# Wideband 3 mm SIS mixers operated with partial saturation


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## ABSTRACT

We built fixed-tuned SIS mixers for use between 70 and 115 GHz on the Berkeley-Illinois-Maryland Association (BIMA) array. The mixers are similar to 215 GHz SIS devices designed by R. Blundell et al. Our 1.4×1.4 $\mu$m Nb/Al–$Al_2O_3$/Nb junctions have extremely sharp I-V characteristics, with $R_{sg}/R_n \sim 40$, and $\omega$RC $\sim 2$. Heterodyne tests were made with a temperature-regulated vane mounted in the input waveguide to the mixer block. With vane temperatures of 20 and 35 K, we measure double sideband receiver temperatures $T_{rcvr}$ of 17 K from 80 to 115 GHz. Some gain compression occurs for input load temperatures greater than 50 K. Hence, with vane temperatures of 85 and 280 K we measure $T_{rcvr} \sim 35$ K. Similar noise temperatures are measured with 77 and 295 K loads mounted outside the dewar. Because the mixers are partially saturated, we bias the junctions approximately 0.1 mV above or below the gain maximum, where the receiver response is a nearly linear function of the input signal level. This yields $T_{rcvr}$ of 35–40 K and makes it possible to calibrate the receivers on the telescopes using the standard chopper wheel method.

With no LO power applied to the mixer, we observe a small IF signal which is proportional to the square of the input load temperature; we believe this is due to self-mixing of blackbody photons in the junction.

**Keywords:** mm waves; fixed-tuned SIS mixers; wideband receivers

## 1. INTRODUCTION

Nb-based SIS (superconductor-insulator-superconductor) tunnel junction mixers are presently the detectors of choice for radio telescopes operating in the 3 mm atmospheric window. SIS mixers have extremely low shot noise and approach quantum limited sensitivity ($T_n \sim h\nu/\mathrm{k}$), where the mixer noise power is dominated by fluctuations in the vacuum state of the incident radiation field. With advances in fabrication technology and integrated superconducting circuit design, receiver noise temperatures as low as $2-3$ h$\nu$/k have been achieved.[1] Typically, millimeter-wave mixers use waveguide-mounted SIS junctions impedance-matched to the input waveguide with mechanical tuners or with integrated tuning circuits. From a practical standpoint, mixers with integrated tuning circuits are superior. Their mechanical simplicity and compact geometry make them easy to build and convenient to install in small cryostats. Without mechanical backshorts, tuning is quick, reproducible, and conveniently automated.

In the past year the Berkeley-Illinois-Maryland Association (BIMA) array[2] has expanded to ten telescopes, requiring mass production of low noise 3 mm receivers with full waveguide bandwidth. For this application we decided to scale the fixed-tuned 176–256 GHz design of Blundell et al.[3] to lower frequencies. The mixers described by Blundell et al. have low noise temperatures over a 40% RF bandwidth and show minimal gain compression on room temperature loads. Our 3 mm devices perform well over a similar RF bandwidth, but typically show evidence for some gain compression even on 50 to 100 K thermal loads. Here we describe the design and test results for these mixers, and discuss how they can be tuned to operate in a linear regime under most observing conditions. These mixers are now in routine use on 9 of the 10 BIMA telescopes.

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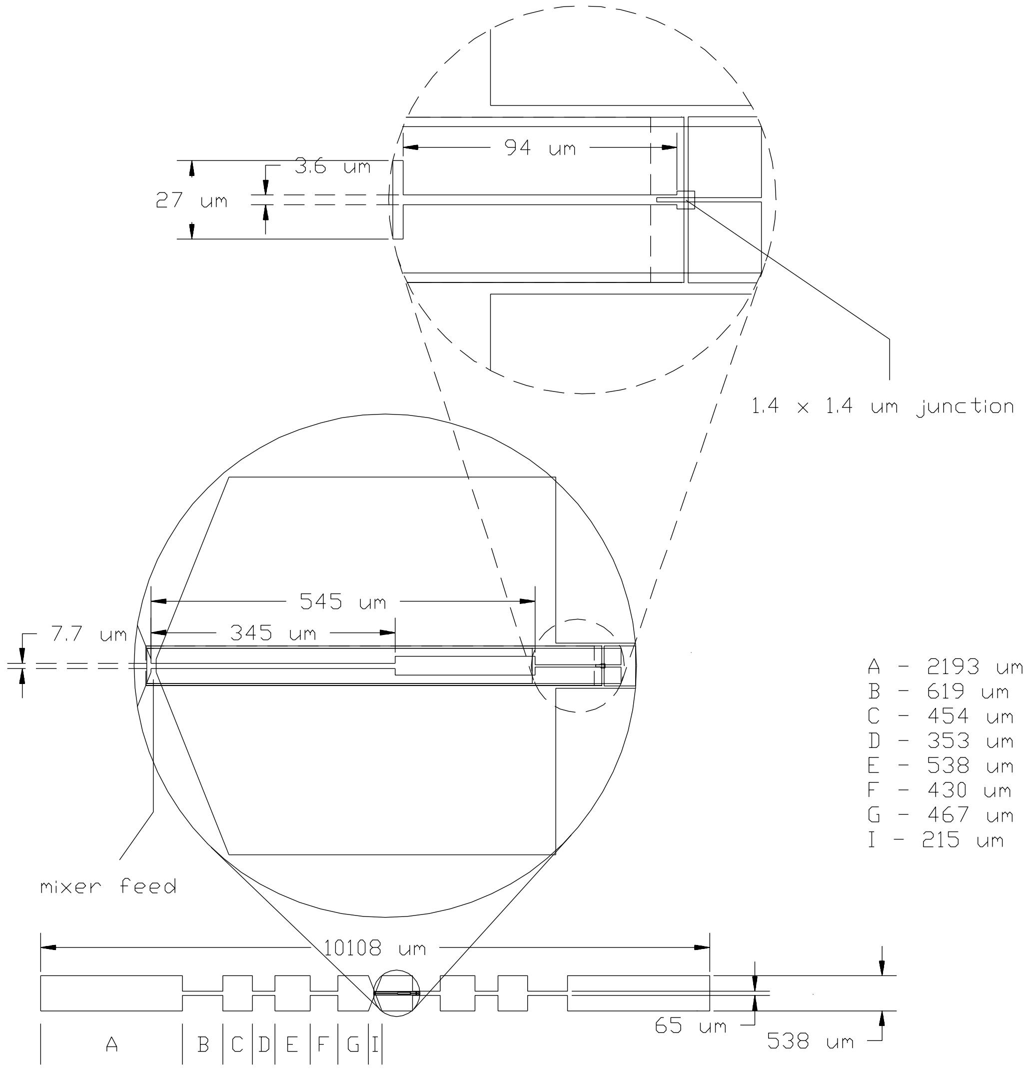


