NbN Hot-electron Mixer Measurements at 200 GHz

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Abstract.

We present noise and gain measurements of resistively driven NbN hot-electron mixers near 200 GHz. The device geometry is chosen so that the dominant cooling process of the hot-electrons is their interaction with the lattice. Except for a single batch, the intermediate frequency cut-off of these mixer elements is ~700 MHz, and has shown little variation among other batches of devices. At 100 MHz we measured intrinsic mixer losses as low as –3 dB. We measured the noise temperatures at several intermediate frequencies, and for the best device at 137 MHz with 20 MHz bandwidth, we measured 2000 K; using a low-noise first-stage amplifier at 1.5 GHz with 200 MHz bandwidth, the receiver noise temperature measured 2800 K. We estimate that the noise contribution from the mixer is 500 K and the total losses are –15 dB at 137 MHz.

1. Introduction.

Heterodyne receivers based on the hot-electron mixing mechanism in bulk-semiconductor indium antimonide, InSb, have operated to about 500 GHz, with sensitivity comparable to that of SIS receiver systems[1,2]. However, the instantaneous bandwidth of InSb-based mixers is limited to less than 10 MHz, which limits their practical usefulness. More recently, two-dimensional heterojunction structures with short electron relaxation times have been developed for heterodyne mixing, and GaAlAs structures have been used to demonstrate mixing at 94 GHz with an instantaneous bandwidth of over 1 GHz [3]. Two other candidates for low-noise mixers based on the hot-electron effect utilize superconducting thin films operated in the resistive state. One type chooses a device geometry in which the cooling of hot electrons is dominated by diffusion [4], and recent experiments at submillimeter wavelengths have indicated good noise performance and wide instantaneous bandwidth of about 3 GHz [5]. The other method employs the coupling between the lattice and electrons as the cooling mechanism [6], and the bulk of recent results have come from experiments with Nb devices [7]. Our present work focuses on devices relying on the shorter electron-phonon relaxation time of NbN, for which an instantaneous bandwidth of several GHz is predicted [8]. We report on our initial measurements of NbN hot-electron waveguide mixers at an input frequency of 200 GHz.

2. Experimental Setup.

The mixer elements used in our study consist of ~50 angstrom thin-film NbN strips about one micron wide and four microns long, with as many as 50 strips in parallel. The detail in figure (1) illustrates the devices. With these dimensions the dominant cooling process of the heated electrons is believed to be their interaction with the lattice. The devices are fabricated on crystalline quartz using standard reactive sputtering and optical lithography. TiAu pads are evaporated and etched to form low-pass RF block filters, and also serve as electrodes through which DC bias is applied. The substrate is mounted in a reduced-height waveguide mixer block with a single backshort tuner, also illustrated in figure (1). Figure (2) shows a schematic of the mixer block, which is mounted in a helium-cooled laboratory cryostat. The radiation is coupled through a lens-horn combination and the local-oscillator is coupled to the signal outside the cryostat using a wire-grid polarizer.

For gain or impedance measurements the IF is brought directly outside the cryostat using a stainless-steel coax, whereas for receiver noise temperature measurements a first-stage cryogenic low-noise amplifier follows the mixer. In receiver noise measurements, the LO is a frequency-multiplied Gunn oscillator. For gain measurements, a signal is provided by either another frequency-multiplied Gunn oscillator or a harmonic generator driven by a microwave frequency synthesizer. The RF coupling losses were determined using the "isotherm" technique [7]. Receiver noise measurements are made using the standard hot/cold load Y-factor technique.

3. Results.

Figure (3) shows the current-voltage (IV) characteristics typical of a mixer element cooled to above 4.2 K, traced using a voltage source. Three distinct regions are identifiable as the voltage bias is changed: at low bias, below the critical current, the device is superconducting and the series resistance is traced; at an intermediate bias, the device exhibits a "resistive" state; at high bias level, beyond that is traced by the curve in the figure, the device is driven normal. It is in the intermediate region where the device is biased for efficient mixing. The figure also shows a current-voltage curve for the mixer element pumped with 200 GHz radiation. As the device is pumped with higher power, the device is driven normal at all bias levels.

