OPTIMIZATION OF HOT ELECTRON BOLOMETER MIXING EFFICIENCY IN NbN AT 119 MICROMETER WAVELENGTH

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ABSTRACT

We describe an investigation of a NbN HEB mixer for 2.5 THz. An intrinsic conversion loss of 23 dB has been measured with a two-laser measurement technique. The conversion loss was limited by the LO power available and is expected to decrease to 10 dB or less when sufficient LO power is available. For this initial experiment we used a prototype device which is directly coupled to the laser beams. We present results for a back-short technique that improves the optical coupling to the device and describe our progress for an antenna-coupled device with a smaller dimension. Based on our measured data for conversion loss and device output noise level, we predict that NbN HEB mixers will be capable of achieving DSB receiver noise temperatures of ten times the quantum noise limit in the THz range.

I. INTRODUCTION

Recent Space THz Technology Symposia have included a number of papers that describe the on-going development of Hot Electron Bolometric (HEB) mixers. This research effort is ultimately justified

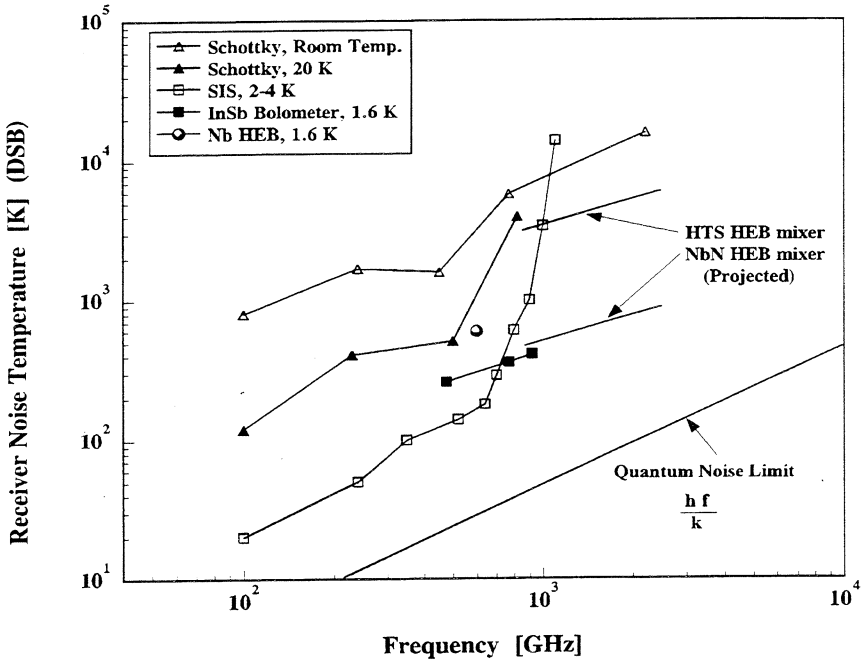

Figure 1: Receiver noise temperature for receivers in the THz frequency range.

by the fact that such mixers are predicted to achieve lower receiver noise temperatures than existing receivers for frequencies of about 1 THz and above. SIS mixers are now the lowest-noise receivers up to at least 700 GHz (see Figure 1); one paper at this conference (Bin et al., 1996) reports less than 1000 K DSB receiver noise temperature at 1 THz. Above 1 THz, the thin film superconductor version of the HEB mixer will have the advantage of not being limited to frequencies below or close to the bandgap frequency of the superconductor. In our paper at the Sixth International Symposium of Space Terahertz Technology, we described the initial phase of the project which aims at developing a low-noise HEB mixer receiver for a frequency of 2.5 THz (wavelength 118.83 μm). We chose to work with NbN films which have the potential for achieving IF bandwidths up to 10 GHz (Gousev et al., 1994). NbN HEB mixers can also operate well in the convenient temperature range of 4K to 8K and are not easily saturated by broad band thermal radiation. The bandwidth in NbN mixers is determined by a phonon cooling mechanism and was originally proposed in (Gershenzon et al., 1990).

There are two major steps in this project: (1) demonstration of mixing in a comparatively large "direct-coupled" prototype device which would require LO power of a few milliwatts; (2) an "antenna-coupled" device with an LO power level of a few μW and a noise temperature goal of ten times the quantum limit. For both versions of the NbN mixer, we use a THz gas laser as LO. **Since the previous conference, we have demonstrated mixing with an intrinsic conversion loss of 23 dB, using a direct-coupled device. The conversion loss was limited by the amount of LO power available.** This result of the conversion loss measurements was first published in (Gerecht et al., 1995a). Another paper at the present conference demonstrated the first receiver noise measurements for an NbN HEB mixer at 2.5 THz (Semenov et al., 1996), lending further evidence for the good mixing performance of NbN at this high frequency. The present paper will describe our 2.5 THz experiment as well as a new configuration of the direct-coupled device and its improved optical coupling efficiency. We also report on our progress in realizing an antenna-coupled device.