**Figure 1.** 3 mm mixer design.

## 2. DESIGN OF FIXED-TUNED MIXER

The mixer design employed by Blundell et al. uses a single SIS junction fed by a series inductive stub. The stub resonates out the junction capacitance, and the resulting real impedance is matched with a two-stage quarter-wave transformer to the mixer feed point, located at the center of a half-height waveguide. We adapted this design for use at 3 mm, similarly choosing $\omega$RC$\sim$ 2, which implies a critical current density of $\sim$5 kA/cm$^2$ for trilayer material with a specific capacitance of 80 fF/$\mu m^2$. At this current density our device yields per wafer were often 100%. To simulate the circuit we assumed that the SIS junction can be represented by a 160 fF capacitor in parallel with a 20 $\Omega$ normal resistance.

### 2.1. Layout and analysis of SIS circuit

The layout of the SIS device is shown in Figure 1. Over the instantaneous RF passband of the mixer the 94 $\times$ 3.6 $\mu$m inductive stub transforms the impedance of the 1.4 $\times$ 1.4 $\mu$m junction to a real value on the order of $R_n/(\omega RC)^2 \approx 5\ \Omega$. A two-section quarter-wave transformer matches the junction-loaded stub to the RF signal feed point, where the mixer embedding impedance is 35 $\Omega$. We optimized the elements of the SIS tuning circuit using PCIRCUIT, a program developed by J. Zmuidzinas for the analysis of superconducting microwave networks. The optimized passband

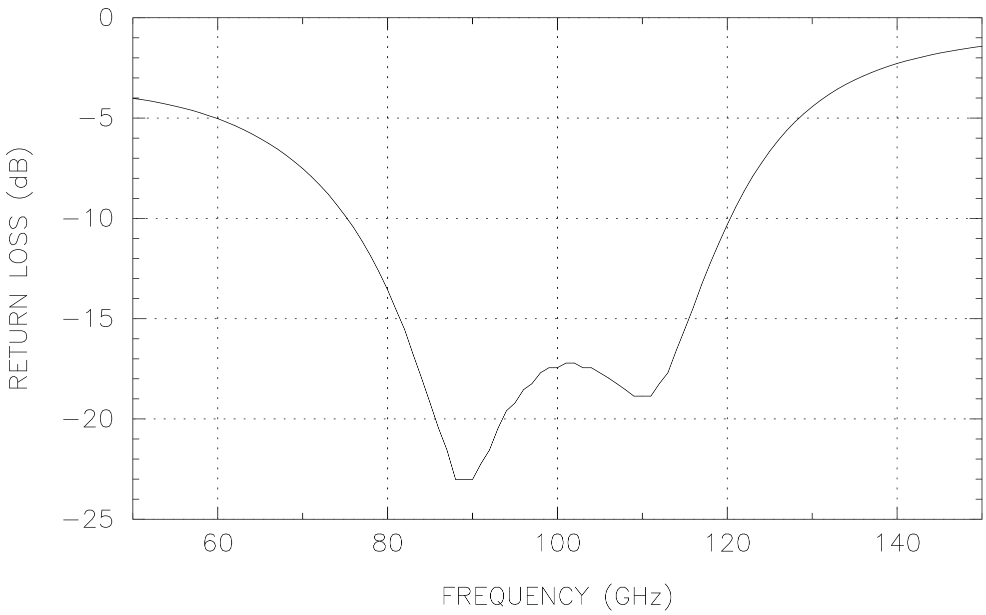


**Figure 2.** Calculated return loss of the SIS tuning circuit.

response is shown in Figure 2. The return loss is $< -10$ dB from 76 to 120 GHz. A symmetric low pass filter, shown at the bottom of Figure 1, blocks radiation from 70 to 120 GHz and passes frequencies from DC to 6 GHz.

## 2.2. SIS chip fabrication

Foundry facilities at the Material Research Lab and the Center for Compound Semiconductors at the University of Illinois were used to make the SIS chips. We developed a six-layer fabrication process, where each layer was patterned by photolithography and liftoff. First a large area Nb/Al–$Al_2O_3$/Nb trilayer is deposited on $0.010''$ thick crystalline quartz to form half of the symmetric RF feed-structure and low-pass filter. The junction is defined in two steps. A 1.4 $\mu$m line across the short dimension of a long, narrow rectangular window is patterned in photoresist on the trilayer, and the Nb counterelectrode on either side of the line is removed by reactive ion etching in a $CF_4 + O_2$ atmosphere. Then a 2000 $\AA$ thick layer of SiO is thermally evaporated onto the photoresist stencil. The base Nb electrode of the etched area serves as the ground plane, and the SiO layer as the dielectric, for the microstrip tuning circuit. After liftoff of the first insulation layer, this process is repeated with a photoresist line orthogonal to the first, which results in a 2 $\mu m^2$ junction. We used this two-step etching technique because it gives reproducible junction areas and high quality I-V characteristics. Two additional layers of SiO are deposited on the etched region so that, extending from the RF feed point to the junction, the insulation profile has steps of 8000, 4000, and 2000 $\AA$ for the two-stage impedance transformer, the inductor, and the junction contact pad, respectively. A Nb wiring layer defines the junction tuning circuit and the second half of the RF feed and low pass-filter structure. The two halves of the low-pass filter, electrically connected through the SIS junction and series inductance, provide the current path for the DC bias circuit.

