MEASURED RESULTS FOR NbN PHONON-COOLED HOT ELECTRON BOLOMETRIC MIXERS AT 0.6-0.75 THz, 1.56 THz, AND 2.5 THz

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I. INTRODUCTION

NbN Hot Electron Bolometric (HEB) mixers represent a promising approach for achieving receiver noise temperatures of a few times the quantum noise limit at frequencies above 1 THz. These HEB mixers have so far demonstrated a DSB noise temperature as low as 500 K at 630 GHz [Kroug et al., 1997; Kawamura et al., 1997], and 980 K at 900 GHz [Kroug et al., 1997]. Noise temperatures of about 1000 K or less can be expected for frequencies above 1 THz in the future. NbN HEB mixers have been shown to have sufficient bandwidths for the anticipated applications such as future receiver frontends for THz astronomical observation from space. A receiver noise bandwidth of 5 GHz and conversion gain bandwidth of 3 GHz were measured by [Ekström et al., 1997]. The LO power required is typically 100 nW, which makes the NbN HEB mixers suitable for use with future solid state tunable THz sources. However, the LO power is not at such a low level that its operating point is affected by input thermal noise power. This paper describes the development of THz HEB mixers for the 1 THz to 2.5 THz frequency range. The HEBs employ NbN as the bolometric material. We present our first results from measurements with these mixers at frequencies of 0.6 THz to 0.75 THz, 1.56 THz, and 2.52 THz. We have measured a DSB receiver noise temperature of $5{,}800\,^{+1400}_{-1000}$ K at 1.56 THz. In a separate experiment, we measured a conversion gain of 3 dB $\pm$2 dB at the same frequency.

II. DEVICE DESIGN AND FABRICATION

NbN Films

The NbN films were fabricated on silicon substrates at Moscow State Pedagogical University (MSPU) by magnetron reactive sputtering in an argon/nitrogen gas mixture. For this work we have primarily used films of thickness 3.5-4 nm in order to maximize the conversion gain bandwidth. The production of such thin films is still an evolving technology, but recent films on both sapphire and silicon substrates have shown much improved properties [Cherednichenko et al., 1997]. The optimum thickness, based on the sapphire work, appears to be close to 3.5-4 nm. The films used in thease measurements have T_c = 7.5 - 9 K, the transition width is about 1 K, and the critical current density is 2 x 10^6 A/cm^2.

Optical Design

Optical design considerations are crucial for efficiently coupling LO and signal power into the device. Quasi-optical coupling to the device is most common for frequencies above 1 THz. We chose to use an extended hemispherical silicon lens coupled to a self-complementary log-periodic antenna (see Figure 1), as successfully demonstrated and analyzed at 250 GHz and 500 GHz by [Filipovic et al, 1993]. The log-periodic antenna is convenient since it can be used over a very wide frequency range; later versions will employ twin-slot or twin-dipole antennas tuned to smaller frequency bands. We scaled the dimensions of the lens and the antenna used in the 250 GHz setup by a factor of ten, resulting in a lens diameter of 1.3 mm. We chose an extension length, beyond the hemispherical lens, of 0.33 times the lens radius. We can predict the amount of beam-scan which would be caused by misalignment of the center of the antenna with respect to the center of the lens: a 20 micrometer misalignment results in a 5 degree beam scan. This makes it imperative to use an accurate alignment procedure, which will be described below. We are not employing a matching layer for the lens at this stage.

Device Fabrication

Devices have been fabricated at MSPU as well as at UMASS/Amherst. The processes are somewhat different at the two locations, but in what follows we will emphasize the UMASS process. The gold log-periodic antenna is fabricated using liftoff. After the pattern has been defined in the photoresist, a 40 nm thick layer of Nb is applied by sputtering. Next, 20 nm of Ti and 100 nm of Au are deposited by E-beam evaporation, and the lift-off is performed. The NbN strips are then defined and etched using Reactive Ion

