Quasi-Optical Slot Antenna SIS Mixers

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Abstract

The slot-antenna mixer is a new quasi-optical SIS mixer design which attempts to simultaneously solve the antenna pattern and impedance-matching problems to obtain highly efficient radiation coupling. The mixers have been fabricated by the authors at JPL's Microdevices Laboratory (MDL). The devices employ robust Nb/Al–oxide/Nb tunnel junctions, and have been tested at Caltech. A receiver noise temperature of 420 K (DSB) was measured at 500 GHz, which is the best yet reported for an SIS or Schottky mixer at this frequency. The design of this mixer is readily scalable to 1000 GHz with current fabrication capabilities. The design allows reasonable junction areas to be used, even at high frequencies, which can easily be fabricated using the Nb/Al-Oxide/Nb and NbN/MgO/NbN processes. For example, an 800 GHz mixer requires a single junction with an area of about 0.5 μm^2. The larger junction areas alleviate the effects of mixer saturation and allow strong suppression of the noise from the Josephson effect by the application of a magnetic field. The slot-antenna mixer should have a reasonable bandwidth, about 1.6:1, which would allow the 500–1000 GHz band to be covered with only 2-3 devices.

I. Introduction

Although mixers based on superconducting tunnel junctions (SIS mixers) are predicted to have sensitivities approaching the quantum limit at frequencies well into the submillimeter and perhaps as high as twice the gap frequency of the superconductor [1-3], the experimental realization of SIS mixers which operate at submillimeter wavelengths has remained difficult. There have been a number of reports in the literature in recent years (e.g. [4–6]) describing SIS mixers employing a variety of schemes to directly couple the radiation from a free–space beam into the tunnel junction. These designs use a system of lenses to focus the radiation onto a microantenna which is integrated on the same substrate on which the tunnel junction is fabricated. These quasi–optical designs avoid the problems associated with waveguides at short submillimeter wavelengths, and would make the fabrication of imaging mixer arrays a relatively straightforward task. However, in the past, the quasi–optical mixers generally did not couple the radiation into the tunnel junction as efficiently as waveguide designs (e.g. [7]). The two critical factors in this coupling are the antenna efficiency - that is, how well the antenna pattern matches the incoming radiation, both in amplitude <u>and</u> <u>phase</u> - and the impedance match between the tunnel junction and the antenna. The slot antenna mixer design is our first attempt at dealing with both of these issues in a design which is simple, robust, straightforward to fabricate, and relatively insensitive to fabrication tolerances.

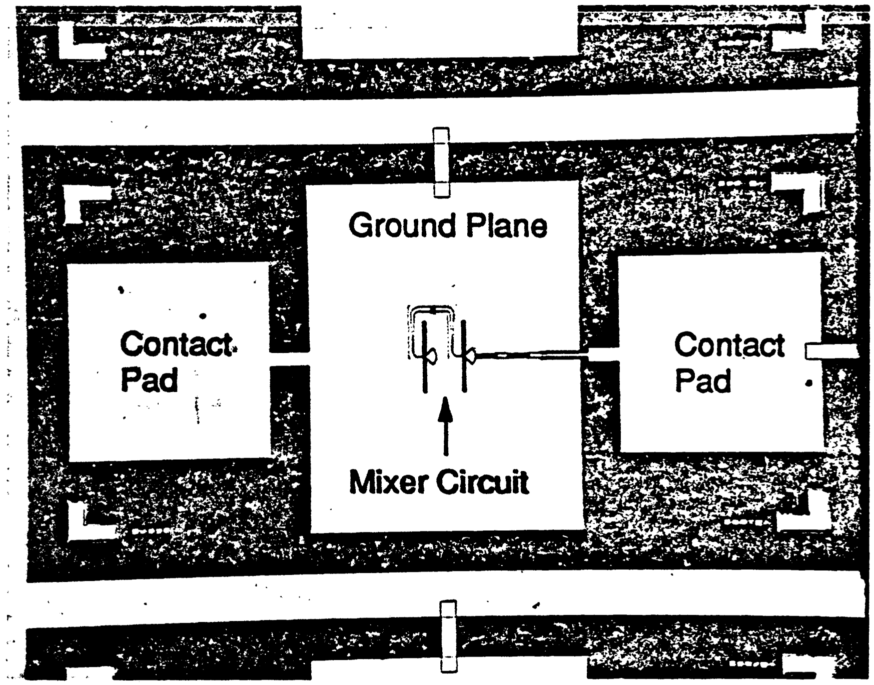

Figure 1a. Quasi-optical slot-antenna SIS mixer chip for 500 GHz.

