NbN HOT ELECTRON BOLOMETRIC MIXER FOR 2.5 THz: THE PHONON COOLED VERSION

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ABSTRACT

We describe an investigation of a NbN HEB mixer for 2.5 THz. NbN HEBs are phonon-cooled devices which are expected, according to theory, to achieve up to 10 GHz IF conversion gain bandwidth. We have developed an antenna coupled device using a log-periodic antenna and a silicon lens. We have demonstrated that sufficient LO power can be coupled to the device in order to bring it to the optimum mixer operating point. The LO power required is less than 1 microwatts as measured directly at the device. We also describe the impedance characteristics of NbN devices and compare them with theory. The experimental results agree with theory except for the imaginary part of the impedance at very low frequencies as was demonstrated by other groups.

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 [1] and 1140 at 870

GHz [2]. Figure 1. shows receiver noise temperatures for existing receivers and also predicted performance of HEBs which are currently under development. The conversion loss and intrinsic noise temperature of HEB mixers are expected to be essentially independent of frequency, up to at least several THz, and thus noise temperatures of about 1000 K or less can be expected for these frequencies. 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. Note that HEB theory predicts that the receiver noise bandwidth should be wider than the conversion gain bandwidth. A receiver noise bandwidth of 5 GHz and a conversion gain bandwidth of 3 GHz were measured by [3]. The LO power required is less than one microwatt which can be further decreased by reducing the active area of the device. The power level required by NbN HEB mixers make them suitable for use with future solid state tunable THz sources [4]. However, the LO power is not at the level to cause the device to saturate by thermal radiation which is a problem with some diffusion cooled HEB mixers. The main problems remaining to be solved before THz NbN HEB mixers are

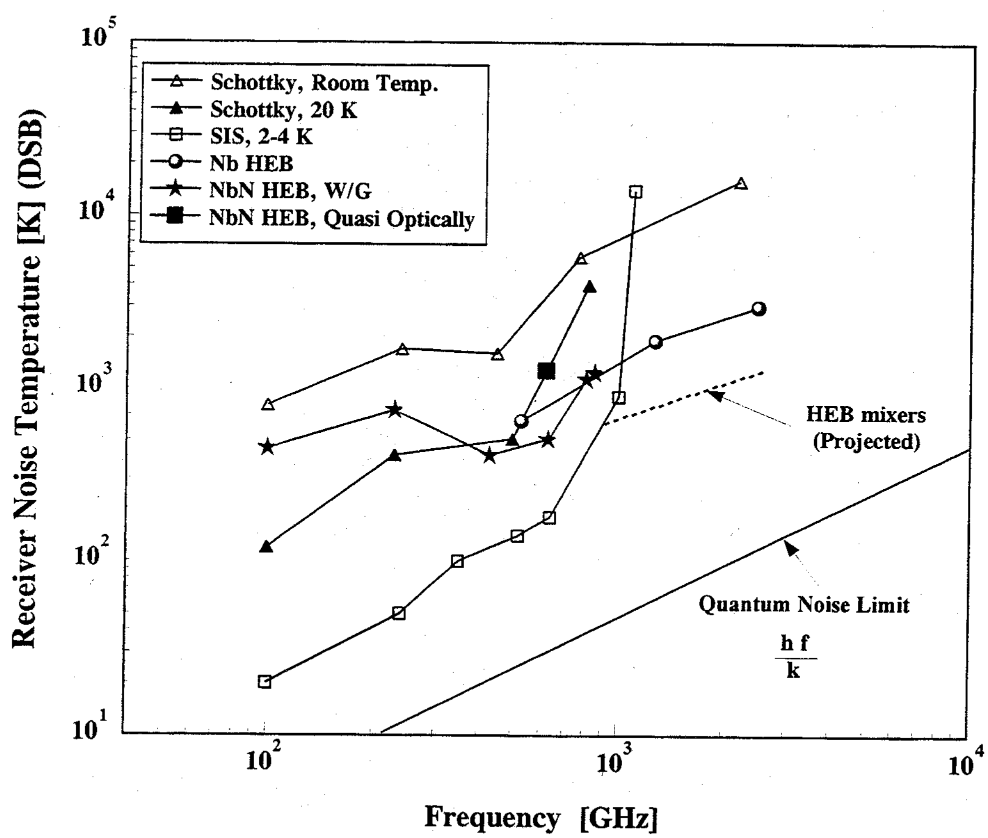

Figure 1: Receiver noise temperature for receivers in the THz frequency range.

ready for use in practical applications are (i) efficient optical coupling to the device, (ii) further investigation of the properties of very thin NbN films which are required to maximize the bandwidth performance, and (iii) development of measurement techniques for very low-noise, wide-band receivers in the THz range.