## 2.3. Mixer block

Figure 3 shows the bottom half of the mixer block, with enlarged cross sectional views of the waveguide structure in which the SIS chip is mounted. The block is machined from TeCu with a numerically controlled milling machine. The quartz substrate is suspended in a channel with the metallization facing up and the feed structure centered over a $0.027''$ deep waveguide section. As indicated in views $x - x'$ and $y - y'$, the substrate is held in place by the top half of the mixer block, which contains the full-height to half-height WR-10 waveguide transition. A $0.001''$ diameter gold wire bonded to one end of the SIS low-pass filter connects the mixer to a bias tee/IF matching network. The other end of the SIS chip is grounded to the mixer block with a spring-loaded pin, which also helps to hold the chip in place. Channels milled into the block on either side of the waveguide accomodate two bent steel strips which focus

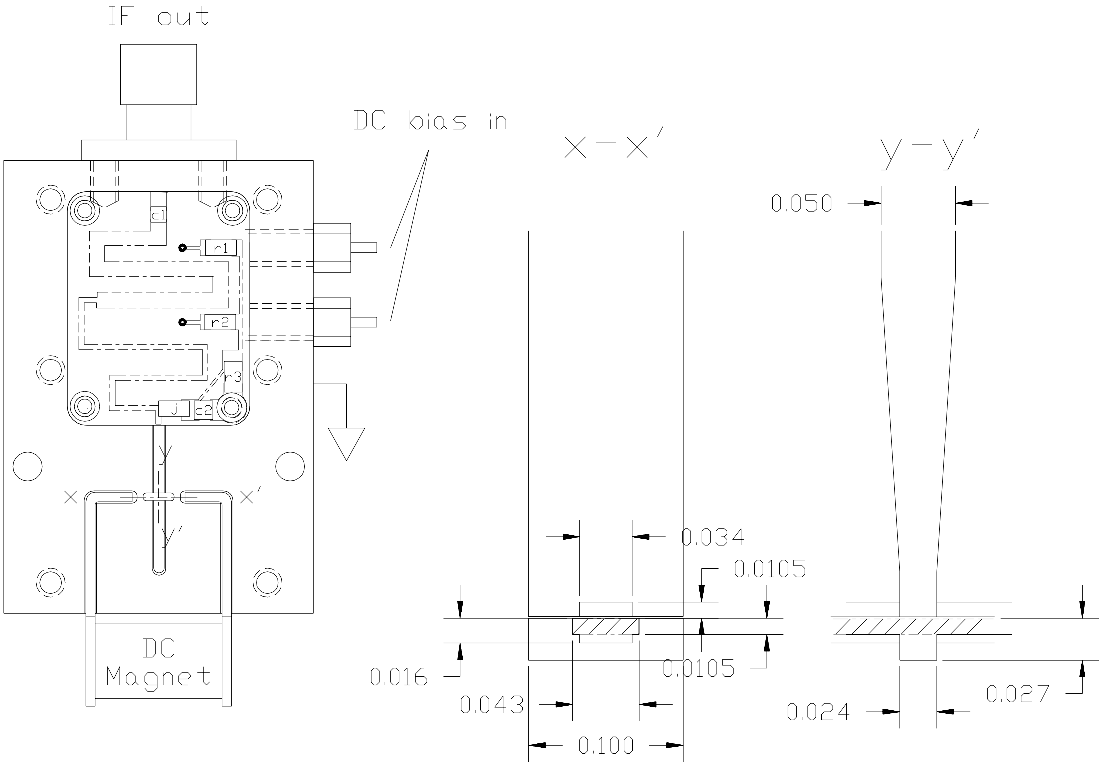


**Figure 3.** Mixer block with integral bias tee and IF matching circuit. Dimensions are in inches. The mixer substrate is hatched in cross sectional views $x - x'$ and $y - y'$.

**Table 1.** Bias tee circuit components

| label | component | function |
|---|---|---|
| r1,r2 | 10 KΩ | SIS protection |
| r3 | 100 Ω | voltage bias stability |
| c1 | 33 pF | IF coupling/DC block |
| c2 | 560 pF | IF filtering |
| j | 10 nH | DC bias/IF block |

the magnetic field from a permanent magnet onto the junction, suppressing Josephson currents which may adversely affect the mixer performance.

A circuit board mounted directly in the mixer block includes the matching network and bias tee. The matching network is designed to transform the $\sim$ 150 Ω IF output impedance of the junction to the 50 Ω input impedance of the HEMT amplifier. The bias tee components are listed in Table 1. The 10 kΩ resistors $r1$ and $r2$ limit the current which can be applied to the SIS junction and protect it from electrostatic discharge. The 100 Ω resistor $r3$, connected in parallel with the junction, allows stable DC biasing of the pumped junction when its dynamic resistance is very large, when the photon steps are nearly flat. The 10 nH inductor $j$ prevents the IF signal from leaking into the DC bias port; the 560 pF capacitor $c2$, in combination with $j$, forms a low-pass filter for the DC bias.