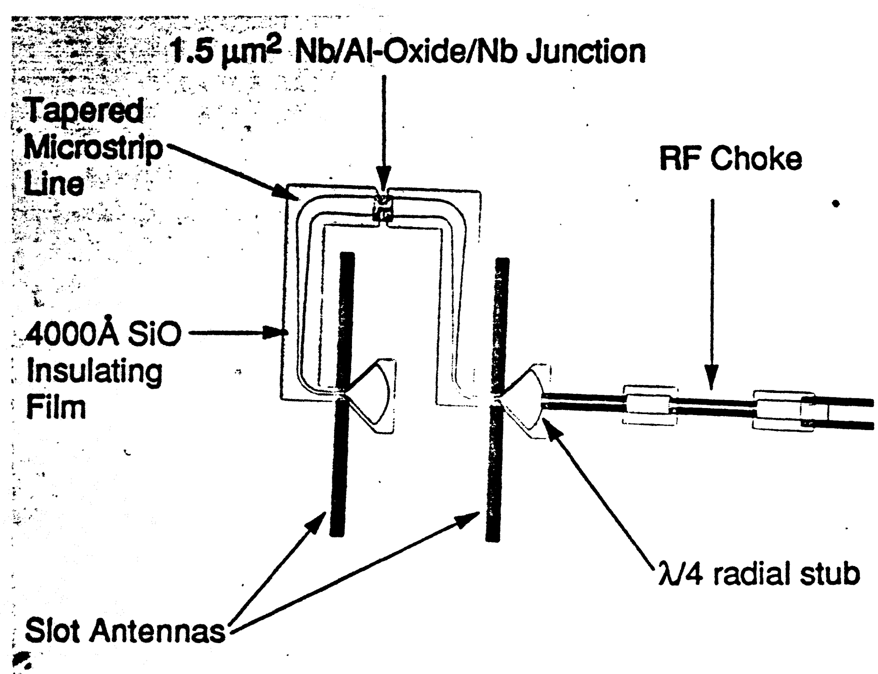

Figure 1b. Close-up view of slot-antenna mixer circuit.

II. Description of Mixer Design

Our mixer design consists of a twin-slot planar feed antenna, a Nb/Al-oxide/Nb or NbN/MgO/NbN SIS junction, and a tapered transmission line joining the junction to the two slot antennas (see Fig. 1). A hyperhemispherical lens is used to focus the incident radiation onto the twin-slot antenna (Fig. 2). A similar configuration for a quasi-optical Schottky mixer was described by Kerr, Siegel, and Mattauch [8]. The principal differences are that the Schottky design omitted the hyperhemispherical lens, used a quarter-wave section of transmission line for matching instead of a taper, and fed the two slots in series instead of in parallel.