II. DEVICE DESIGN AND FABRICATION

General

The IF bandwidth of any HEB mixer is usually quoted to be:

$$B = \frac{1}{2\pi\tau} \tag{1}$$

The value of the time-constant, τ, depends on a number of parameters of the film that will be discussed in detail below. In practice, bandwidths from about 1 GHz to 4 GHz have been demonstrated so far with NbN devices.

The NbN films are DC magnetron sputtered on substrates of either silicon or sapphire. We chose these substrates since it had been shown (Voronov et al., 1994) that thin NbN films on these substrates have high critical temperatures (T_C) and sharp transitions (ΔT_C). Typical films on sapphire have T_C of about 14 K for a thickness t = 7 nm and 12.5 K for t=5 nm. The transition width may be as narrow as 0.2 K for 7 nm films and 0.35 K for 5 nm films. Surface resistance values for the films vary from 220

Ω/square for 7 nm thickness to 420 Ω/square for 5 nm thick films. Transition temperatures for films on silicon are slightly lower (~ 11-12 K) and ΔT_C's are slightly wider compared with films of the same thickness on sapphire. Films with 3 nm thickness have also been investigated and the initial measured properties of these films show much higher Ω/square, lower T_C and wider ΔT_C. Recently, we have fabricated films with sicknesses as low as 3 nm with much improved properties, and these will be tested in future experiments. The quality of the films is very important for a good mixer performance and has been steadily improved in the last couple of years.

Direct-Coupled Devices

Submillimeter gas lasers, pumped by CO_2 lasers, can produce output powers from a few mW to 100 mW or more at discrete frequencies from below 1 THz to several THz. They are thus ideal laboratory sources of LO power for initial experiments with NbN HEB mixers. We have chosen to work with the 118.83 micrometer wavelength line of methanol (a frequency of 2.52 THz) allowing us to utilize direct focusing of the laser onto a device of size 700 micrometers by 350 micrometers. The device dimensions were chosen

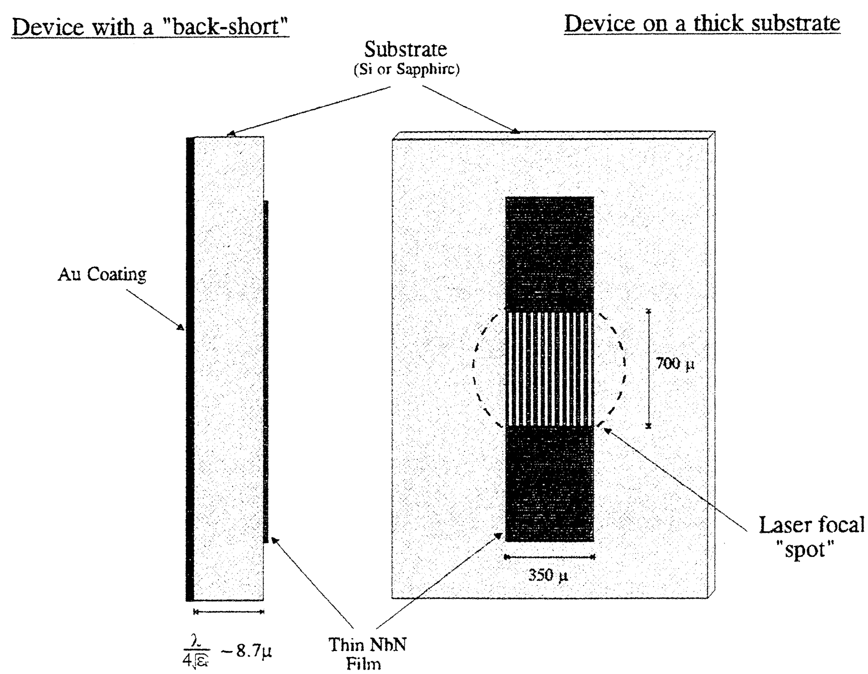

Figure 2: Direct-coupled device.

to approximate those of the focused spot from the optical system. The device is shown in Figure 2. It consists of about 175 strips of NbN each has a width of 1 micrometer and a spacing of 1 micrometer between them. Since the strips are very narrow compared with the wavelength, the device absorbs THz power as a uniform resistive sheet. The optical coupling factor assuming an incident plane wave was calculated in our previous paper (Gerecht et al., 1995b). Due to the rather high resistance per square of the film and the high dielectric constant of the substrate, we predict a coupling factor of about 8% for a typical device. There will also be another factor involved in the optical coupling to the actual device and it can be obtained by convoluting the (gaussian) form of the laser focal spot with the shape of the device. This factor is roughly 50% or a little larger. Note that the surface resistance of the film at 2.5 THz is close to the normal state surface resistance since the frequency is well above the bandgap frequency. We have previously proposed (Gerecht et al., 1995b) a configuration which can result in close to 100% coupling factor. In this configuration we utilize a very thin ($\lambda / 4\sqrt{\varepsilon} = 8.7\ \mu m$) silicon substrate and evaporate a