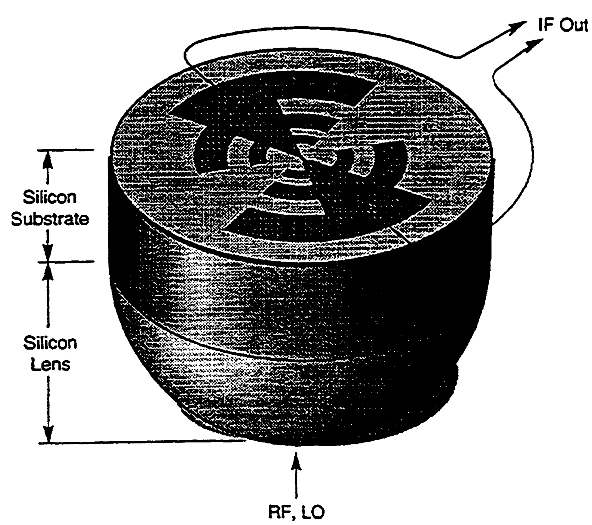


Figure 1: Log-periodic antenna fabricated on an extended hemispherical lens.

Etching (RIE). The substrate is thinned by lapping to a thickness equal to the lens extension length. The position of a square alignment window for the lens is defined in a photoresist layer on the opposite side of the substrate from the antenna and device, using an infrared mask aligner, whereupon the alignment window is etched by RIE to a depth of 100 nm. The lens is attached to the silicon substrate using purified bees wax. The final dimensions of the device strips are about 0.6 μ long by 1.0 μ wide. The number of strips is from one to three. The mask also has a different pattern for which all teeth are larger by a factor of two, i.e. the smallest teeth determine a highest frequency of the antenna of about 1.25 THz. This antenna can have up to five strips.

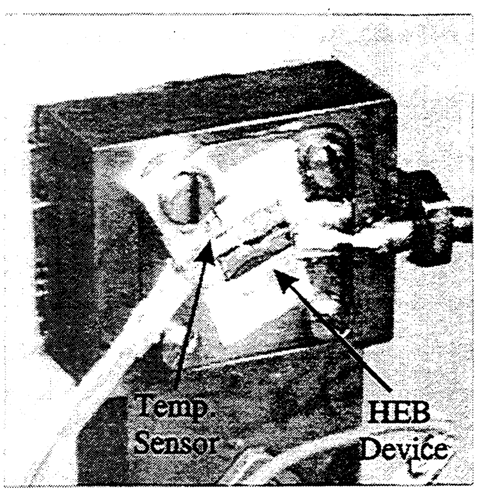
III. EXPERIMENTAL SETUP

Receiver Configuration

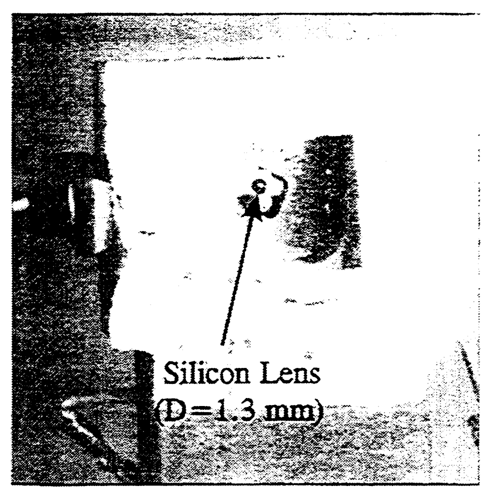
The integrated antenna/HEB device and lens are attached to a copper post, which is thermally anchored at the other end to the liquid helium reservoir of an IRLAB dewar (see Figure 2 and Figure 3). The antenna is connected to the IF and bias system via a microstrip/semirigid coax line and bias tee. A cooled HEMT amplifier with isolator input is also used inside the dewar (Figure 3). This IF amplifier has a bandwidth from 1250 to 1750 GHz, with noise temperature of about 10K.

Optical Setup

The optical coupling loss as well as the receiver noise temperature are measured with a CO_2 laser pumped FIR methanol laser as the LO source. The laser setup is illustrated in Figure 4. Mylar beam split-



(a)



(b)

Figure 2: Photographs of the OFHC copper pedestal: (a) close-up of the device mount and contacts, (b) close-up of the opposite side of the pedestal showing the silicon lens.