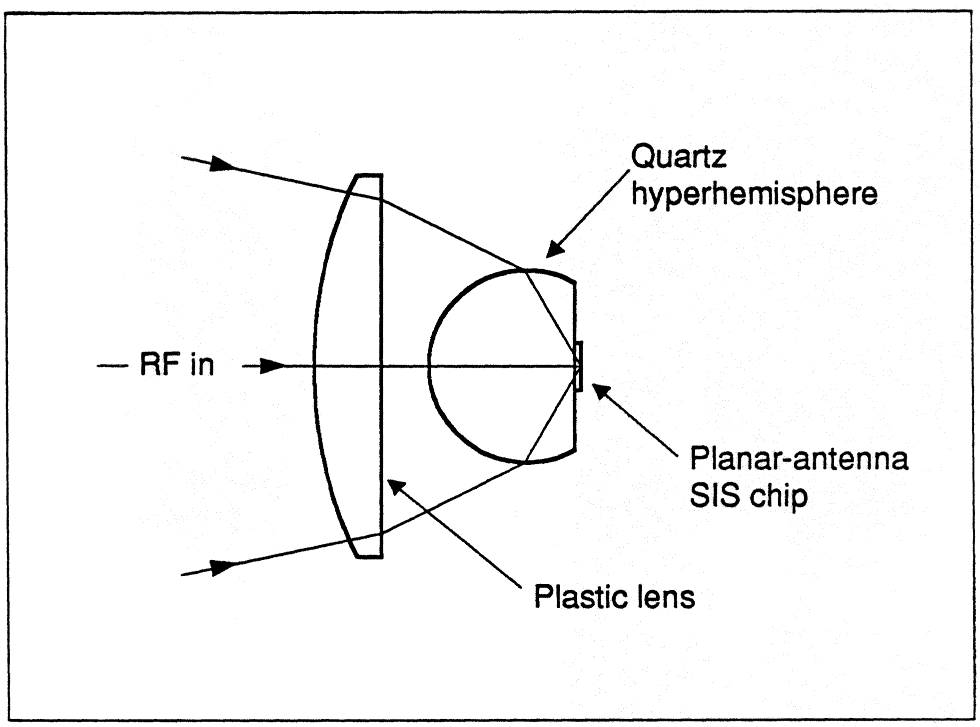

Figure 2. Slot antenna mixer optics.

A slot antenna on a semi-infinite dielectric substrate has a number of desirable properties. First of all, the antenna impedance is quite low and can be computed using a moment–method technique described by Kominami, Pozar, and Schaubert [9] which is essentially a numerical solution of Maxwell's equations. We have developed a program to perform this computation. The impedance as a function of frequency calculated for a single slot in the case of a crystal quartz substrate ($\varepsilon_r = 4.53$ on average) is shown in Fig. 3. In between two high-impedance resonances lies a broad region of low impedance. The impedance of a single slot antenna of length $L = 0.47\ \lambda$ (where λ is the free-space wavelength) and width $W/L = 0.04$ is $Z_a = 35+j0\ \Omega$. The antenna impedance bandwidth is quite broad. The frequency band over which the fractional power coupled from the antenna into a 35 Ω load is better than 50% is one octave. Detailed circuit simulations of the mixer indicate a 1.6:1 bandwidth for the mixer. We will be testing this prediction in the near future by using a newly–constructed fourier transform spectrometer (FTS) in our laboratory to measure the SIS direct-detection response in the manner of Hu *et al.* [10], as well as performing heterodyne tests over a range of frequencies.

Since the antenna impedance program also calculates the electric field distribution in the slot, the results of this program may be used to calculate rigorous antenna patterns. A contour plot of the resulting pattern radiated into the dielectric is shown in Fig. 4. The separation between the slots ($S = 0.29\ \lambda$) was adjusted to produce a symmetric pattern with a half-power beam width of 47°. The main beam efficiency is calculated to be $\eta_{MB} = 70\%$. The remaining power is radiated into small E-plane sidelobes (4%) and backwards into air (26%). The phase of the antenna pattern was also investigated. The antenna does have a small phase error, but fortunately this error causes a reduction in the coupling efficiency of only 2%. Aberrations in the focusing lenses can also produce phase errors in the antenna pattern of the overall receiver. The aberrations were calculated, and were also found to reduce the coupling efficiency by a negligible amount, < 2%. Finally, the polarization properties of the antenna are important. The twin-slot antenna has excellent polarization characteristics since it responds only to electric fields perpendicular to the slots.