We have earlier performed experiments with fairly large (700 μm x 350 μm) NbN HEB devices which demonstrated for the first time that efficient HEB mixing was possible in NbN at 2.5 THz [5]. These results were reported at the previous Space THz Technology Symposium [6]. Based on this experience, we have designed a new NbN device, which is coupled to the THz radiation by a log-periodic antenna through an extended hemispherical lens. This paper describes the development of this new configuration and our first results from measurements with this mixer.

The IF bandwidth of NbN HEB devices cannot be easily measured at THz frequencies. This measurement requires one fixed source for the RF input and a tunable source for the LO, or vice versa. The tunable source may be a photonic mixer source, or a sideband generator, which produces a tunable sideband from a fixed laser frequency [7]. Such measurements have so far not been performed due to the complexity of setting up the experiment. Instead, one typically infers the bandwidths of THz mixers from measurements at lower frequencies of either impedance, mixer IF response, or IF output noise. We present new measurements of the IF impedance of a NbN HEB device.

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 presently still an evolving technology. The substrate has to be heated during the process and the partial pressures of nitrogen and argon need to be controlled separately. The details of the process are described in [8]. Some difficulties in reproducing high quality films still exist. The surface quality of the silicon substrates appears to be a very important factor. Furthermore, the characteristics of some of the devices, such as critical current, critical temperature and, occasionally, contact resistance, deteriorated after one or several cool-downs to liquid helium temperature. Another problem which occurs in some device batches is that there is a process which makes the conversion gain drop by several dB from the lowest frequencies (MHz) to a few hundred MHz. The conversion gain is then less in the portion of the IF band (GHz) where the noise temperature is measured. This phenomenon has been observed for similar devices used by [3] and also in our work. These problems will undoubtedly be solved. Very thin NbN films on sapphire substrates have been more reproducible as shown in another paper at this conference [9]. The optimum thickness, based on the sapphire work, appears to be close to 3.5-4 nm. The films used for the devices we have tested so far have T_c = 7.5 - 9 K and the transition width is about 0.5-1 K. The surface resistance value for a typical film is about 450 Ω/square.

Optical Design

Optical design considerations are crucial for efficiently coupling LO and signal power into the device. It is clear that quasi-optical coupling to the device is the only alternative for frequencies as high as 2.5 THz. We chose to use an extended hemispherical silicon lens coupled to a log-periodic spiral antenna (see Figure 2) as successfully demonstrated and analyzed at 250 GHz and 500 GHz by [10]. A similar design

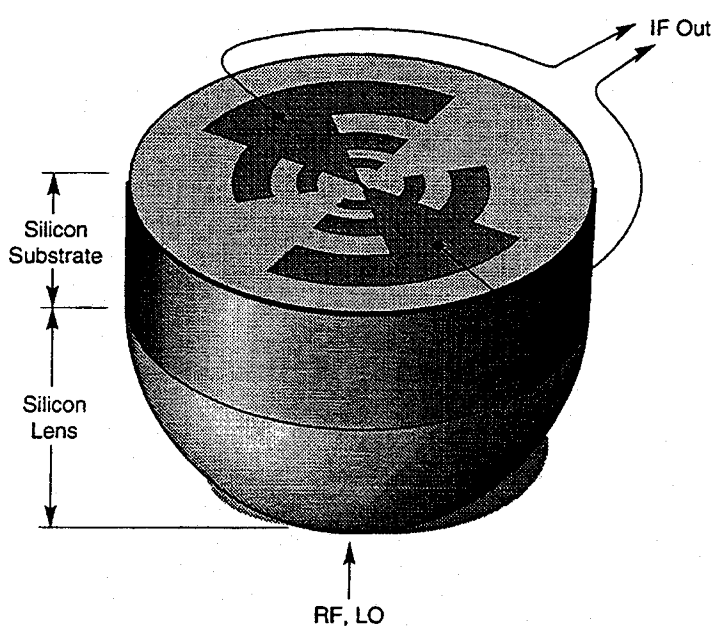

Figure 2: Log-Periodic antenna fabricated on an extended hemispherical silicon lens.

was also integrated with a Schottky-barrier diode and used at 760 GHz by [11]. The log-periodic spiral antenna is convenient at this stage since it can be used over a very wide frequency range; later versions will employ twin-slot or twin-dipole antennas tuned to specific frequencies. We scaled the dimensions of the lens and the antenna used in the 250 GHz experiments 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. The characteristics of the lens radiation pattern can then be predicted from the results of [10]: A beamwidth of about 5-6 degrees and directivity of 30 dB as well as a gaussian coupling efficiency of 50-60 %. We can also predict the amount of beam-scan which would result from 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 at this stage. The manufacturing of such a small silicon lens turned out to be a significant challenge which was, however, overcome[1]. An alternative would have been to utilize a larger hyper-hemispherical lens but this would have necessitated the incorporation of a second lens in the dewar in order to bring the beam to a focus.

