a smooth oscillatory behavior similar to that expected from theory [13], [14] with no sharp spikes or discontinuities. The IF output power is expected to decline towards zero bias; the fact that there is some power output at zero bias indicates some remaining Josephson currents which were not fully suppressed. These remain visible on the IF curve even though the IV curve appears smooth. Nevertheless, we believe that this is the best IF behavior reported from a planar quasi-optical SIS receiver.

The best results obtained with this receiver used SIS junctions with an area of 0.2 μm^2. The normal state resistance was 56 Ω, the critical density was 1.5 μA μm^{-2} (15 kAcm^{-2}) and the ωRC product of the junctions was approximately 2. The mixer and receiver noise temperatures and mixer conversion loss are plotted as a function of IF frequency in Fig. 10. The LO frequency was 230 GHz. The lowest noise is achieved at 1.35 GHz where a T_M of 89 K DSB, a T_R of 156 K

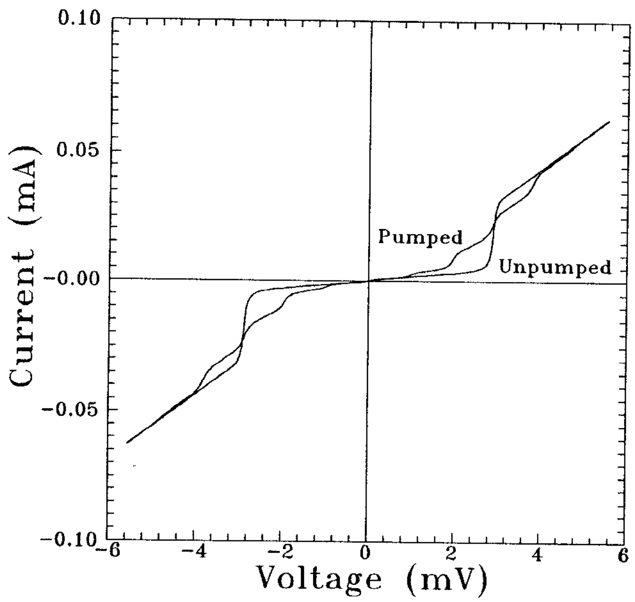

Fig. 8. Typical pumped and unpumped IV curves for a Nb-AlO$_x$-Nb SIS junction used in the planar receiver.

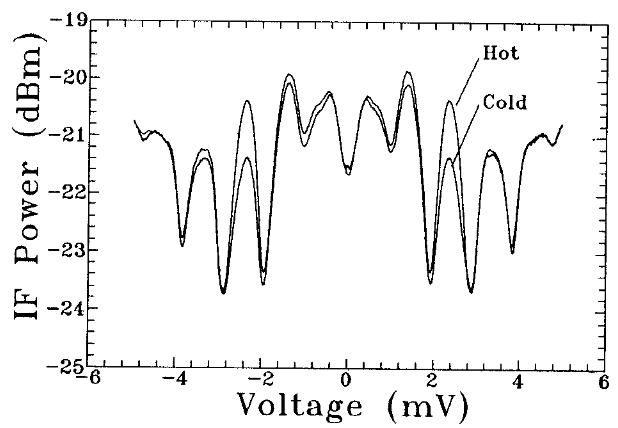

Fig. 9. IF output power as a function of bias voltage for hot and cold load inputs. The curve exhibits a smooth oscillatory behavior similar to that expected from theory with no sharp spikes or discontinuities indicating excellent control of Josephson currents.

DSB and conversion losses of 8 dB (into a matched load) were measured. The IF mismatch loss is approximately 1 dB across the IF band. Estimated uncertainties in the noise temperatures are ±5 K, and in the loss, ±0.5 dB. These values neglect any uncertainty due to RF load reflections or beam spillover. The largest Y-factor was obtained on the first quasiparticle step below the energy gap, at a bias voltage of approximately 2.3 mV. An inferior Y-factor was noted on the second step. The mixer noise temperature and conversion loss are seen to be essentially constant across the IF band. Mixer noise temperature is referred to the optically coupled loads at the system input and includes the effects of all components through to the IF connectors at the output of the balun transformers. The receiver noise temperature follows the noise behavior of the IF amplifier.