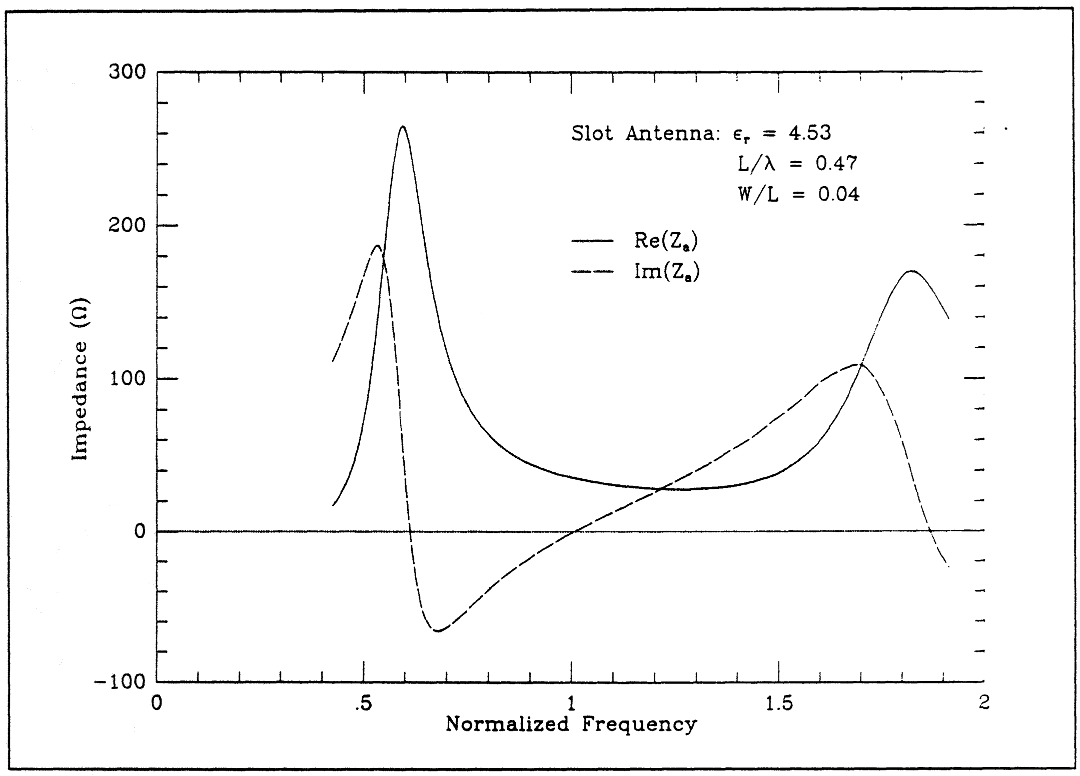

Figure 3. Slot antenna impedance as a function of frequency (on quartz).

The quartz hyperhemispherical lens serves two functions. First, it transforms the fairly broad beam of the twin-slot antenna (HPBW = 47°) to a narrower beam (HPBW = 22°). Second, it prevents power from being radiated into surface-wave modes as occurs when finite-thickness dielectric substrates are used. Essentially, the hyperhemisphere makes the dielectric substrate look semi-infinite. However, there is a reflection loss associated with the air-dielectric interface of the lens. For quartz, we calculate that the beam-averaged transmission through this interface is 86%, just a little lower than the transmission at normal incidence (87%). This loss can be almost completely eliminated by applying a quarter-wave anti-reflection coating on the hyperhemisphere.