The devices used in our study have room temperature resistances of a few kΩ per strip, and a contact, or series, resistance from about 3 Ω to 50 Ω. The quality of the superconducting film varied greatly among the batches, and it has been possible to characterize only some of the devices because of the limit on available LO power. The amount of LO power required to pump the devices we have studied is about $\sim 1\ \mu$W.

a) IF conversion gain, bandwidth and impedance.

The conversion loss of a mixer is defined as the ratio of the input signal power to that measured at the IF output. Furthermore, conversion losses can be separated into antenna coupling loss, and other losses which usually include the intrinsic loss of the down-conversion process and the IF impedance mismatch. At microwave wavelengths the power levels of the signal and IF are easily measured using standard techniques. At higher frequencies, an indirect technique is used to separate the losses. The signal power coupled to the device is calculated from the amount of heating it produces in the film, relying on the assumption that radiation and DC have the same heating effect on the device. To measure the IF gain curve, the signal is set at a particular frequency and power, and the LO is adjusted in frequency, and in power to reach the operating point.

In figure (4) the conversion loss as a function of IF for a signal frequency of 200 GHz is shown. Also shown is a gain curve measured at 20 GHz, shifted vertically for presentation. The similarity between the microwave and millimeter-wave measurements suggests that microwave measurements, which can be performed using simple apparatus, can be used to preselect good devices for measurements at higher frequencies.

Except for one batch, there is typically very little variation in the roll-off of the gain within and among batches of devices we have fabricated. In our samples of devices, the conversion rolls off in the range 500 to 800 MHz, and the best conversion gain is estimated to be –3 dB. In some batches, there is a rise in the response at very low IF's, indicating bolometric heating of the mixer element, and this is explained by the film being too thick. As shown in figure (5), if the bias or the device temperature is increased, there is a somewhat slight increase in the bandwidth, however, the mixer conversion is poorer. It is not clear whether the bandwidth improvement can be entirely attributed to an actual change in the response time of the detector, or is merely the result of the change in the mixer IF output impedance. Figure (6) shows bandwidth measurements of a mixer element that shows 3 dB conversion roll-off at 2 GHz, measured at a signal frequency of 20 GHz. However, the bandwidth measurements could not be repeated at 200 GHz because the sample was destroyed. An inspection of the mixer elements under an optical microscope revealed that the mask alignment was better for device 1 than for device 2 [referring to figure (6)].

Figure (7) shows the measured IF output impedance for the mixer elements. The impedance of the mixer at its nominal operating point changes smoothly with frequency. At very low IF's (kHz) the impedance is real, and is equal to the differential resistance on the IV curve. At higher frequencies, the device becomes capacitive. At the highest IF (> 5 GHz), the impedance tends towards the series resistance of the mixer element. In figure (7) the IF return loss is also shown for various operating points: nominal operation is ~4.2 K and at the lowest stable bias point. Figure (8) shows the IF return loss of the mixer operated at various temperatures.

b) Noise temperature measurement.

The ultimate figure of merit for an astronomical receiver system is its sensitivity. In order to estimate the sensitivity of the mixer, we performed noise temperature measurements at 200 GHz using the standard hot and cold load method. We have measured the receiver noise temperatures at several IF's. The lowest IF band was at 137 MHz, well below the roll-off in the gain of these devices, and the bandwidth was 20 MHz. Here, the best receiver noise temperature was 2000 K. Using a lower noise amplifier at 1.5 GHz, with 200 MHz bandwidth, the receiver noise temperature measured 2800 K. In all these measurements, we ensured that the operating point remained stationary to better than to 0.2% of the current, which was the best we could monitor. Knowing the noise of the amplifiers and the relative conversion losses allowed us to estimate the mixer noise and total losses. The mixer noise is estimated to be ~500 K and the total losses to be –15 dB at 137 MHz and –24 dB at 1.5 GHz.

c) Subharmonic mixing.