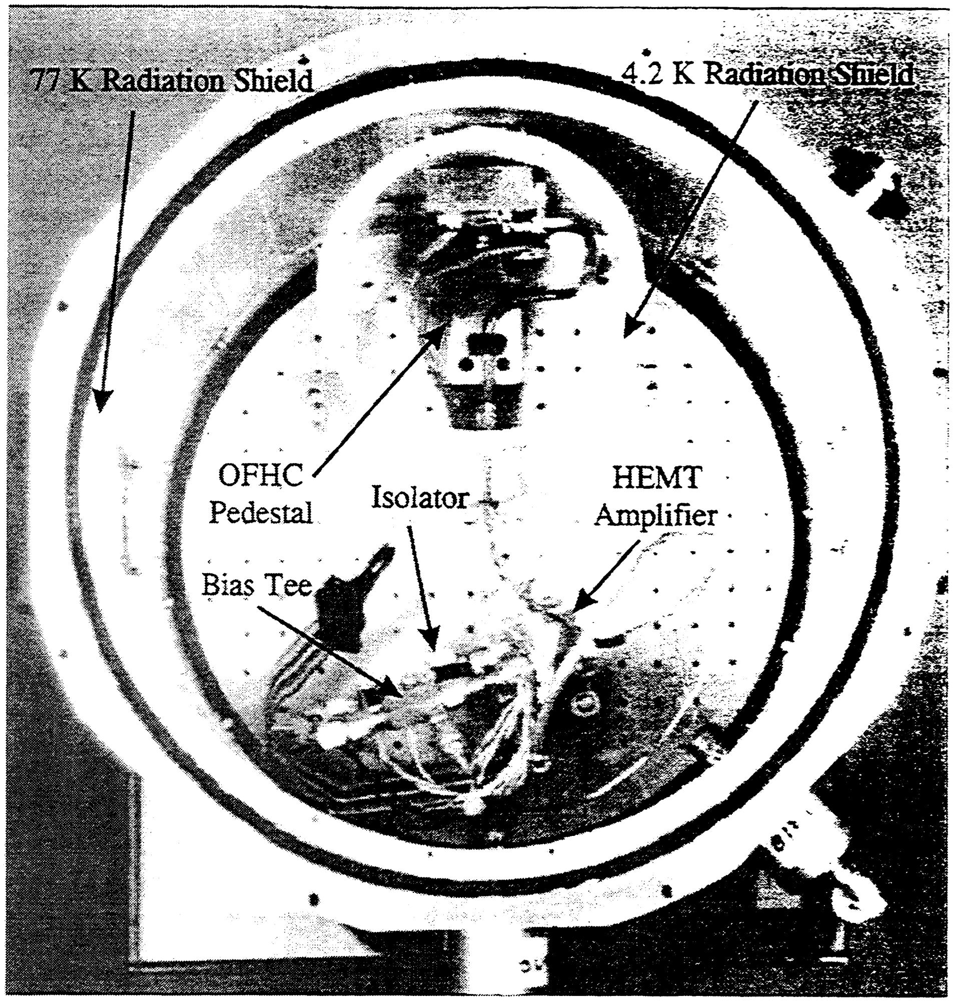


Figure 3: Top view of the IRLAB dewar showing the *dc* and *IF* connections.

ters with a thickness of 6, 12.5, and 25 micrometers, respectively, act as diplexers between the LO and a chopped hot/cold noise source. The radiation is focussed by an offset paraboloidal reflector or a TPX lens. In order to measure the conversion gain directly, we employ two lasers at UMASS/Lowell as shown in Figure 5. The active medium of these lasers is difluoromethane, and the frequency 1.56 THz. The lasers were slightly detuned and produced an IF of 600 kHz. The gain bandwidth of NbN HEB devices at the IF cannot be easily measured at THz frequencies. At present, we measure the mixer gain bandwidth at 94 GHz instead. Since the LO power required is so low, the same optical configuration (including the lens), can be used at 94 GHz also, although the antenna response does not extend this low in frequency.

Noise temperature measurements at 0.6 THz to 0.75 THz were also performed at Chalmers University in a setup which used a BWO as LO source and a 12.5 μm beam splitter. The experimental arrangement was as described in [Ekström et al., 1997].