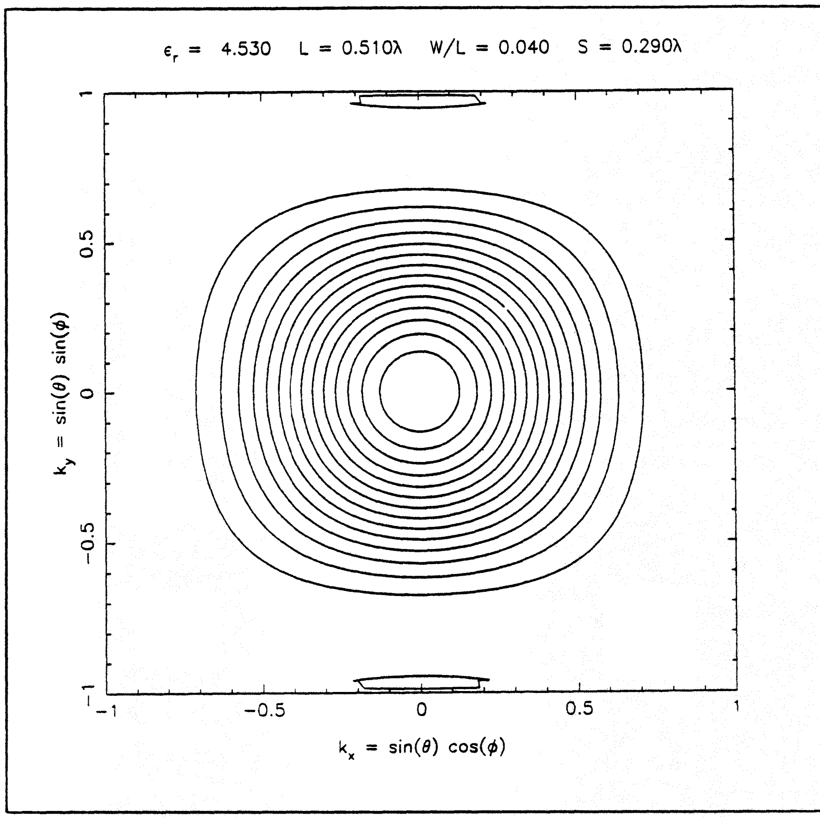

Figure 4. Power pattern of twin-slot antenna. Contours are linearly spaced, from 5 % to 95 % of the peak.

As compared to other submillimeter mixer designs, the slot-antenna mixer uses an SIS junction with a fairly large area. The junction area is scaled inversely with frequency, from $\approx 0.9\ \mu m^2$ at 500 GHz to $\approx 0.5\ \mu m^2$ at 800 GHz; the design rule is that $1/\omega C = 4\ \Omega$ (see below). These areas are calculated using a specific capacitance of $C_s = 85$ fF μm^{-2} [11], a value now believed to be appropriate for Nb/Al–Oxide/Nb junctions with current densities of ≈ 10 kA cm^{-2}. Unfortunately, the mixers were designed assuming a specific capacitance of $C_s = 50$ fF μm^{-2} appropriate for lower current density junctions, which leads to junction areas of 1.5 μm^2 at 500 GHz. The actual areas turned out to be $\approx 2.3\ \mu m^2$, because the mask design overcompensated for possible shrinkage in the junction dimensions during processing (see section III).

Larger–area junctions have a higher saturation power, require a smaller magnetic field to suppress the Josephson effect, are easier to fabricate, and are electrically more robust . The disadvantage is that a larger junction has a lower impedance, and the circuit design of the mixer must compensate for this. At 500 GHz, the reactance of the junction capacitance is $1/\omega C \approx 4\ \Omega$ for a high current density (≈ 10 kA cm^{-2}) 1 μm^2 Nb/Al-oxide/Nb junction. This is much lower than the normal–state resistance of the junction, and so the magnitude of the junction complex impedance is $|Z| \approx 1/\omega C$ to a good approximation. Our mixer design does not attempt to tune out the junction capacitance with an inductive shunt or an open–circuit transmission line stub. Rather, we transform the antenna impedance down to a level of $1/\omega C$, to obtain the best possible match to the junction under the constraint that the source resistance is required to be purely real. We have intentionally avoided using resonant circuits in this initial design, because such circuits have tight dimensional tolerances and require good knowledge of the behavior of superconducting transmission lines at high frequencies. In our design a sacrifice is made in the coupling efficiency by not attempting to tune out the junction capacitance. The coupling efficiency due to this impedance mismatch is roughly

$$\eta = \frac{2}{1+\sqrt{1+Q^2}}$$

where Q is the $\omega R_N C$ product of the junction. For instance, if Q=3, this coupling efficiency is $\eta \approx 0.5$; the overall efficiency for coupling radiation into the junction (including the antenna efficiency) is estimated to be ≈ 0.3. In the future we will be experimenting with circuits which tune out the junction capacitance and eliminate this loss, at the expense of a narrower bandwidth.