It is generally assumed that subharmonic mixing is not possible or is an insignificant component in the hot-electron mixing mechanism. It is thought that the device looks linearly resistive at high frequencies, above the instantaneous bandwidth of the mixer. With this in mind, we have tried to measure subharmonic mixing. At microwave frequencies, with an signal frequency of 20 GHz, LO pump frequency of 10.5 GHz, an IF signal appeared, weaker by ~6 dB than that obtained by fundamental mixing. With this intriguing result, we tried to and have observed subharmonic mixing at a signal frequency of 460 GHz, subharmonically pumped at about 230 GHz. The LO frequency was varied to measure the mixer gain curve, and the IF response was flat to within 1 dB from 1 MHz to 1.5 GHz. At this point, we are not able to calculate the conversion losses, as we were not able to pump the device at 460 GHz. While this appears to be an intriguing result, we do not rule out that our result is an artifact of our experimental setup.

4) Summary.

We have performed preliminary mixing experiments using the hot-electron effect in NbN at 200 GHz. We have observed that the mixing mechanism is very efficient, estimated for most devices to be better than –6 dB. The instantaneous bandwidth of these devices is typically 700 MHz, although we have seen a mixer element with a bandwidth of 2 GHz. In our setup, the devices are rather poorly matched; a better match would certainly improve our receiver noise temperature measurements. Our measurements indicate a mixer-noise contribution of 500 K, which is fifty times worse than an SIS mixer working at the same wavelength [9]. However, if a similar performance can be repeated at 1 THz, these mixers may become very important.

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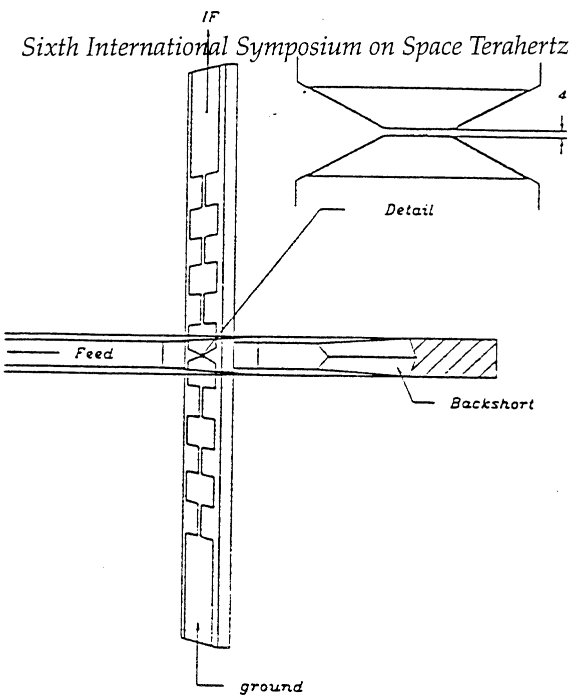

Figure 1. Schematic of waveguide mixer.

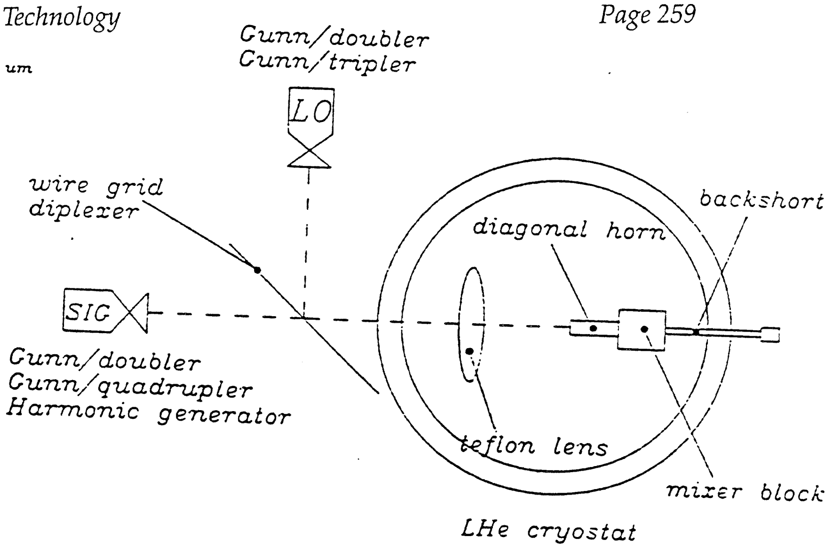

Figure 2. Schematic of the experimental setup.