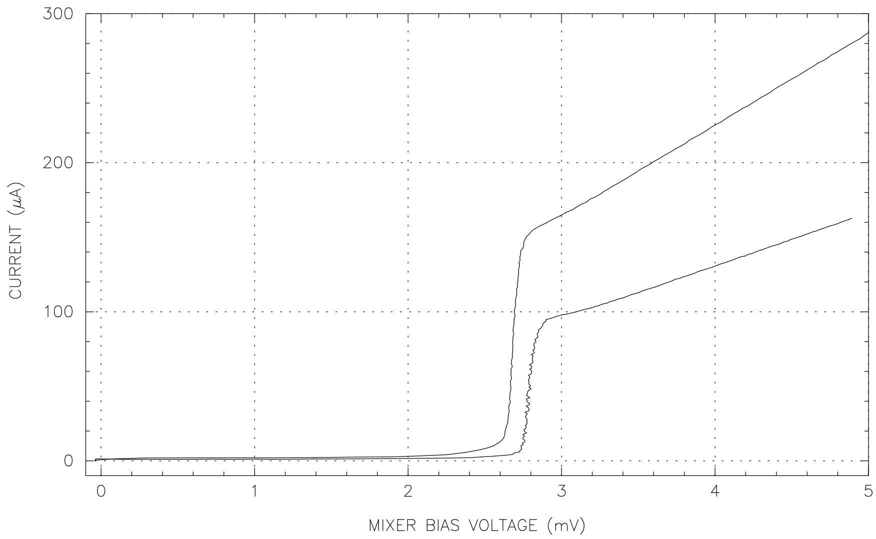


**Figure 4.** Unpumped I-V curves for two typical BIMA junctions. The measurements were made at 3.7 K.

## 3. MIXER TESTS

All mixer tests were done in a standard BIMA dewar[2] with mixers and corrugated feed horns cooled to 4 K by a closed-cycle Gifford-McMahon refrigerator. RF signals enter the dewar through a 300 K Teflon lens which serves as a vacuum window, then pass through Teflon windows in the 50 K and 15 K radiation shields before reaching the feed horn. A ∼0.5% reflecting Mylar beamsplitter mounted outside the dewar directs local oscillator power to the mixer. The IF port of the mixer is coupled with a 10 cm long stainless steel coaxial cable to a 3-stage HEMT amplifier mounted on the 15 K radiation shield. The IF bandwidth is 830 MHz, centered at 1750 MHz, and the input noise temperature of the IF amplifier chain is roughly 4 K.

Figure 4 shows the unpumped I-V curves for two representative BIMA junctions. The normal resistances are 17 and 28 ohms. The subgap to normal resistance ratios $R_{sg}/R_n$ are about 40.

### 3.1. RF Bandwidth

Figure 5 shows the double sideband receiver noise temperature measured as a function of LO frequency for a BIMA mixer. Measurements were made with 77 K and 295 K loads held in front of the beamsplitter, outside the dewar. The mixer was voltage biased on the first photon tunneling step – but not at the midpoint of the step, as discussed below. No corrections have been made for losses in the beamsplitter or dewar optics. In this case four sets of measurements were made, with the physical temperature of the mixer block regulated at 3.5, 4.5, 5.0, and 5.5 K. With the mixer between 3.5 and 4.5 K, the receiver noise temperature is in the range 35 to 40 K from 75 to 115 GHz.

### 3.2. Gain compression

We were surpised to find that biasing the junctions at the center of the first photon step rarely yields the best receiver temperatures. In general the optimum bias point is offset 0.08 to 0.15 mV from the center of the step. This suggests that the mixers are partially saturated, i.e. the input signal amplitude becomes too large to be treated as a linear perturbation on the applied LO drive.[4–6]

#### 3.2.1. Variable temperature load

To test whether the mixers were saturated, we built a variable temperature waveguide load which could be mounted directly to the input flange of the mixer, allowing tests of the mixer response with input temperatures of 20 to 300 K. Figure 6 shows the design. The load consists of a 0.002″ thick metallized mica vane (200 ohms/square) extending through a slot in the top wall of the waveguide. The vane is heated by a metal film resistor. The two resistor leads are soldered to strips of copper foil glued to either side of the vane; the foil strips are electrically isolated from each

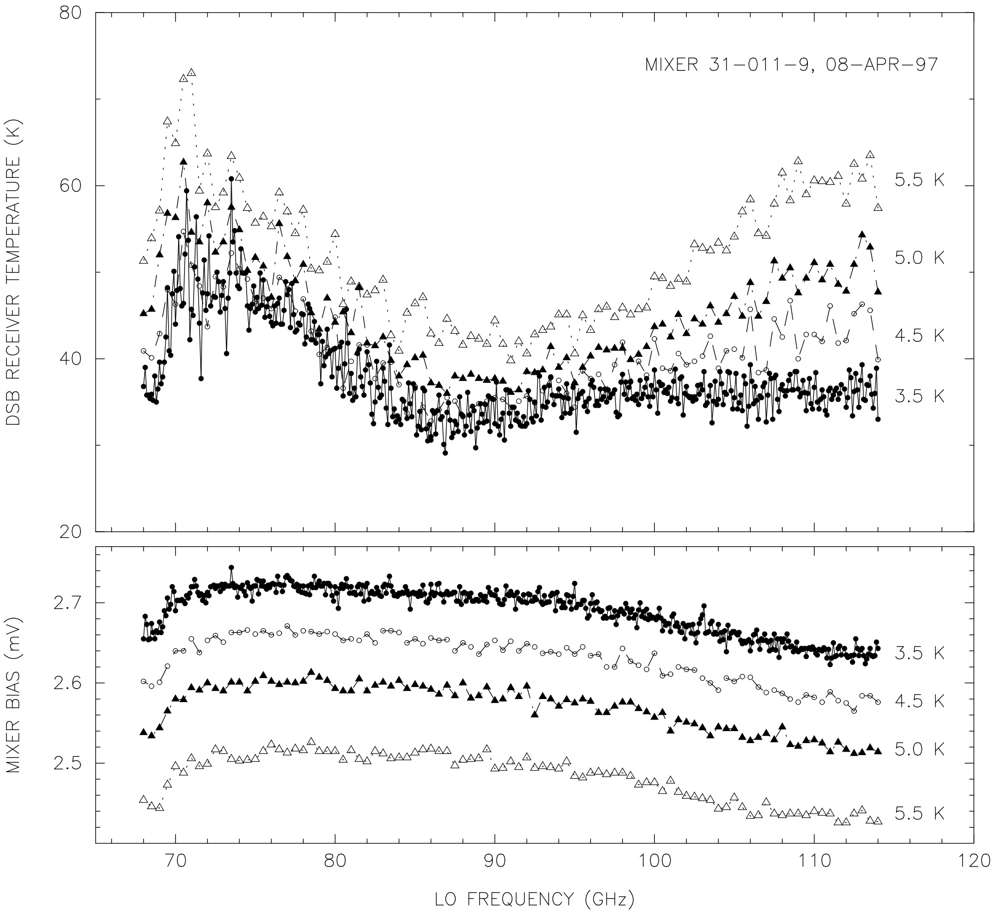


**Figure 5.** (*top panel*) Double sideband receiver noise temperatures as a function of LO frequency for a typical mixer. This is a fixed-tuned mixer with no mechanical adjustments. Four sets of measurements were made, with the mixer block regulated at 3.5, 4.5, 5.0, and 5.5 K. (*bottom panel*) Mixer bias voltages used for the measurements.

other by the layer of mica. A calibrated silicon diode temperature sensor also is soldered to one piece of foil. The vane/heater/sensor assembly is suspended from a thin-walled fiberglass tube which in turn is mounted to a bracket soldered to the waveguide. A thick copper strap heat sinks the bracket to the 12 K stage of the refrigerator. A radiation shield encloses the vane and fiberglass tube to minimize the heat load on the 4 K mixer block.