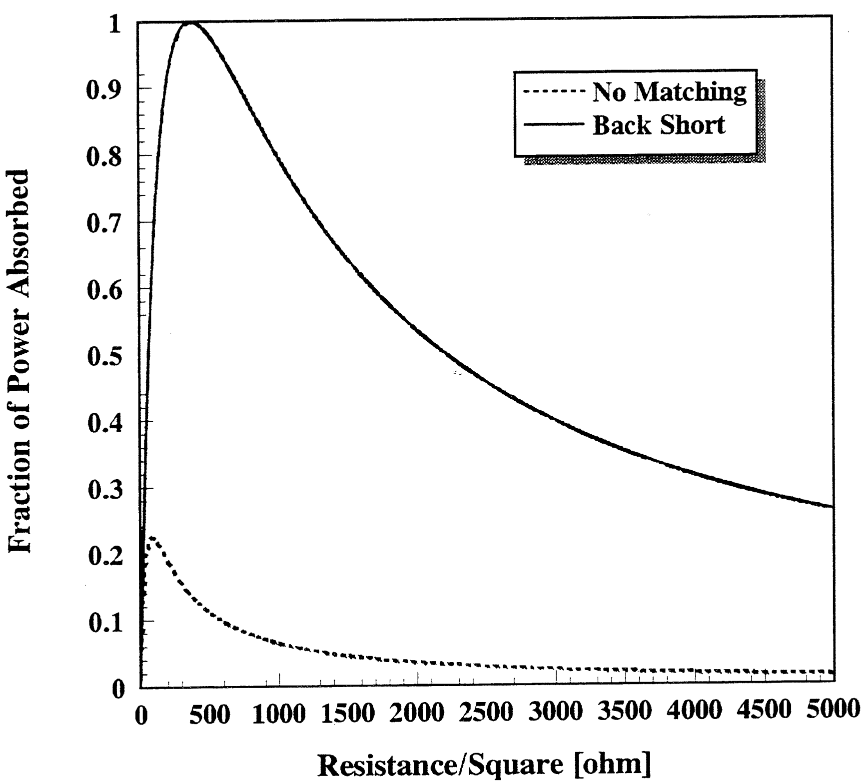

Figure 3: Theoretical power coupling to the NbN device for different configurations.

layer of gold on the back side of the substrate forming, in effect, a "back-short" behind the device. Figure 3 shows the calculated coupling factor as a function of the resistance per square for the device with the back-short and for the device without the back-short. The direct-coupled devices are contacted by pressing indium onto the contact regions. The fabrication of the device on this thin substrate is an extremely delicate process. First we deposit NbN on a substrate of the required thickness and then fabricate the device and the back-short. The device is then mounted onto a copper post which is connected at the other end to the cold plate of an IRLABS liquid helium dewar. A heater and temperature sensor are also attached to the copper post close to the device.

Antenna-Coupled Device

Antenna-coupling of Schottky-barrier diodes as well as SIS devices has been successfully demonstrated up to about 1 THz (Filipovic et al., 1993). Less work using this approach has been done for frequencies above 1 THz. However, there is no fundamental reason that this configuration cannot be implemented and perform

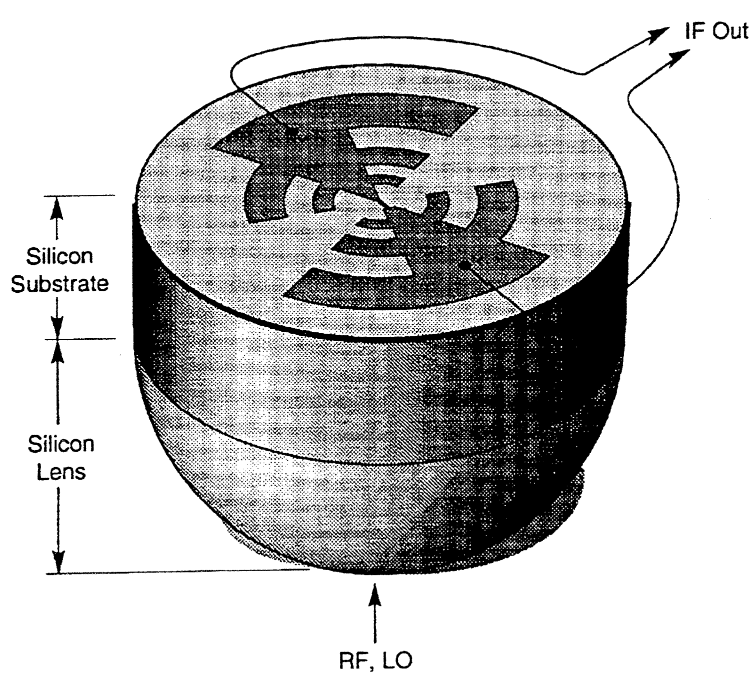

Figure 4: Log-periodic antenna fabricated on an extended hemispherical silicon lens.