To match the 35 Ω twin-slot antenna impedance to the $\approx 1\ \mu m^2$ SIS junction we use two tapered superconducting microstrip transmission lines. These lines are tapered from a characteristic impedance of 35 Ω at each slot to an impedance of 8 Ω at the junction. Since the two transmission lines feed the junction in parallel, the impedance seen by the junction is 4 Ω. The transmission lines do not disturb the slot antenna because the slot antenna has a ground plane everywhere except for the slot. The characteristics of the superconducting microstrip transmission lines used for the design of the mixer were calculated using an adaptation of the method described by Whitaker *et al.* [12], but since the design uses a tapered line, it is fairly insensitive to the actual phase velocity and characteristic impedance of the microstrip lines.

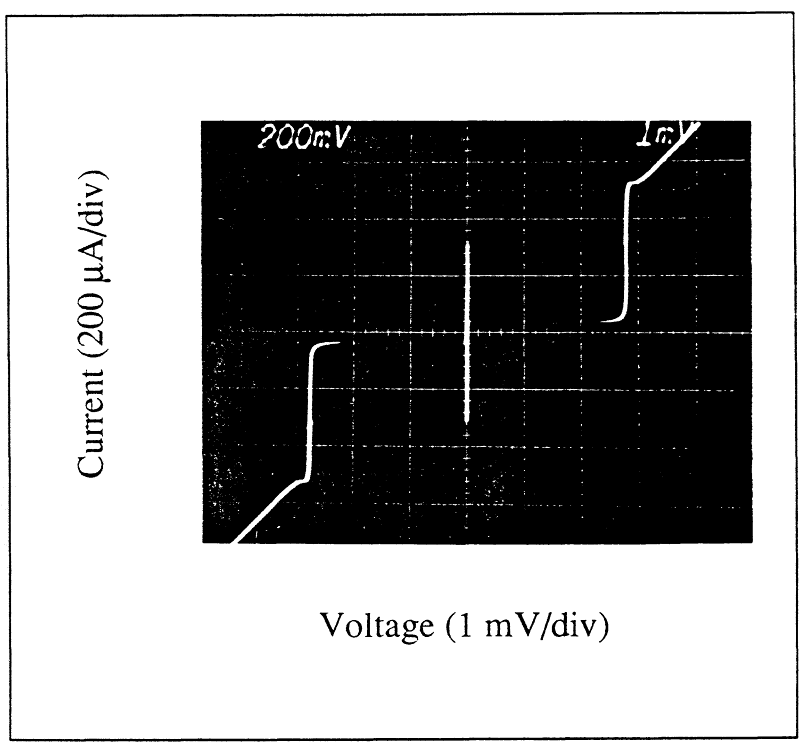

Figure 5. An I-V curve of a Nb/Al-Oxide/Nb junction in a slot-antenna mixer circuit.

III. Device Fabrication

The twin-slot mixers are fabricated at the Microdevices Laboratory at JPL. The mixers fabricated for testing at 500 GHz employed Nb/Al-Oxide/Nb tunnel junctions; mixers with NbN/MgO/NbN junctions will be fabricated in the near future for testing at 800 GHz. The mixers are manufactured using a four mask level fabrication process, which is similar to the planar NbN/MgO/NbN process described by LeDuc *et al.* [13]. In the first step, the Nb/Al–Oxide/Nb trilayer is sputtered on a substrate on which a lift–off stencil has been patterned using AZ 5214 photoresist in image–reversal mode. Most of the gross features of the mixer are defined in this step, including the slot antennas, the contact pads, and the ground plane. Following lift-off of the trilayer, reactive-ion etching (RIE) in a 63% CCl_2F_2, 31% CF_4, and 6% O_2 mixture at a pressure of 30 mT is used to define the junction, which is protected from the etch by AZ 5206 photoresist patterned in positive mode. Only the areas of the trilayer which are near the path of the transmission lines are exposed to the etch. After the etch but before the photoresist is removed, a 1500 Å layer of SiO is evaporated on the sample to isolate the junction and to provide a portion of the SiO needed for the transmission line dielectric. The evaporation is performed with the sample mounted on a rotating platform which is tilted at an angle with respect to the evaporation source. The combination of the tilt and rotation ensures good step coverage for the SiO film. The photoresist is then removed, exposing the junction area. Another layer of SiO, about 2500 to 3500 Å thick, is evaporated on the sample, this time through a lift–off mask patterned with AZ 5214 photoresist in image–reversal mode. The junction is protected by photoresist during this evaporation, of course. The total SiO thickness obtained in these two steps is 4000 – 5000 Å, which is the thickness needed for the microstrip transmission lines. After lift–off, a Nb wiring film is deposited on the entire substrate and patterned with RIE using an AZ 5214 photoresist mask. The microstrip lines are patterned in this step.