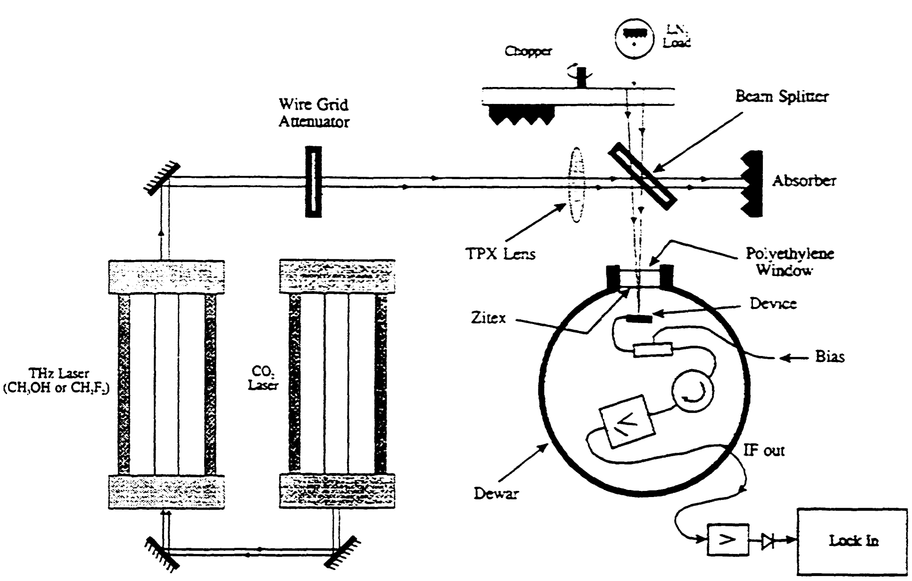


Figure 4: Optical setup for measurement of optical coupling loss and receiver noise temperature.

FTS Spectra of the Device Response

Fourier Transform Spectra were obtained at Chalmers University by employing the device as a detector, at a temperature close to T_c.

IV. RESULTS AND DISCUSSION

FTS Spectra of the Device Response

Figure 6 shows the spectra obtained for a NbN device integrated with the larger version of the log-periodic antenna described above. The device was mounted in two perpendicular orientations in order to elucidate the frequency-dependence of its optimum polarization. [Kormanyos et al., 1993] showed that the polarization for optimum response varies periodically with frequency at an amplitude of ±22.5°. This is consistent with the spectra we observed, in which dips in the response occur at frequencies which are one octave apart. As the orientation of the device was changed by 90 degrees, peaks appear where dips occur for the perpendicular orientation. The highest frequency peak corresponds to when the second smallest tooth is one quarter wavelength long when considering the effective dielectric permittivity of the silicon medium. In order to utilize self-complementary log-periodic antennas, one has to be aware of their sensitivity to the incident polarization. The power available, when lasers are used as the LO sources, is in general sufficiently large such that a polarization rotater can be used to produce the optimum polarization. This was confirmed in our experiments at both 1.56 THz and at 2.52 THz.

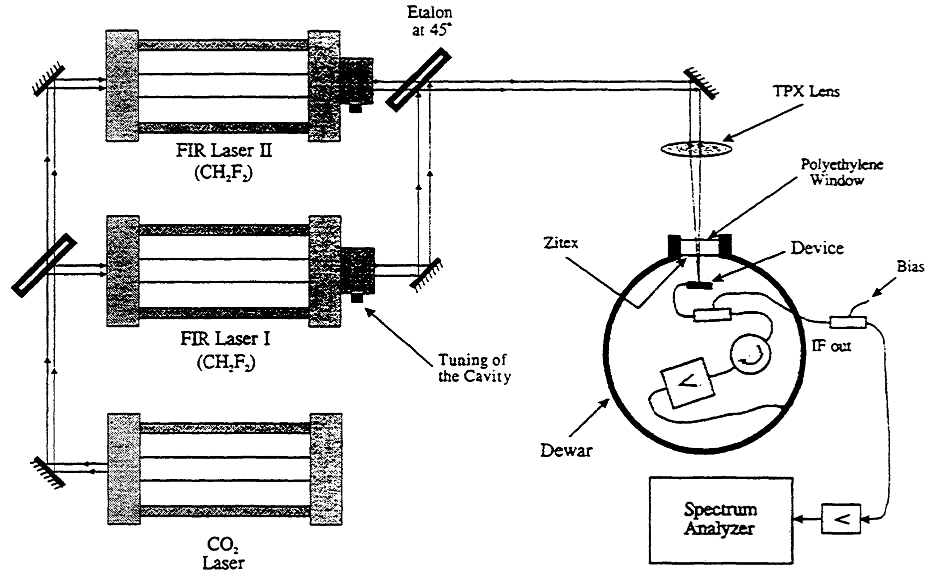


Figure 5: Optical setup for measurement of conversion gain.

Noise Temperature Measurements

Our results from the noise temperature and conversion loss measurements at different frequencies are summarized in Table I below.