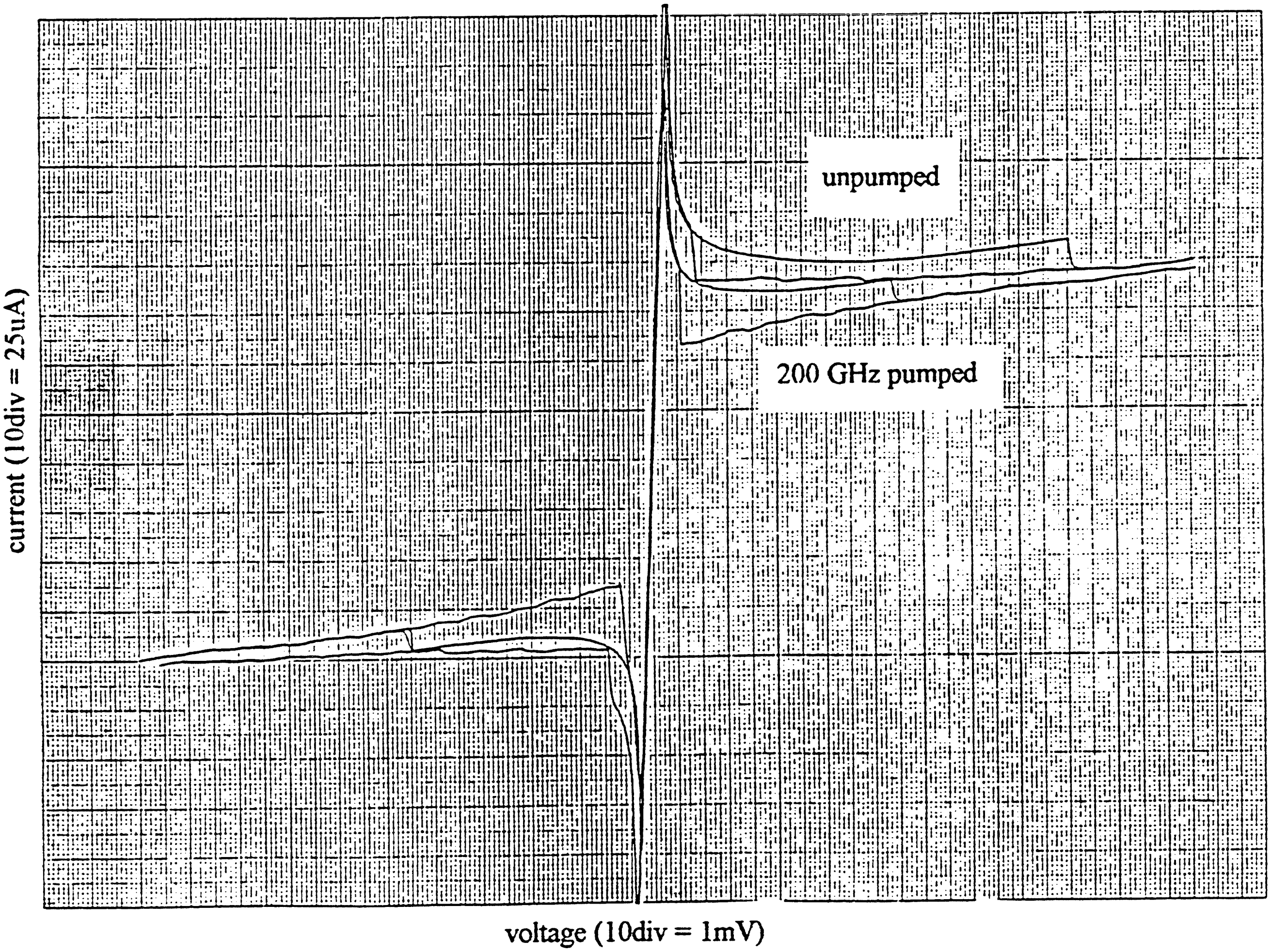

Figure 3. Current-Voltage (IV) characteristics of mixer element.