Figure 5: SEM close-up of the log-periodic antenna (gold) and NbN strips.

as well at 2.5 THz. We have chosen to scale down a lens configuration for 250 GHz designed and investigated by (Filipovic et al., 1993). The lens size then scales from 13.6 mm to 1.3 mm. We chose to use the same antenna element, a log-periodic spiral, which has excellent broadband properties. The work of Filipovic et al shows that one can attain coupling efficiencies to a gaussian beam in the range of 70-80%. The configuration is illustrated in Figure 4 and an SEM photograph of the actual device and the gold log-periodic antenna is shown in Figure 5. The device consists of three parallel NbN strips 1 µm wide with 1 µm spacing. The gap in the antenna is also about 1 µm long. The resistance of the device can be adjusted in order to match the antenna impedance by varying the number of strips and their widths.

We have developed a procedure for fabricating and aligning the antenna-coupled device with a very small lens (1.3 mm). The small dimensions of the silicon lens and the added extension require a photolithographic procedure rather than the more commonly used mechanical alignment procedure. Optical off-axis mismatch considerations require that the device and the lens registration accuracy be within ±60 micrometers. We have solved this problem by introducing an additional set of alignment marks which in turn produce alignment marks on the other side of the substrate by means of etched through holes. These holes are then used as alignment marks for a well etched on the other side of the device substrate. The well acts to position the center of the lens precisely on top of the center of the antenna and device. By accurately controlling the depth of the well, the thickness of the substrate under the device is thinned to form the extended portion of the extended hemispherical lens (about one third of the lens radius).

The following steps were performed to fabricate the antenna coupled device:

- 30-70 Å NbN was deposited on a silicon wafer by magnetron sputtering
- NbN strips were defined and etched using Reactive Ion Etching (RIE)
- the gold log-periodic antenna was fabricated using liftoff
- through holes were etched using Ethylenediamine Pyrocatechol (EDP)
- the well for the lens was etched (also with EDP) on the other side of the substrate using the through holes as alignment marks
- the lens was attached to the silicon substrate with Tech-Wax

III. OPTICAL SETUP

Laser setups at both UMASS/Amherst and at UMASS/Lowell were used for the experiments. An optical setup as shown in Figure 6 was used for conversion loss measurements at UMASS/Lowell. Two THz gas lasers are pumped by the same CO_2 laser, insuring good tracking of the frequencies output by the two lasers. The two laser beams are combined by means of a wire grid set at 45 degree angle. The laser beams are then focused by an off-axis paraboloidal mirror through a 0.75 mm polyethylene window into the dewar. Shorter IR wavelengths are further attenuated by a sheet of a black polyethylene at 77 K. The device is mounted on a copper post thermally attached to the bottom of the liquid helium container of the dewar. A resistive heater allows us to vary the device operating temperature.

The LO laser operates in a single waveguide mode which produces a Gaussian spatial output profile with the first sidelobes 20 dB down. The signal laser has an oversized half-symmetric resonator which supports more than one transverse mode (frequency). Careful alignment still produces a far-field spatial pattern which is Gaussian to a level of 15 dB below the peak. Mixing is observed at an IF frequency of up to a few MHz by de-tuning the cavity of one of the THz lasers. Conversion loss measurements performed at microwave frequencies, to be described below, show that the bandpass curve is flat from a few MHz to