Table I: Noise Temperature and Conversion Loss Summary

f (GHz)	T_{DSB} (K)	T_{out} (K)	T_{IF} (K)	T_{mix} (K)	$L_{c,tot}$ (dB)	$L_{c,i}$ (dB)	$L_{c,opt}$ (dB)
94	NA	NA	NA	NA	NA	9	NA
600-750	900	105	24	730	12.7	7.7	5
1,560	5,800	10	13	2,500	27	18-20	7-9

The Y-factor was measured by inserting a liquid nitrogen cooled absorber by hand into the path of the beam several times. In the 1.56 THz experiment, the IF output power was recorded on a chart recorder, and the results of many individual Y-factor measurements were averaged. The Y-factor was determined to be 0.155 dB ±0.03 dB, which yields a DSB receiver noise temperature of $5{,}800^{+1400}_{-1000}$ K. The fact that it was possible to perform the Y-factor measurement at this noise temperature level without the use of a rotating chopper is a tribute to the excellent amplitude stability of the UMass/Lowell laser used for this experiment. The stability is also evident in the I-V curves recorded by our fast (about 1 ms) computerized recording system. Figure 7 shows the optimum operating point of the device in the noise temperature measurement. Near

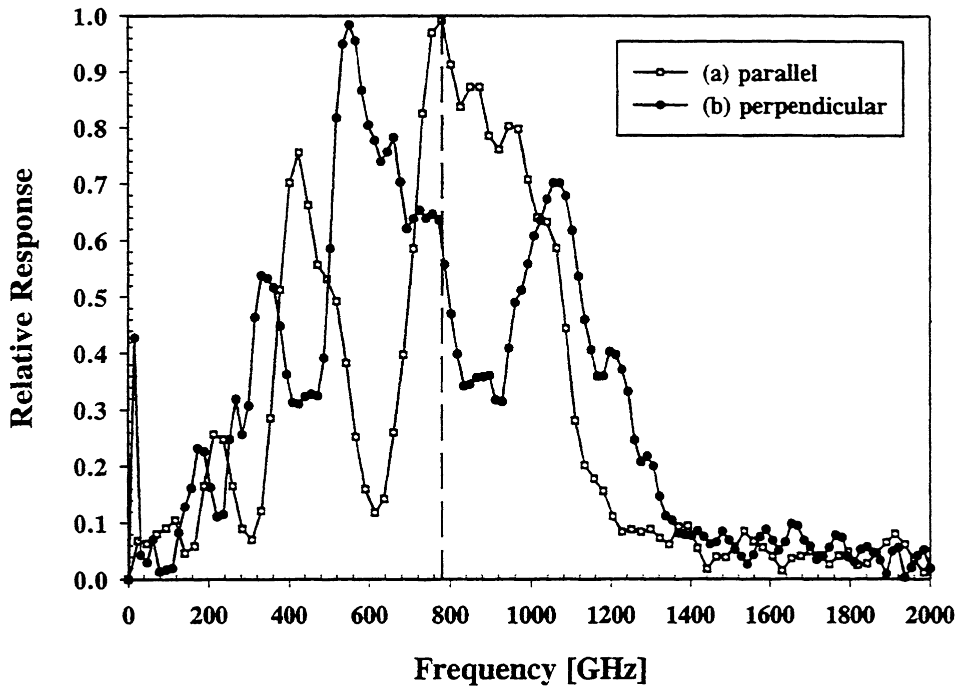


Figure 6: FTS spectra of the device for (a) device orientation parallel to the FTS polarization, and (b) perpendicular to the FTS polarization.

the optimum operating point (0.97 mV, 38 μA), the device is very sensitive to variations in LO power. Nevertheless, only very small variations are evident in this recording. In contrast, the I-V curve obtained with the free-running 2.52 THz laser shows large fluctuations in the sensitive region of the I-V curve (see Figure 8). The antenna/lens combination clearly performed well at 1.56 THz, as evidenced by the fact that during a chopped noise measurement on the system, it was possible to blank out essentially the entire signal by blocking the cold source with a piece of absorber of a size equal to the predicted beamwidth, about 8 degrees at this frequency. The LO power absorbed by the device was 240 nW (for the 600-750 GHz device it was about 100 nW). There was no measurable change in the DC operating point when the input load of the mixer was changed from room temperature to liquid nitrogen temperature.