At each data point on the curves, the change in IF reflection coefficient, and the change in bias point, caused by switching

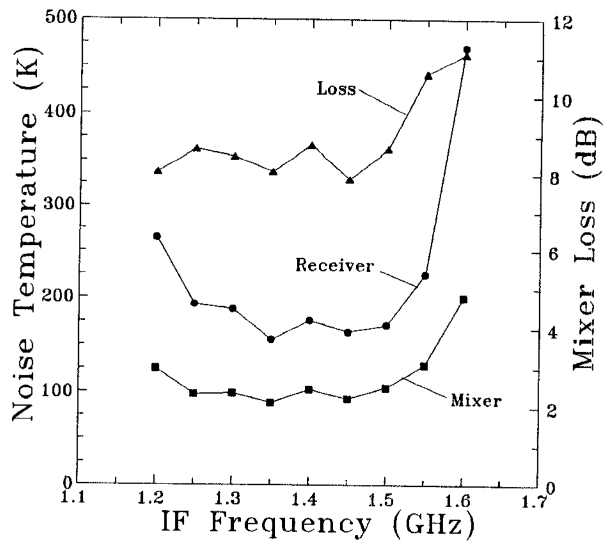

Fig. 10. Mixer and receiver DSB noise temperatures and mixer loss as a function of IF frequency for 0.2 μm^2 junctions. The best results are obtained at 1.35 GHz where a T_M of 89 K, a T_R of 156 K and conversion losses of 8 dB were measured.

between the hot and cold loads was measured. This was necessary to ensure that the observed Y-factor was not produced by different LO pumping conditions, or change in bias point when observing the hot and cold loads. Different pumping would be expected to change the junction output impedance and the IV curve shape. The reflection coefficient change was verified to be less than 1%, and the change in bias voltage less than 0.02 mV. This indicates that the observed Y-factor has no appreciable component due to these factors.

Experiments were also conducted using 0.5 μm^2 SIS junctions with a normal resistance of 80 Ω and a critical current density of 0.65 $\mu A \, \mu m^{-2}$ (6.5 $kAcm^{-2}$). The ωRC product was approximately 4. For these junctions the mixer noise temperature was approximately 150 K and the loss into a matched load 10 dB, across the IF band as shown in Fig. 11. The best receiver noise temperature was 259 K.

The results for the 0.2 μm^2 junctions were checked using a monochromatic RF signal produced by applying a voltage-tuned oscillator to the bias input of the LO multiplier to create sidebands of the LO. This method cannot give absolute results as the input power is unknown [17], but allows relative measurements to be performed. The variation in noise temperature and conversion loss over the IF band, and the variation with bias voltage, measured with this technique was found to be identical to that obtained with the broadband loads.

VII. Discussion

The planar receiver described here used SIS junctions produced in the same laboratory as those used in two recent state-of-the-art waveguide receivers [3], [4]. The waveguide devices used single untuned junctions and were designed and operated at the same frequency as our planar receiver. The junctions were of similar size, were produced by the same fabrication process and had very similar characteristics. It is

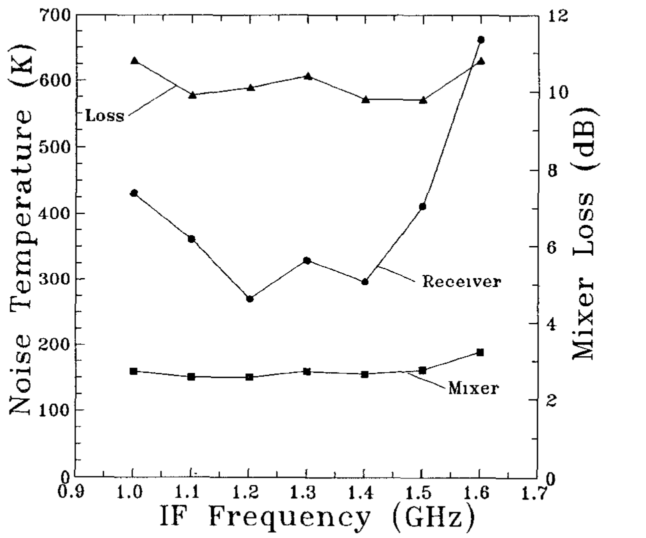

Fig. 11. Mixer and receiver DSB noise temperatures and mixer loss as a function of IF frequency for 0.5 μm^2 junctions. The best results are obtained at 1.2 GHz where a T_M of 150 K, a T_R of 259 K and conversion losses of 10 dB were measured.

therefore useful to compare the results obtained here with these receivers.