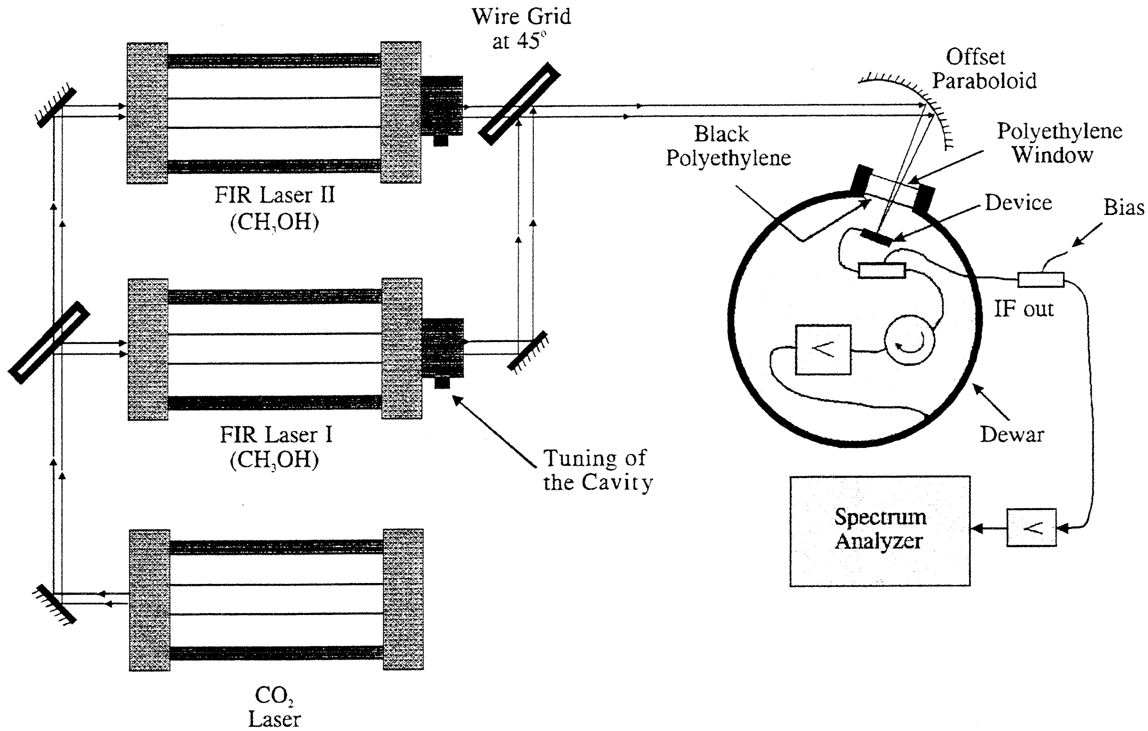

Figure 6: Optical layout for conversion loss measurements.

over 1 GHz. Thus, we conclude that the conversion loss measured at about 1 MHz should apply in this entire range of intermediate frequencies.

At UMASS/Amherst, a single laser enabled us to measure optical coupling loss as well as receiver noise temperature. This configuration is shown in Figure 7. A similar configuration is used for noise temperature measurements at UMASS/Lowell. The UMASS/Amherst laser has a maximum output power of 100 mW (CW) using the 119 μm line. The laser power output was increased to this level by utilizing a capacitive grid type uniform output coupler (Densing et al., 1992). A mylar beam splitter transmits 64% of the laser power while diverting 36% into a matched load. The beamsplitter allows radiation from a hot-cold load to be directed into the beam path. This blackbody radiation is derived by chopping between a room temperature absorber and a liquid nitrogen bath. The device is biased through a cold bias tee connected through an isolator to a broadband cooled HFET amplifier with close to 30 dB gain and about 90 K noise temperature (including isolator losses). The IF system bandwidth is limited by the isolator to 950 - 1400 MHz. In some experiments we used a room temperature IF amplifier with a noise temperature

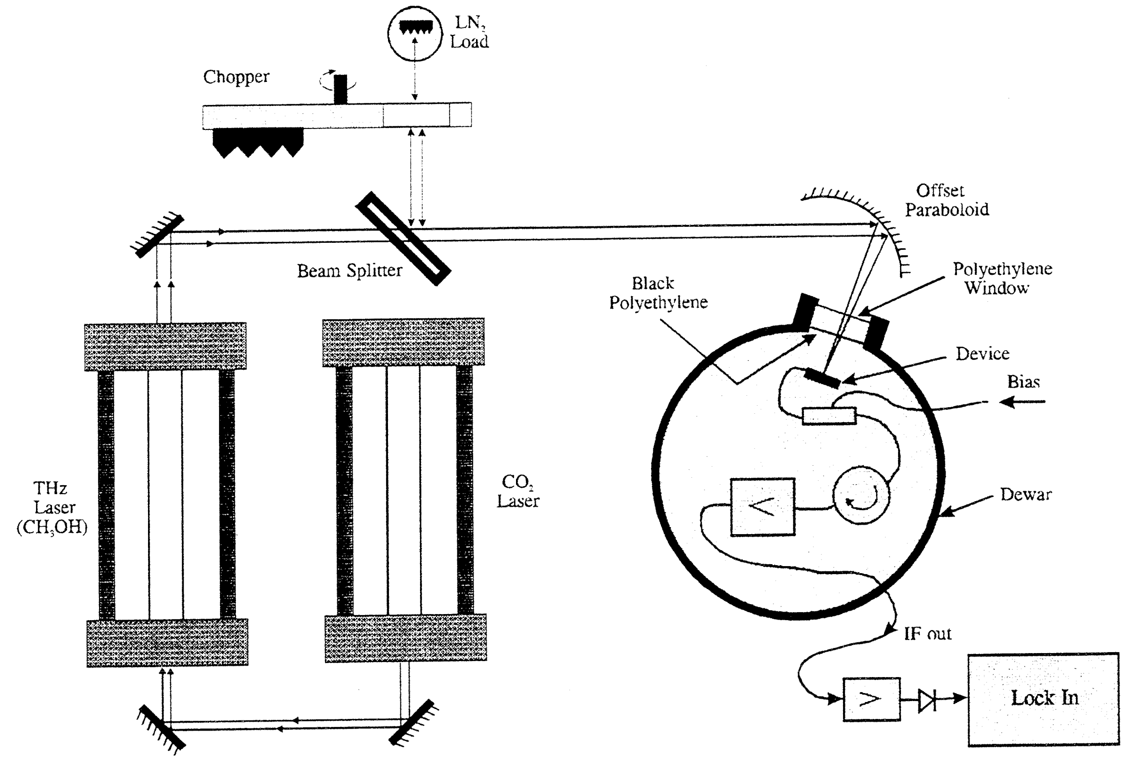

Figure 7: Optical layout for noise measurements.

of 150 K. After further amplification, the IF power is measured with a microwave detector connected to a lock-in amplifier with its reference derived from the chopper. The setup is aligned by using the HEB device itself as a detector and observing the signal through the bias port. The device is biased close to T_c for maximum responsivity which is of the order of 10's of V/W.