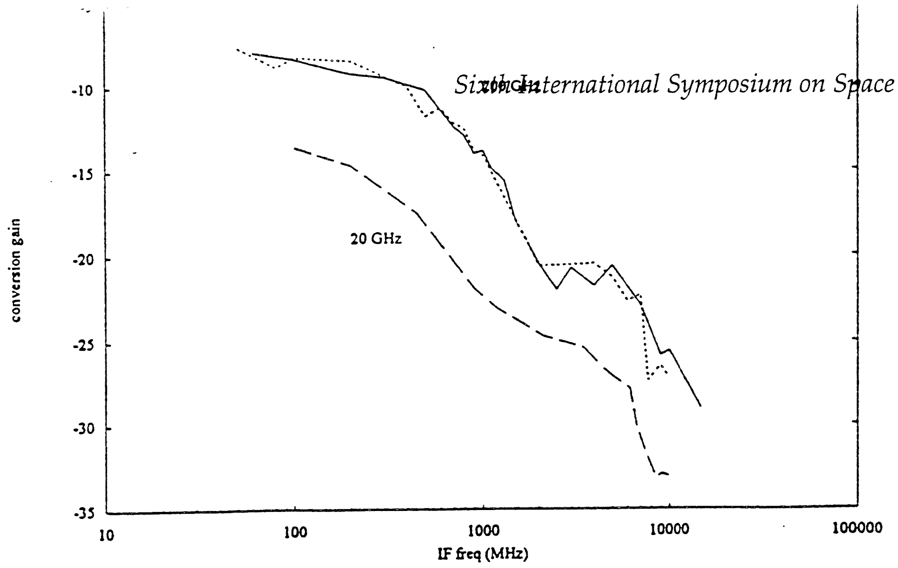

Figure 4. Conversion measurements at 200 GHz

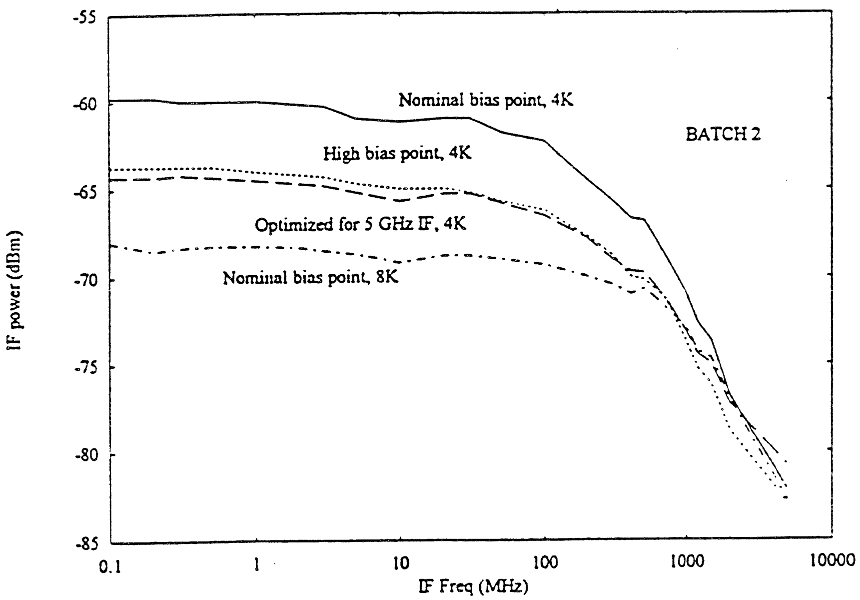

Figure 5. Bandwidth dependence on operating point.