Table I shows the estimated break-down of the total conversion loss into components. We assume that the optical coupling loss is essentially given by the known losses of different components, such as the polyethylene window, the Zitex thermal radiation filter, the reflection loss of the lens, etc.. The remaining loss to be accounted for by the mixer itself, the intrinsic conversion loss, including IF output mismatch, is about 18-20 dB for the 1.56 THz mixer. This somewhat high intrinsic loss can be explained by the HEB theory [Ekström et al., 1995] and the specific I-V curve for this device when irradiated by the 1.56 THz LO, taking into acount the IF output mismatch. Nevertheless, a detailed explanation will have to await the completion of a new, more complete, theoretical model for the HEB device [Merkel et al., 1998]. It is interesting to compare the I-V curves recorded with LO power at different frequencies in Figure 8, however. Radiation at both 1.56 THz and 2.52 THz should be above the bandgap frequency of the NbN film, and thus it would be expected that both frequencies should be uniformly absorbed by the device. Yet, the I-V curves differ noticeably when the device is irradiated by 1.56 THz and 2.52 THz. The curves with 356 GHz and 94 GHz radiation are quite different from the higher frequency curves and also differ among themselves. Note that all I-V curves were recorded for the same device without changing the device configuration. Neither of the I-V curves in Figure 8 agrees with curves recorded without LO power at higher device temperatures, which gives another indication that the HEB model needs to be refined. HEB mixer theory predicts a 10 dB intrinsic conversion loss with an LO at 94 GHz which is in good agreement with the measured value of 9 dB (Table I). The exact shape of the I-V curve thus is very important for the actual performance of the device in terms of conversion loss. Note that different devices (phonon-cooled or diffusion-cooled, operated at different frequencies) often differ drastically in terms of the intrinsic conversion loss as well as the output noise level from the devices. Both conversion loss and output noise are relevant in establishing the receiver noise temperature and a comparison of the ultimate potential receiver noise performance of different types of devices will require the more detailed understanding of the device models we refer to above. It should be clear, however, that receiver noise temperatures of HEB mixers at THz frequencies are likely to progressively get lower. Our own measurement of 5,800 K at 1.56 THz was for a single device, the only one tested so far. Experience at the lower frequencies has already shown that refinement in the receiver configuration, as well as in device fabrication, will gradually lead to lower noise temperatures.

Measurement of Conversion Gain

The intrinsic (device only) *conversion gain* at 1.56 THz was measured in the two-laser setup to be +3 dB, with a probable error of ±2 dB. The device used for this measurement was fabricated in Moscow

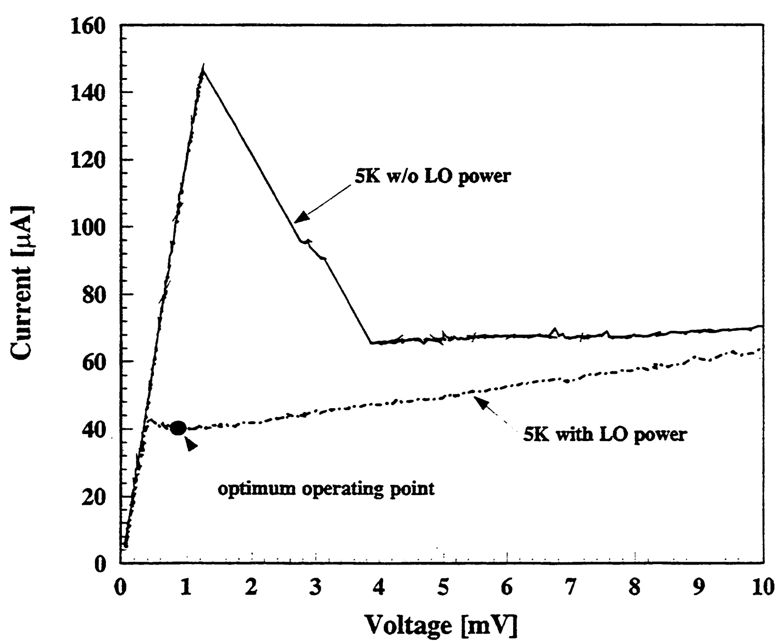


Figure 7: I-V curve for the device used in the 1.56 THz noise temperature measurement.