IV. EXPERIMENTAL RESULTS

Measured Conversion Loss at 2.5 THz

Due to the large size of the device, it was expected to require a fairly large LO power, of the order of a few milliwatts. The LO power is minimized by operating at a device temperature (T_{op}) close to T_c. If T_{op} is too close to T_c, however, the conversion loss increases quickly. A typical optimum choice of T_{op} is roughly ten times ΔT_c below T_c. If the laser power is sufficiently large, the device current will be

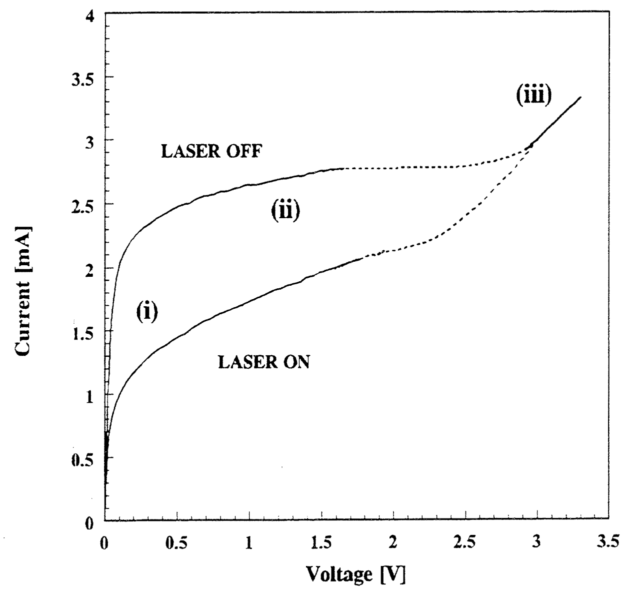

Figure 8: Measured I-V curve for a typical NbN device.

depressed substantially as shown in the IV-curves of Figure 8. These particular curves were recorded when the incident laser power outside the dewar window was 20 mW. In our mixing experiment, the laser power incident on the dewar window was 6 mW and the depression of the current was smaller indicating that insufficient LO power was available. This was shown to be the case in the mixer measurements. We utilized a device on a silicon substrate of normal thickness with a NbN thickness of 70 Å. One can measure the power actually absorbed in the device by making use of the fact that along a line of constant resistance in the I-V diagram the electron temperature is constant; therefore, the total absorbed power (P_{DC} + P_{LO}) is also constant anywhere along this line. We found that the absorbed power in the best operating point was 0.16 mW resulting in an **optical coupling loss of 15.6 dB** when taking into account that the incident power was 6 mW. About 3 dB of the optical coupling loss was due to the fact that the device fingers were oriented horizontally whereas the incident polarization was at 45 degrees to the horizontal. The incident signal laser power was 0.7 mW. A typical display on the spectrum analyzer such as that shown in Figure 9 was obtained. The peak at about 1 MHz is the mixing product of the two main modes of the lasers. Other smaller peaks are due to higher order transverse modes of the signal laser but are at least 20 dB below the main peak. We could verify the origin of the smaller peaks by blocking the beam of one laser. Knowing the gain of the amplifier inserted before the spectrum analyzer, we obtained a **total conversion**

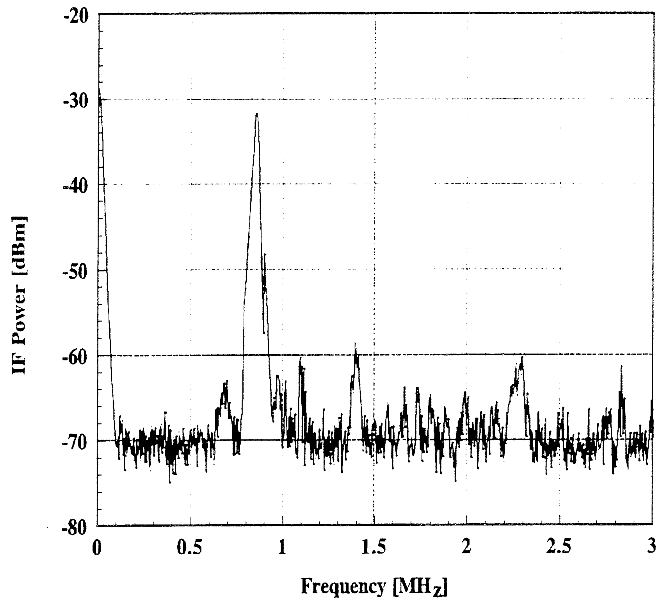

Figure 9: Spectrum analyzer recording of the IF output from the 2.5 THz mixer.