The waveguide receivers gave mixer noise temperatures of 60 K SSB and 48 K DSB respectively at 230 GHz. The mixer noise temperature of 89 K DSB reported here, despite being one of the lowest reported at this frequency from a planar circuit, is approximately a factor of 2 larger. The waveguide mixers obtained conversion losses of approximately 2 dB compared to 8 dB for our planar mixer. This indicates that planar mixers with no tuning may deliver good noise performance provided sufficiently small junctions are used. The reason for the high conversion loss of this mixer is not understood, though a value of 8–10 dB is typical of untuned planar devices [7], [9]. It is probable that tuning would reduce the loss.

We are in the process of measuring the absolute gain of the receiver elements.

VIII. Conclusion

We have demonstrated a planar quasi-optical SIS mixer and low noise receiver which is suitable for array applications. Best performance of an individual element at 230 GHz was a mixer noise temperature of 89 K DSB, a receiver temperature of 156 K DSB and a conversion loss of 8 dB. The IF output shows a smooth variation with bias, indicating good control of Josephson currents. The noise results are consistent with recent measurements using similar junctions in waveguide receivers, being only a factor of two higher. The conversion loss is rather large, but consistent with other planar mixer values. We will report on array performance in a future publication.

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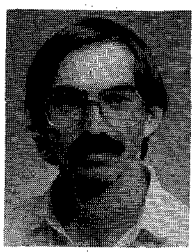
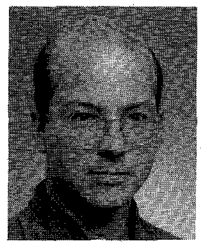
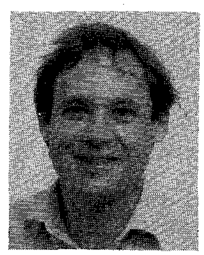


Henry G. LeDuc received his B.S. in physics from Montana State University, Bozeman in 1977, and the M.A. and Ph.D. in physics from the University of California, Davis in 1979 and 1983, respectively. His thesis work involved far-infrared spectroscopy of solid state ionic conductors.

He has been a Member of the Technical Staff at the California Institute of Technology's, Jet Propulsion Laboratory since 1983 and is currently the subgroup leader of the Low Temperature Superconductivity group. His group primary focus is the development of SIS tunnel junctions for heterodyne receiver applications.



Scott R. Cypher received the B.S. degree in 1987 from the State University of New York at Albany completing a double major in physics and computer science. During this time he also assisted in research of metal base transistors at the General Electric Corporate Research and Development Center in Schenectady, NY. He then joined the Sensor Technology group at California Institute of Technology's Jet Propulsion Laboratory, first working on the design and use of NbN/MgO/NbN edge junctions as SIS mixers. Currently he is working on fabrication and process control of planar Nb/AlOx/Nb SIS mixers.



Peter H. Siegel (S'77–M'83) was born in New Rochelle, NY in August 1954. He completed his undergraduate work at Colgate University, Hamilton, NY in Jan. 1976 and attended graduate school at Columbia University receiving his M.S. and Ph.D. degrees in electrical engineering in 1978 and 1983 respectively. From 1975 to 1983 Dr. Siegel worked on millimeter-wave components at the NASA Goddard Space Flight Center, Institute for Space Studies, NY, NY under Dr. A. R. Kerr. Following a one year fellowship with the National Research Council, Dr. Siegel went to Charlottesville, Virginia to work at the National Radio Astronomy Observatory under Dr. S. Weinreb where he was responsible for developing millimeter-wave mixers for the Kitt Peak 12 meter radio telescope. In 1987, Dr. Siegel joined the Microwave Observational Systems section of the California Institute of Technology Jet Propulsion Laboratory where he is currently a technical group leader for Submillimeter-Wave Radiometer development under Dr. M. A. Frerking.

Dr. Siegel's current research interests include millimeter-wave devices and subsystems. He is in charge of developing the millimeter and submillimeter-wave heterodyne front ends for the Earth Observing System Microwave Limb Sounder as well as working on advanced receiver technology for submillimeter-wave astrophysics.