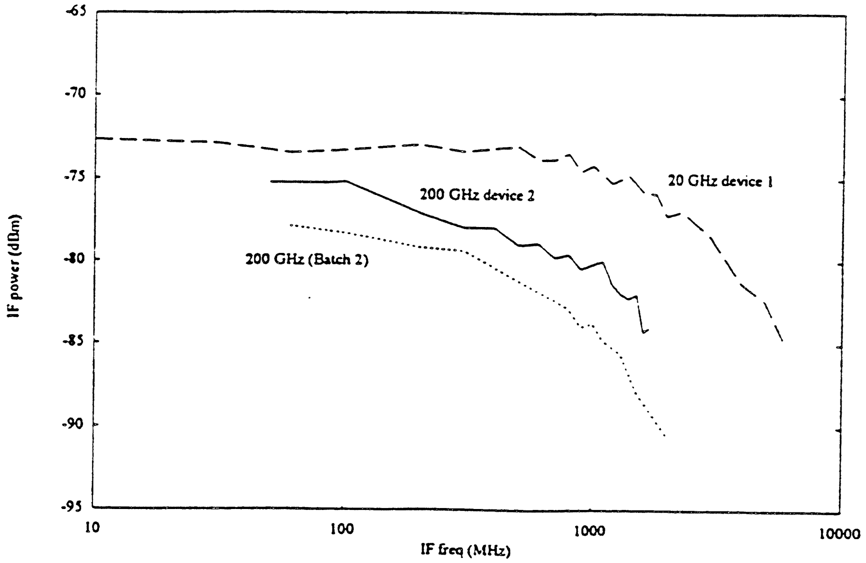

Figure 6. Bandwidth measurement of a mixer element.

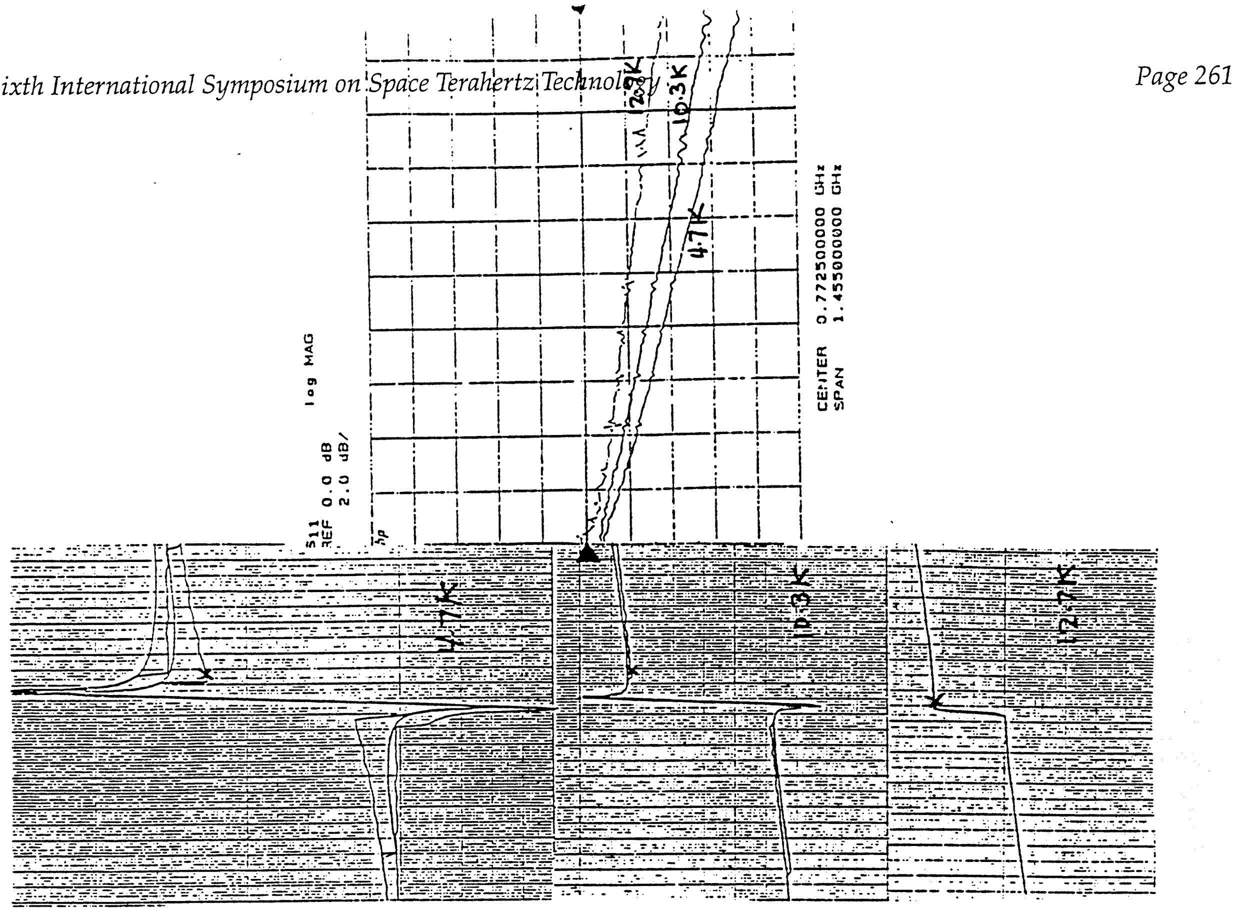

Figure 8. Mixer reflection loss at various operating temperatures.