With a vane mass of only $\sim$0.25 g and maximum heater power of 0.5 W, the vane temperature can be driven from 20 K to 40 K in just 0.3 sec, and from 20 K to 300 K in 50 sec. A computer regulates the heater voltage, stabilizing the vane temperature within $\pm$0.1 K. With the heater off, thermal conduction through the fiberglass support tube and the pair of 34 gauge copper wires to the resistor cools the vane from 280 K to 20 K in approximately 600 sec.

The attenuation of the vane cannot be made arbitrarily large because local oscillator power must be transmitted through it. It is easy to calibrate the (cold) vane transmission by measuring the mixer response to 295 and 77 K loads outside the dewar. The transmission ranges from 4.2% at 75 GHz to 0.9% at 115 GHz. In computing receiver noise temperatures, we corrected the input load temperatures for leakage of room temperature radiation past the vane. For example, with the vane at a physical temperature of 20 K, the true load temperature at 115 GHz is 22.5 K. As it is heated, the vane expands and its attenuation increases slightly. Therefore, we were careful to readjust the LO power level before each measurement.

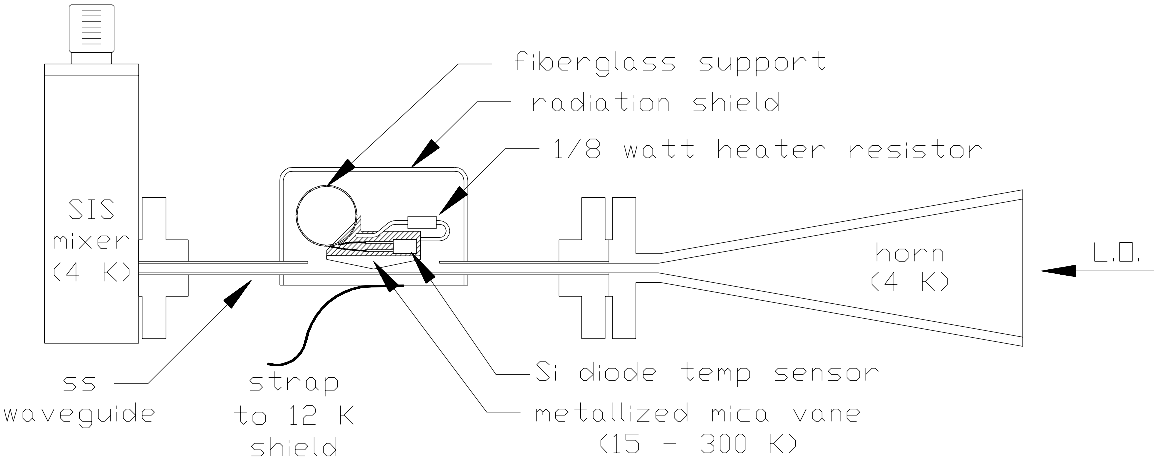


**Figure 6.** Variable temperature load.

### 3.2.2. Measurements with the variable temperature load

The results of a representative gain compression test are shown in Figure 7. The mixer response was measured as a function of bias voltage with the vane regulated at 20, 85, 150, 215, and 280 K. The I-V curves recorded for all vane temperatures are overlaid in the bottom panel of Figure 7; the photon-assisted tunnelling steps are clearly apparent. Note that the I-V curves are all identical. Hence, the shot noise and IF match do not change with vane temperature.

Receiver noise temperatures computed from the IF power ratios are shown as a function of bias voltage in the top panel of Figure 7. The noise temperature calculated for 20 and 85 K loads varies little across the extent of the first photon step. This suggests that the IF contribution to the receiver noise is low, implying that the conversion gain of the mixer is near unity or greater. The mixer has lower gain on the second photon step, but the noise temperatures are still quite good (37 K).

The inset in the middle panel clearly shows that the mixer response at the middle of the first photon step (open circles) is not a linear function of load temperature. If one fits a straight line to the 20 K and 85 K points, the predicted IF power at 215 K is 1.25 $\times$ the power observed – 1 dB gain compression occurs with a 215 K input load! Because the mixer response is partially saturated near the middle of the photon step, the receiver noise temperatures plotted in the top panel all show a "hump" at the middle of the step. As shown by the dashed curve, this hump is extremely pronounced if one computes the noise temperature from the 85 and 280 K data; this curve is nearly identical to what we measure with 77 K and 295 K loads outside the dewar, without the vane.

By offsetting the mixer bias from the center of the photon step, one can find a point where the IF power is related in a nearly linear fashion to the temperature of the input load. In Figure 7 this point lies 0.13 mV below the center of the step (see data marked by filled circles). The receiver noise temperatures show minima at this bias.

The data in Figure 7 hint that the mixer is partially saturated even with an 85 K input load. Hence, we made measurements of the noise temperatures with the vane at 20 and 35 K. Figure 8 compares these results with measurements made using 77 and 295 K loads outside the dewar. The average noise temperature from 80 to 115 GHz is 17 K with the cold vane, 32 K with the external loads. Vane measurements are not affected by losses in the dewar optics. However, we note that these losses must be small because noise temperatures measured with the vane at 85 and 280 K also give receiver temperatures of about 32 K. Hence, the higher noise temperatures measured on external loads are due largely to saturation, not optics losses.