loss of 41.5 dB. Subtracting the optical coupling loss and the polarization loss from the total loss, we find **the intrinsic conversion loss to be 41.5 dB - 15.6 dB - 3 dB = 23 dB.** We have subtracted 3 dB for the polarization loss which would not occur in a real system; in that case, the device would be oriented along the signal polarization. It was clear that the mixer was "LO-starved"; the IF power decreased by 7 dB when the LO was attenuated by 6.2 dB. This was also made clear by measuring the conversion loss as a function of the operating temperature as shown in Figure 10. The conversion loss increased as the temperature decreased due to the LO power deficiency. A typical intrinsic conversion loss of 10 dB has been obtained in earlier NbN HEB mixers at lower frequencies of up to 350 GHz. It seems reasonable to assume that the conversion loss of our device would decrease to about that level when sufficient LO power is available. Also, the paper by (Semenov et al., 1996) in this conference proceedings infers an intrinsic conversion loss of a NbN HEB mixer at 2.5 THz of about 10 dB. It has thus been established that the optimum intrinsic conversion loss of NbN HEBs at frequencies as high as 2.5 THz is at most about 10 dB. We have indicated a **qualitative prediction** of the conversion loss as a function of operating temperature (see Figure 10). This curve assumes that the LO power is sufficient for optimum conversion loss. In our measurements, the LO power was not sufficient. At the lower temperature, the LO power required

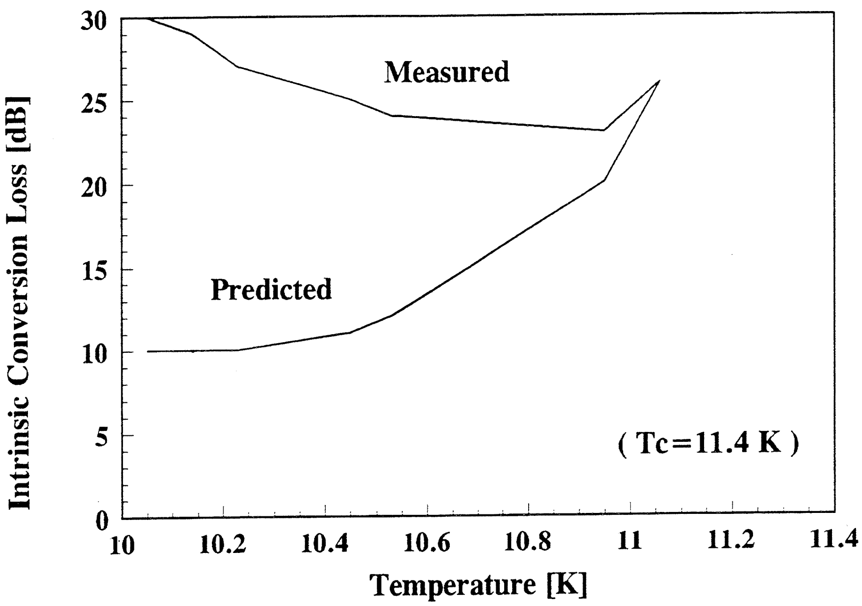

Figure 10: Temperature dependence of the conversion loss.

increases and the measured conversion loss thus goes up as the temperature is decreased. This is in agreement with the measured data.

We have tested one device with a backshort, fabricated from a silicon substrate roughly ten micrometers thick. The fabrication procedure is still not completely worked out and the superconducting properties of the NbN film may have been affected as evidenced by a non-standard I-V curve with more than one "jump". The device had a normal resistance above T_C of 215 ohms. The optical coupling loss was measured to be 10 dB, which is lower by about 6 dB compared with the device on a thicker silicon substrate described above. The coupling loss includes loss from both the polyethylene window and the black polyethylene filter of about 2-3 dB. Further work will be done to demonstrate optical coupling closer to that predicted from theory (see Figure 3) by using a device with a more ideal I-V curve.

Bandwidth Measurements at 14-20 GHz

It has been shown that microwave measurements of the IF bandpass curve for NbN mixers yield practically the same 3 dB bandwidth as when the measurements are performed in the millimeter/submillimeter wave range (Kawamura et al., 1995, 1996; Schoelkopf et al., 1996). In our case, the devices are mounted on a dip stick which is inserted into a liquid helium storage dewar. The RF frequency is typically close to 20

GHz while the LO is varied between 20 and 14 GHz to yield IF frequencies up to 6 GHz. The LO power level is adjusted at each frequency to insure that the bias current is always the same; consequently, the *absorbed LO power* is always the same. Figure 11 shows the results obtained for the same device for which the conversion loss was measured at 2.5 THz. The 3 dB bandwidth is 3 ± 0.5 GHz. A wider bandwidth is obtained for NbN on silicon substrates than for NbN on quartz substrates (Kawamura et al., 1996). We are in the process of measuring devices with several different thicknesses in order to clarify the processes which determine the bandwidth for NbN HEBs on silicon substrates. In general, the bottle-neck in the energy loss process for the device may be due to either (1) electron-phonon processes, or (2) the escape time of phonons from the film to the substrate. Since the electron-phonon relaxation time $\tau_{e\text{-}ph}$ at a temperature of 11 K has been measured to be about 15 ps (a bandwidth of 10.6 GHz), it is likely that the phonon escape time, τ_{es}, may still have a major influence on the bandwidth for the 70 Å film. The measured curve is essentially flat at the lowest frequencies and thus we can expect that the conversion loss measured at 2.5 THz should be valid for the entire flat region in the IF response.