The fabrication results were quite good. The SIS junctions tested at 500 GHz had areas of $A \approx 2.3\ \mu m^2$, normal-state resistances of $R_N = 9\ \Omega$, current densities of $J_c \approx 10$ kA cm^{-2}, and $\omega R_N C \approx 4.6$. A typical I-V curve is shown in Fig. 5. The yield was high: 36 out of 37 devices tested had good I–V curves. The r.m.s. variation in the current step at the gap voltage was 4.5%, and the typical normal to subgap resistance ratio was $R_{sg}/R_N \approx 10$.

IV. Laboratory Results

Initial laboratory tests of the slot-antenna mixer at 500 GHz have been very encouraging. The local oscillator was a quintupled Gunn oscillator. The quintupler was obtained from Radiometer Physics (Peter Zimmerman) in West Germany [14]. The local oscillator was introduced into the signal path by using a 12% reflective mylar beamsplitter. With this arrangement, the mixer could be pumped with substantially more than the minimum LO power necessary for efficient mixing. The receiver sensitivity was measured with the standard hot/cold load Y–factor technique, using sheets of Eccosorb at room temperature (295 K) and dipped in liquid nitrogen (80 K). The IF was calibrated using the SIS junction shot noise as a variable temperature load. The measured I.F. power for the hot and cold loads as a function of voltage is shown in Fig. 6. This figure was obtained by suppressing the Josephson effect with a magnetic field. Structure is still visible in Fig. 6 in the vicinity of the second Shapiro step at 2 mV, but is suppressed to a remarkable degree compared to the case with no magnetic field. The application of the magnetic field allows low–noise mixing over a large fraction of the first photon step below the gap voltage. Without the field applied, reliable mixer operation could not be obtained. The results for the noise temperature are as follows (SSB values are 2 x DSB) :

Receiver noise temperature (DSB)	T_{rec}	=	420 K
Conversion loss (DSB)	L_c	≈	10 dB
IF Contribution	$L_c T_{IF}$	≈	110 K
Mixer noise temperature (DSB)	T_m	≈	240 K
(IF & beamsplitter contribution subtracted)			

These results give us confidence that with proper design, the application of a magnetic field will strongly suppress noise from the Josephson effect and will allow low-noise SIS mixing up to at least the gap frequency (700 GHz for Nb; ≈ 1400 GHz for NbN), and confirms previous experience with Pb–alloy SIS mixers at 500 GHz [15]. Excess noise produced by the Josephson effect has been thought to be a major limiting factor in the performance of SIS mixers at high frequencies [1,16]. While it is well known that a magnetic field applied to a junction suppresses the DC Josephson current, it has not been clear that a magnetic field would suppress high–frequency noise currents as well. Our results agree with the conclusions of Winkler, Claeson, and Rudner [17,18], who studied SIS mixing in Al tunnel junctions at frequencies (≈ 75 GHz) approaching the superconducting gap frequency of Al (≈ 90 GHz). These experiments indicated that magnetic fields would indeed allow the low–noise operation of SIS mixers close to the superconducting gap frequency.