## 3.3. Self-mixing of a broadband noise source

A possible source of confusion in noise temperature measurements is "self-mixing" of broadband RF noise by the sharply nonlinear SIS device. Evidence for this effect is presented in Figure 9, which shows a series of receiver measurements with no applied LO. At bias voltages between 2.1 and 2.6 mV, corresponding to the first photon tunneling step for $\sim$ 3 mm photons, the IF output power is proportional to the *square* of the input load temperature (inset,

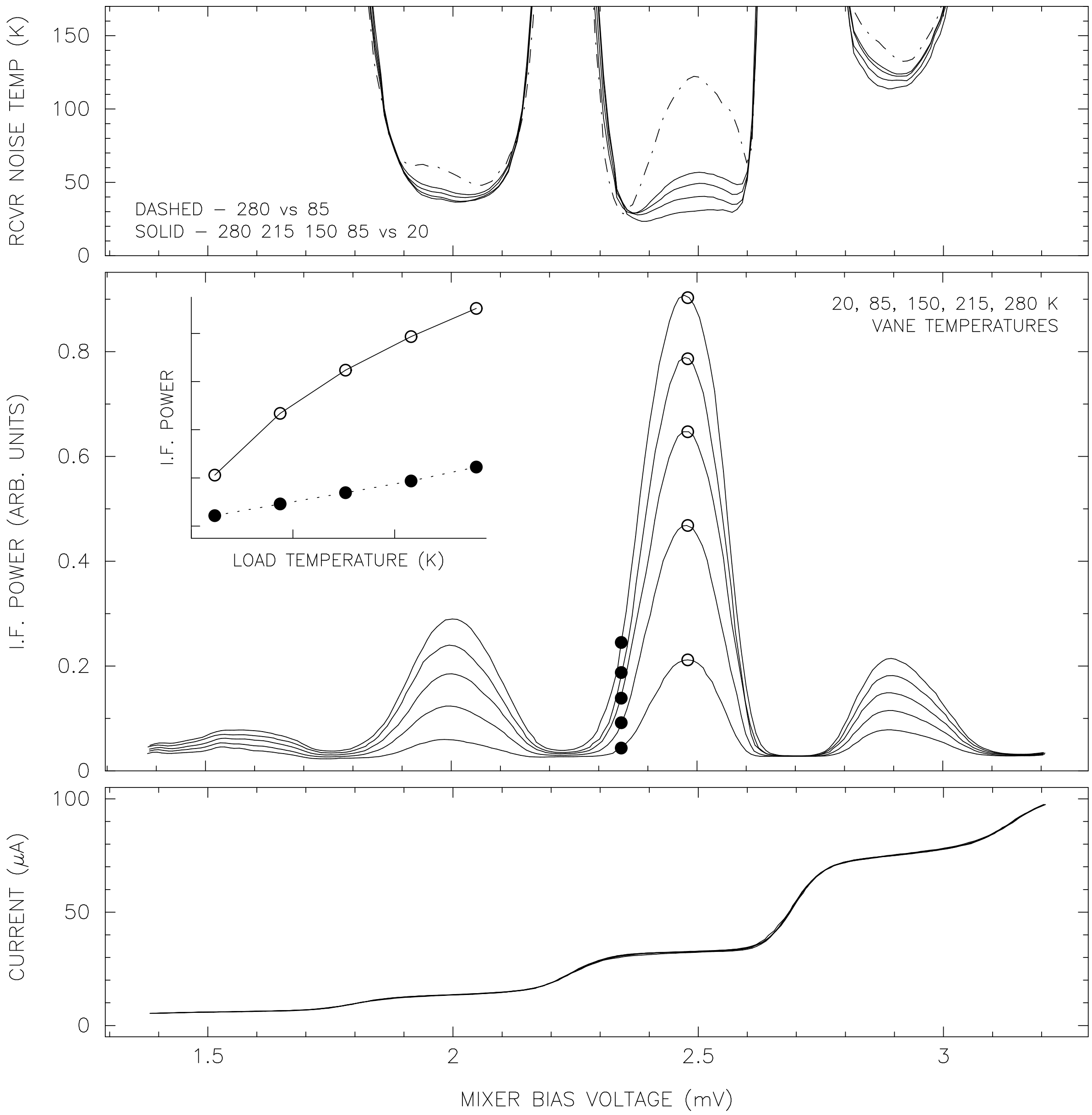


**Figure 7.** Receiver tests at 109 GHz using the temperature-regulated vane as the input load. The mixer current (*bottom panel*) and receiver IF power (*middle panel*) were recorded as functions of bias voltage while the vane was regulated at 20, 85, 150, 215, and 280 K. Receiver noise temperatures (*top panel*) were computed from IF power ratios. The lowest noise temperatures of ~35 K are found at 2.35 mV, near the edge of the first photon step, where the mixer response is linear. Noise temperatures at 2.48 mV, the midpoint of the photon step, are significantly higher due to gain compression (*inset, middle panel*).

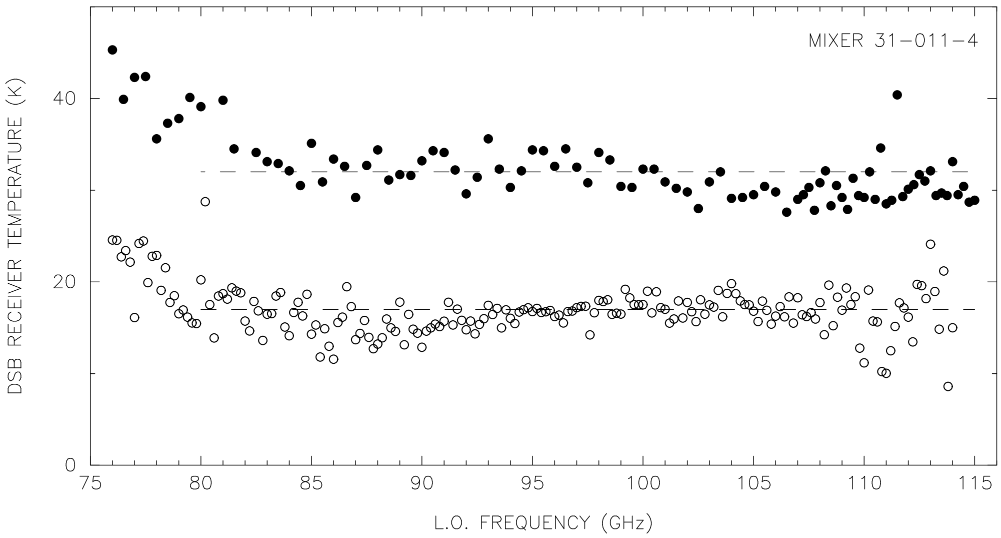


**Figure 8.** Comparison of receiver temperatures measured with 77 and 295 K loads outside the dewar (filled circles), and with 20 K and 35 K loads provided by the temperature-regulated vane (open circles).