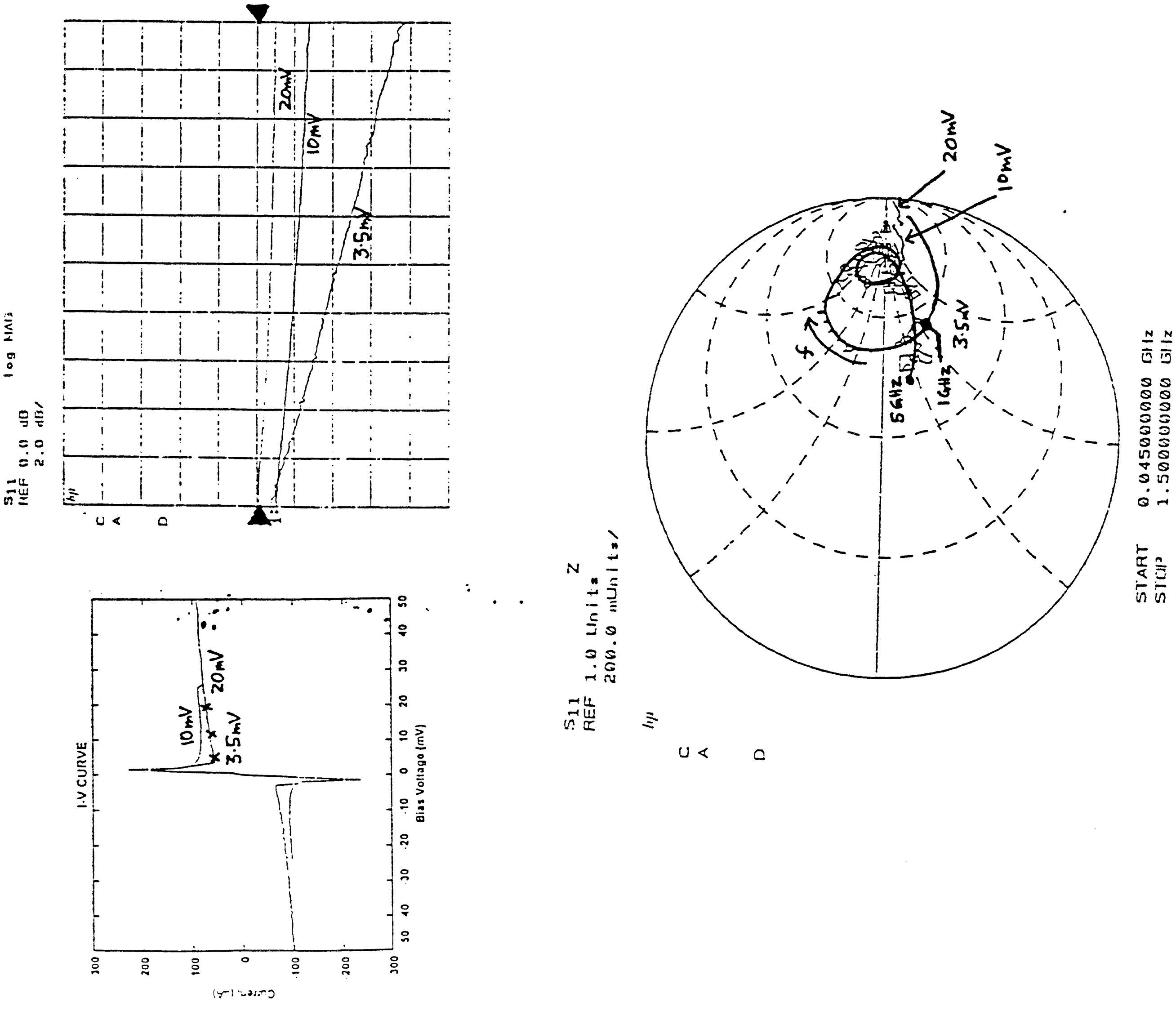

Figure 7. Mixer output impedance at various operating points.