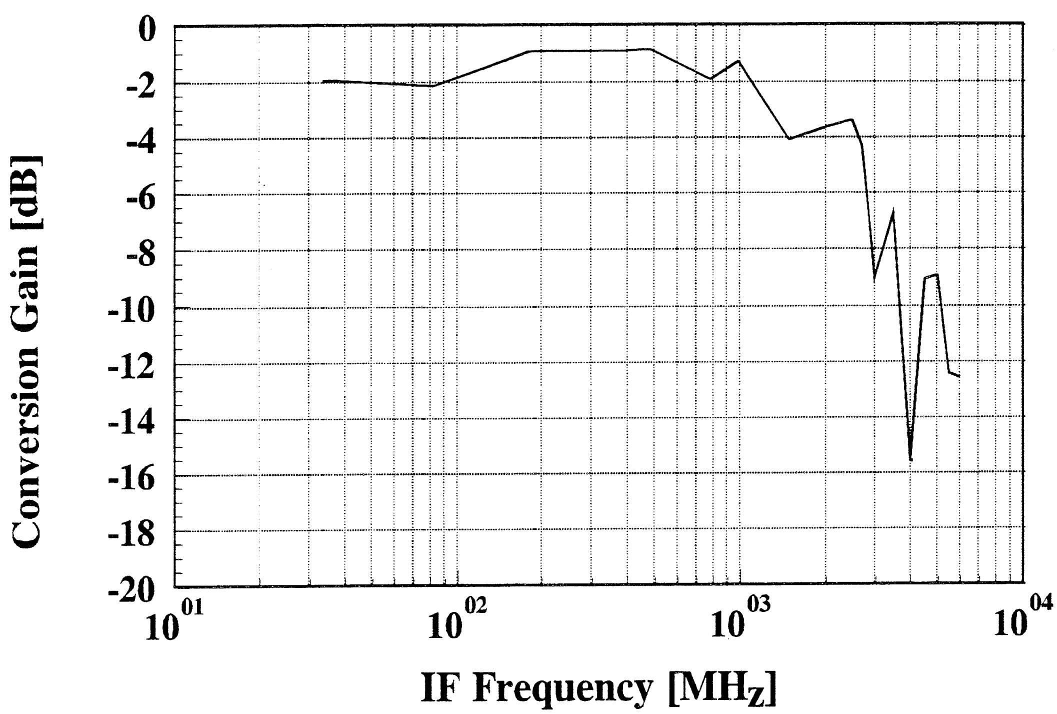

Figure 11: IF response curve for a 70Å thick NbN device.

V. DISCUSSION

This paper and the following paper in this proceedings by Semenov et al. have demonstrated that NbN can be an efficient HEB mixer at a frequency well above 1 THz. The conversion loss is estimated in both of these efforts to be at most 10 dB for an optimum mixer and a lower conversion loss is theoretically feasible. The IF bandwidth was measured to be 3 GHz in this work and 4 GHz for similar devices in the paper by Yagoubov et al. in this proceedings. DSB receiver noise temperatures for 2.5 THz are expected to be similar to those measured for lower frequency NbN HEB mixers once optical coupling problems have been ironed out. Semenov et al. measured 40,000 K with a mixer noise temperature of 18,000K, which is already approaching the performance of Schottky mixers. The DSB receiver noise temperature can be predicted quite confidently since the intrinsic conversion loss can now be estimated to be 10 dB or less. Also, the NbN device output noise temperature (T_d) has been consistently measured in many experiments to be in the range of 50-100 K. If we choose the upper limit for these parameters, an optical coupling loss of 3 dB and T_{IF} = 10 K, we obtain,

$$T_{R,DSB} = (L_c\text{-}2) \times (T_d/2) + (L_c/2) \times T_{IF} = 1{,}000 \text{ K} \tag{2}$$

With careful work, it is expected that this receiver noise temperature, which represents eight times the quantum noise limit, can be reached at 2.5 THz. The actual noise bandwidth, which hasn't been measured so far for any HEB, is expected to be wider than the conversion gain bandwidth. Special advantages of NbN HEB devices include: the relative ease of fabrication due to the large size (compared to diffusion-cooled HEBs), LO power of a few microwatts or less, operating temperatures from 4 to 8 K and thermal saturation temperatures in the range of 10,000 K (Kawamura et al., 1996) obliviating the need for input-filters, which are required for lower saturation power mixers. We can therefore conclude that the NbN HEB mixer should find a niche of useful applications as a low-noise THz receiver.

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