top panel). This suggests that blackbody photons in the 70–120 GHz RF passband are mixing with other blackbody photons at nearby frequencies, thereby generating signals within the IF passband. The quadratic dependence on load temperature is consistent with mixing of two signals with comparable amplitudes. In normal operation the LO power level is much higher than the signal level, so to first order the IF amplitude varies linearly with the signal input power. We note that the I-V curves for the different vane temperatures (overplotted in the lower panel of Figure 9) are identical. This implies that any mismatch at the mixer's IF port is independent of vane temperature. Hence, HEMT amplifier noise reflected from the mixer's IF port cannot explain the "self-mixing" signal.

Comparing the IF power levels in Figure 9 with those in Figure 7, which are on the same scale, one finds that self-mixing contributes only a few percent of the total IF power measured with LO applied. Hence, we expect that self-mixing does not significantly perturb our noise temperature measurements.

## 4. CALIBRATION AND TUNING OF PARTIALLY SATURATED MIXERS

To calibrate the antenna temperature of the signal received from an astronomical source, one must correct for attenuation by the earth's atmosphere. This is most conveniently done with the chopper wheel method,[7] whereby the power measured on the sky and on a $\sim 295$ K load are compared. This technique works poorly if the 295 K load partially saturates the mixer. A possible solution is to use a beamsplitter to couple fraction $f$ ($\sim 0.1$, say) of the beam onto the load and $1 - f$ onto the sky. Provided that $f$ is accurately known, one can then extrapolate to find the unsaturated response to the 295 K load. Tests of this technique are now underway.

Currently, the BIMA calibration procedure requires that we block the entire beam with the 295 K load. This necessitates biasing the junctions to a voltage where the mixer response is reasonably linear. Because the optimum bias point is a sensitive function of mixer temperature, LO frequency, and sky opacity, the software optimizes it each time the receivers are tuned, using the following algorithm: (1) set the bias voltage to the predicted midpoint of the photon step; (2) adjust the LO attenuator to get the desired mixer bias current; (3) record the receiver IF power while scanning the bias voltage $\pm 0.15$ mV from the initial value, first on the 295 K load, then on the sky; (4) return to the bias voltage which maximizes the ambient/sky Y-factor. With the mixers tuned in this way, the standard chopper wheel calibration gives source antenna temperatures which are in good agreement with expected values.

Extensive lab tests of each mixer are used to generate a tuning table with the predicted bias voltages and optimum bias currents as functions of LO frequency and mixer temperature. For completeness, we test the mixers up to 7.5 K, although we almost always operate them between 3.5 and 4.2 K. Sample test data are shown in Figure 10.

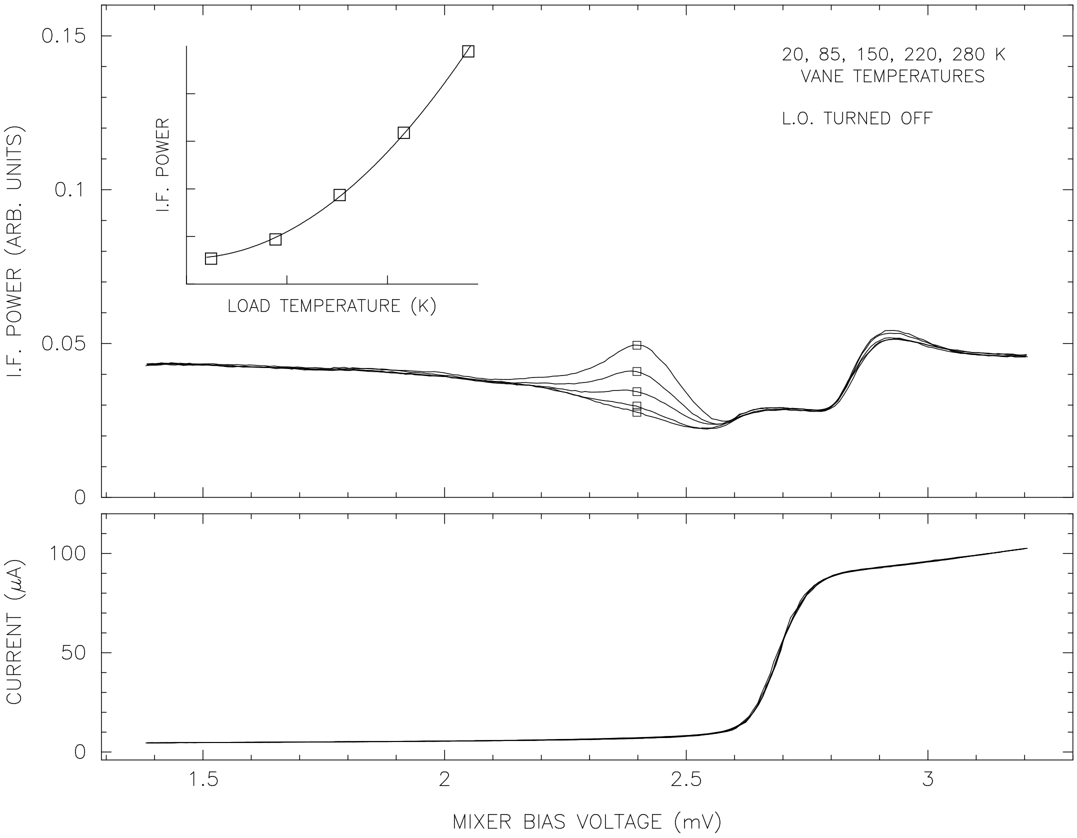


**Figure 9.** Mixer current and receiver IF power measured with the local oscillator turned off, for input load temperatures of 20, 85, 150, 215, and 280 Kelvin. The IF power at 2.4 mV is proportional to the *square* of the load temperature (*inset, top panel*), suggesting that it arises from self-mixing of input noise.