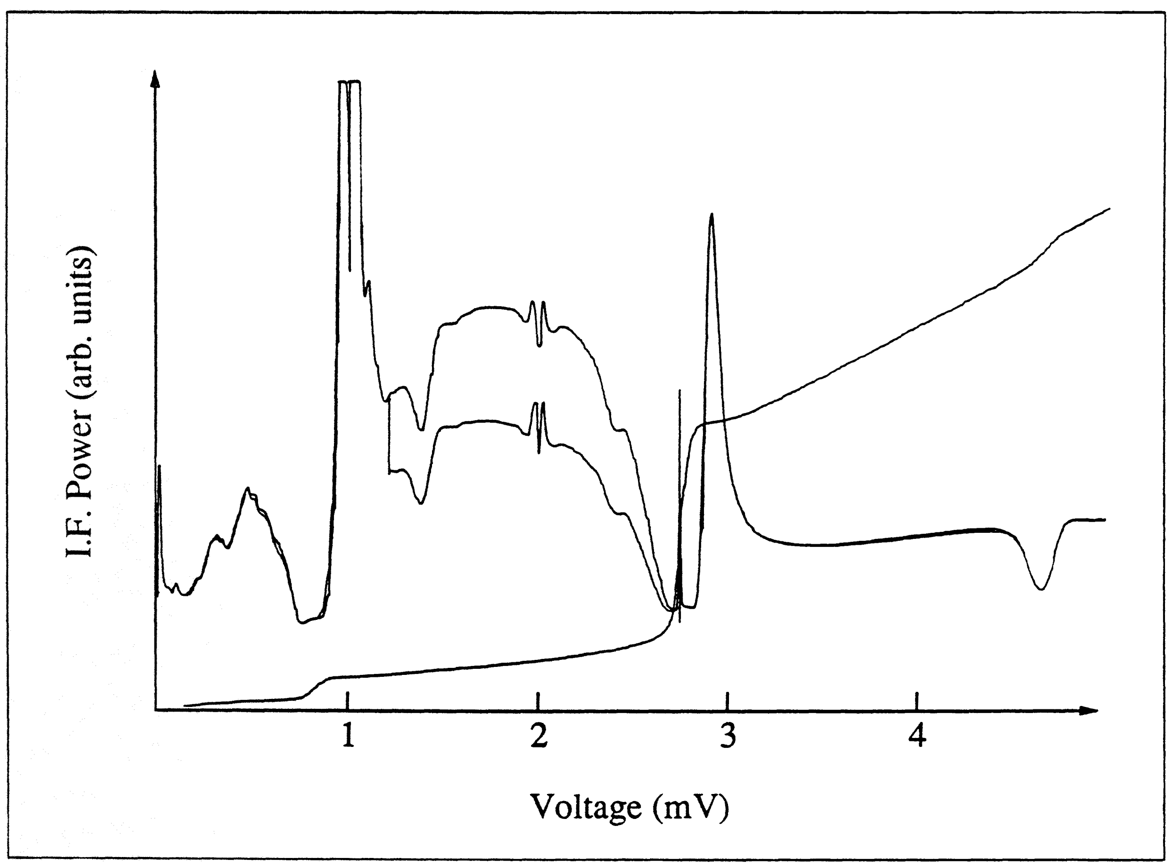

Figure 6. A measurement of the hot (295 K) and cold (80 K) load response of the twin-slot mixer at 500 GHz. The pumped I-V curve is also shown.

The mixer tests also show that there is room for improvement. The conversion loss is substantially higher than expected, and could be due to an impedance mismatch larger than calculated, excess loss in the microstrip transmission lines, or problems in the optical coupling. These will each be investigated. Also, the IF contribution to the system noise is larger than expected, and the cause of this needs to be located and corrected. In addition to these unknown factors, there are several parameters in the current design which are known not to be optimal. For instance, the junction area is too large by a factor of 2.5, the current density should be higher, the transmission line dimensions need to be adjusted, the lenses are not anti-reflection coated, and the beamsplitter reflectivity could be reduced. We therefore fully expect that a substantial improvement of the mixer sensitivity can be achieved, and that receiver noise temperatures at 500 GHz in the range 100–200 K (DSB) will be obtained. In the future, we also expect to measure the frequency response of the mixer by direct-detection experiments using a fourier-transform spectrometer as well as by heterodyne sensitivity measurements, to map the receiver beam pattern, and to measure the coupling efficiency of the receiver to a telescope.

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