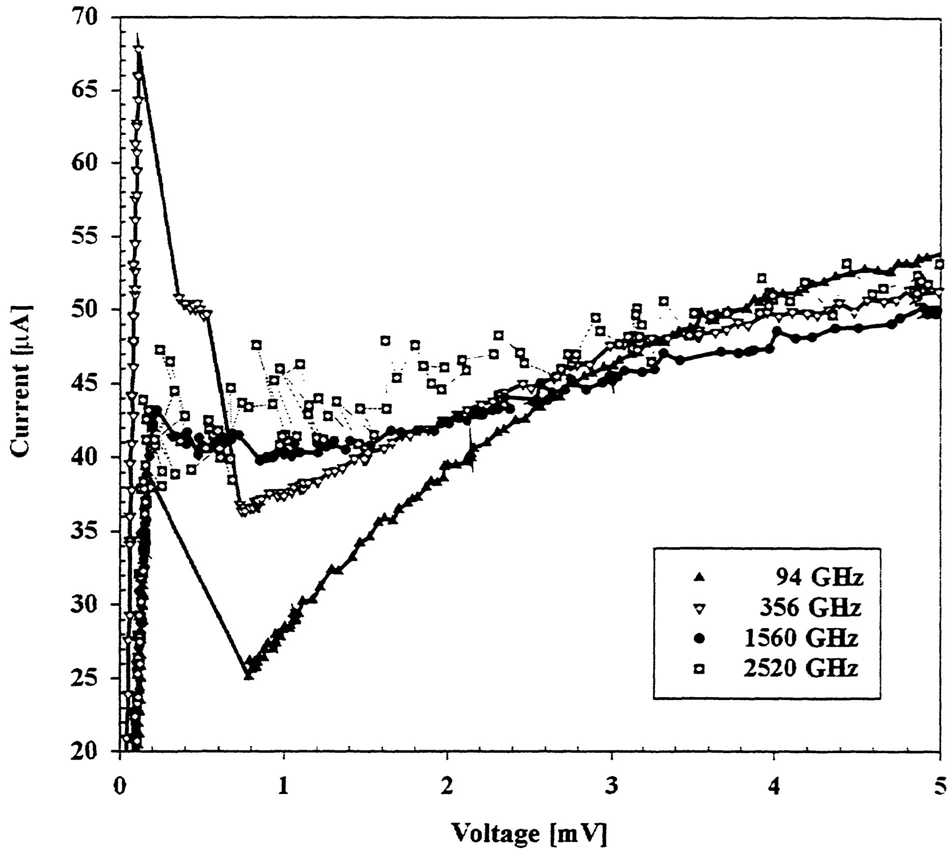


Figure 8: I-V curves of the device irradiated by four different frequencies.

and utilized an equiangular spiral antenna. The absorbed power from the RF laser was obtained by the technique we employed for the absorbed LO power at a high enough RF power level to make this possible. Calibrated attenuators were then used to lower the RF power until the mixer was shown to be operating in its linear region. The IF power was observed on a spectrum analyzer and the IF voltage was measured directly on an oscilloscope. The optical coupling loss was estimated to be about 33 dB in this case. Note that HEB mixer theory allows actual conversion gain to be realized. The conversion gain at higher IF frequencies may be somewhat lower; so far, the best intrinsic conversion gain of any HEB THz mixer at about 1 GHz IF, inferred from noise measurements, is about – 6 dB (Kroug et al., 1997). The apparent difference in conversion loss at different IF frequencies indicates another area in which our present device models are inadequate.

V. CONCLUSION

We have demonstrated receiver noise temperatures of 900 K at 600-750 GHz, and 5,800 K at 1.56 THz for a NbN HEB device, coupled through a silicon lens and a log-periodic antenna. The very small LO power required by such devices when optimally matched (as low as 100 nW) has been verified. We have also demonstrated 3 dB conversion gain of an HEB mixer device at 1.56 THz, for a 600 kHz IF frequency.

We expect that measured receiver noise temperatures of NbN HEB mixers will continue their downward trend at frequencies above 1 THz in the future. NbN HEB THz mixers are especially advantageous in the following respects:

- Submicron size is not required
- Can be operated at 4.2 K; Al devices require He3 cooling
- LO power 100 nW, smaller for submicron devices
- Present receiver noise temperatures are as low as for diffusion-cooled mixers up to 1 THz
- Operating point not sensitive to 300 K radiation

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