Since we tune to the edge of a gain peak, small variations in the mixer's physical temperature cause large fluctuations in the receiver gain. To stabilize the gain (generally within $\sim 1\%$), the BIMA control computer actively regulates the mixer temperature with a small heater resistor, updating the heater power every 0.32 seconds. Generally it is possible to regulate to an accuracy of a few milliKelvin for periods of days or weeks.[8]

## 5. ACKNOWLEDGEMENTS

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## REFERENCES

1. C. E. Tong, R. Blundell, S. Paine, D. C. Papa, J. Kawamura, X. Zhang, J. A. Stern, and H. G. LeDuc, "Design and characterization of a 250 - 350 GHz fixed-tuned superconductor-insulator-superconductor receiver," *IEEE Trans. Microwave Theory Tech.* **44**, pp. 1548–1556, 1996.
2. W. J. Welch. et al., "The Berkeley-Illinois-Maryland-Association Array," *PASP* **108**, pp. 93–103, 1996.
3. R. Blundell, C. E. Tong, D. C. Papa, R. Leombruno, X. Zhang, S. Paine, J. A. Stern, and H. G. LeDuc, "A wideband fixed-tuned SIS receiver for 200 GHz operation," *IEEE Trans. Microwave Theory Tech.* **43**, pp. 933–937, 1995.

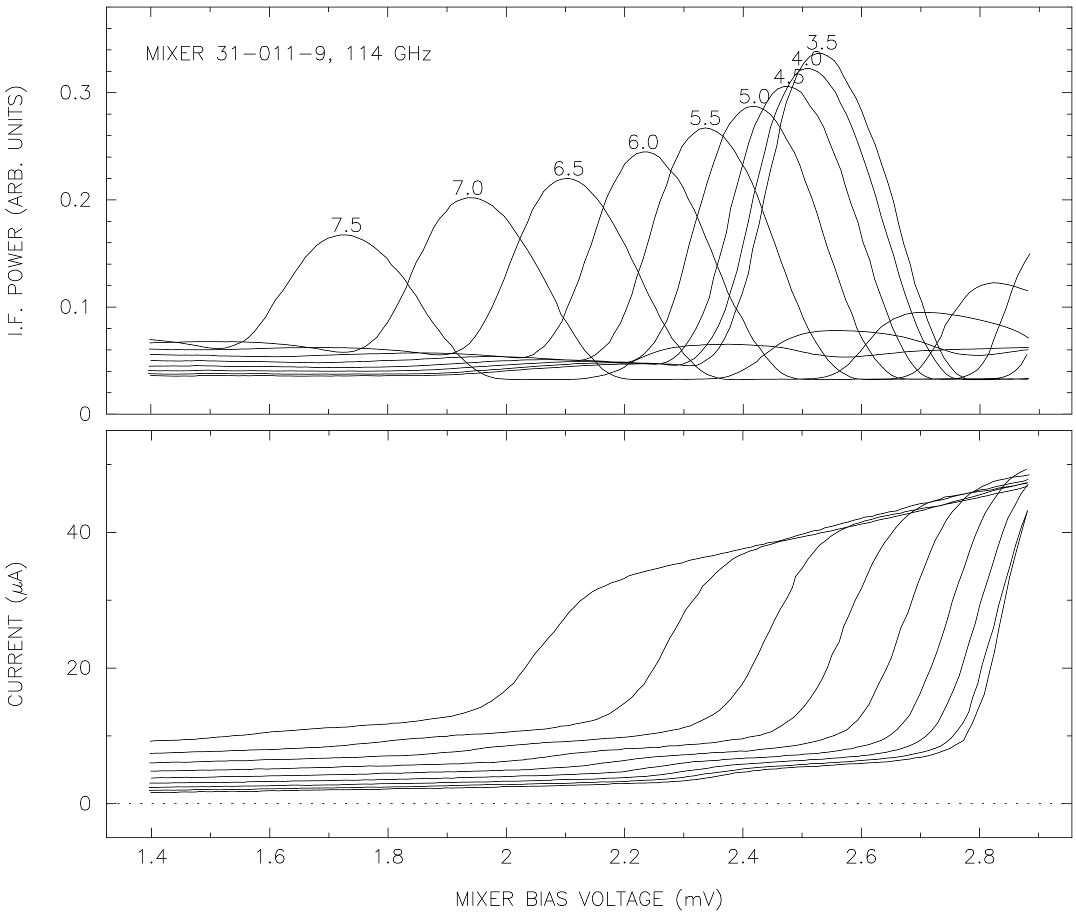


**Figure 10.** Mixer I-V curves and IF power as a function of bias voltage with the mixer regulated at temperatures of 3.5, 4.0, 4.5, 5.0, 5.5, 6.5, 7.0, and 7.5 K.


4. A. D. Smith and P. L. Richards, "Analytic solutions to superconductor-insulator-superconductor quantum mixer theory," *J. Applied Phys.* **53**, pp. 3806–3812, 1982.
5. J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," *Rev. Mod. Phys.* **57**, pp. 1055–1113, 1985.
6. M. J. Feldman and L. R. D'Addario, "Saturation of the SIS detector and the SIS mixer," *IEEE Trans. Microwave Theory Tech.* **MAG-23**, pp. 1254–1258, 1987.
7. B. L. Ulich and R. W. Haas, "Absolute calibration of millimeter-wavelength spectral lines," *ApJS* **30**, pp. 247–258, 1976.
8. R. L. Plambeck, "Long term performance of 4 K Gifford-McMahon refrigerators on the Bima Array," in *Advances in Cryogenic Engineering*, P. Kittel, ed., **43**, New York: Plenum, in press