The choice of a smaller lens has advantages in terms of being adaptable for extending the receiver system to a focal plane array as illustrated in Figure 3. The figure shows a "fly's eye" configuration with individual lenses for each pixel. Larger lenses are more limited in terms of the number of elements which can be accommodated in the focal plane without severe aberrations. Also significant is the fact that the element spacing in this focal plane array is sufficiently large to match the typical size (about 1 mm x 1 mm) of MMIC amplifier chips. We anticipate employing commercial MMIC IF amplifiers which would be inserted into etched wells in the silicon substrate/motherboard. The routing of all transmission lines would be done on a separate dielectric (BCB) which we are presently exploring for other applications.

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 fabrication technique developed here begins with the deposition of 3.5-4 nm NbN on a silicon wafer as described

[1] The lenses were made by Janos Technology, Townshend, VT

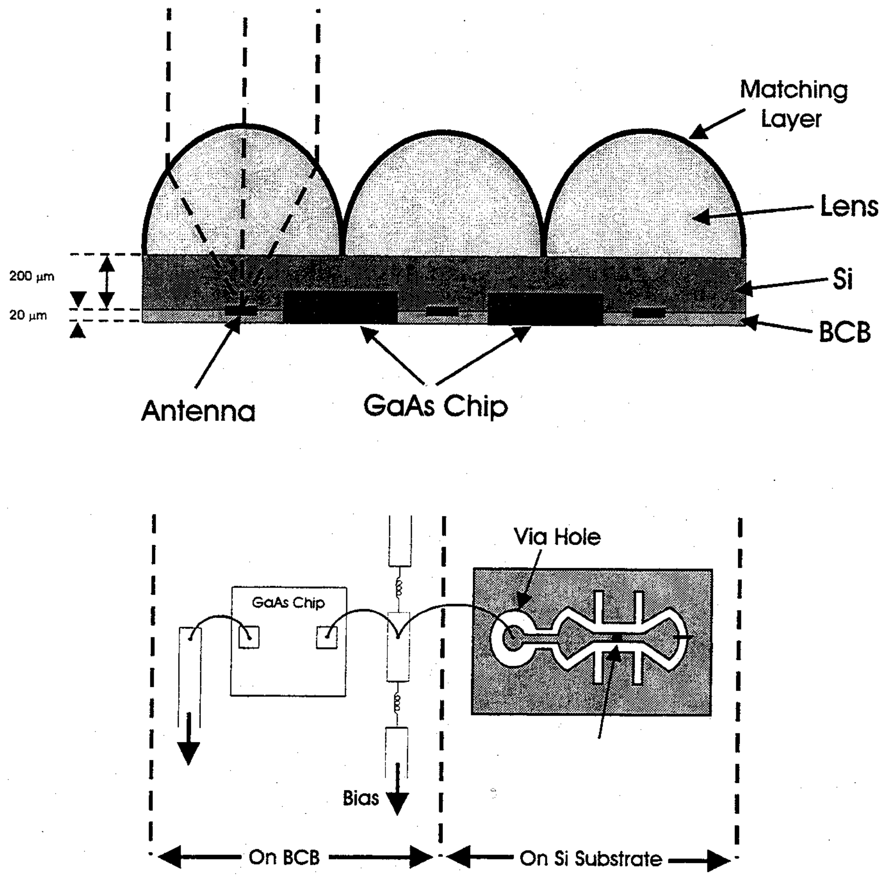

Figure 3: Lens array with NbN mixers for focal plane imaging system: fly's eye configuration.

above. Presently we are employing analysis techniques such as EDAX and XPS to further enhance our understanding of the film structure and the effects that various processing steps have on the films. 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. This layer is used to guarantee the lowest possible contact resistance. Next, 20 nm of Ti and 100 nm of Au are deposited by E-beam evaporation followed by the liftoff step. The NbN strips are then defined and etched using Reactive Ion Etching (RIE). Next, the substrate is thinned to a thickness equal to the lens extension length. The position of a square alignment window for the lens is then defined in a photoresist layer on the opposite side of the substrate from the antenna and device using an infrared mask aligner. The alignment window is etched by RIE to a depth of 100 nm and the lens is attached to the silicon substrate using purified bees wax. The substrate is mounted on a holding frame made of OFHC copper and the antenna contacted through indium wires. The final dimensions of the device strips

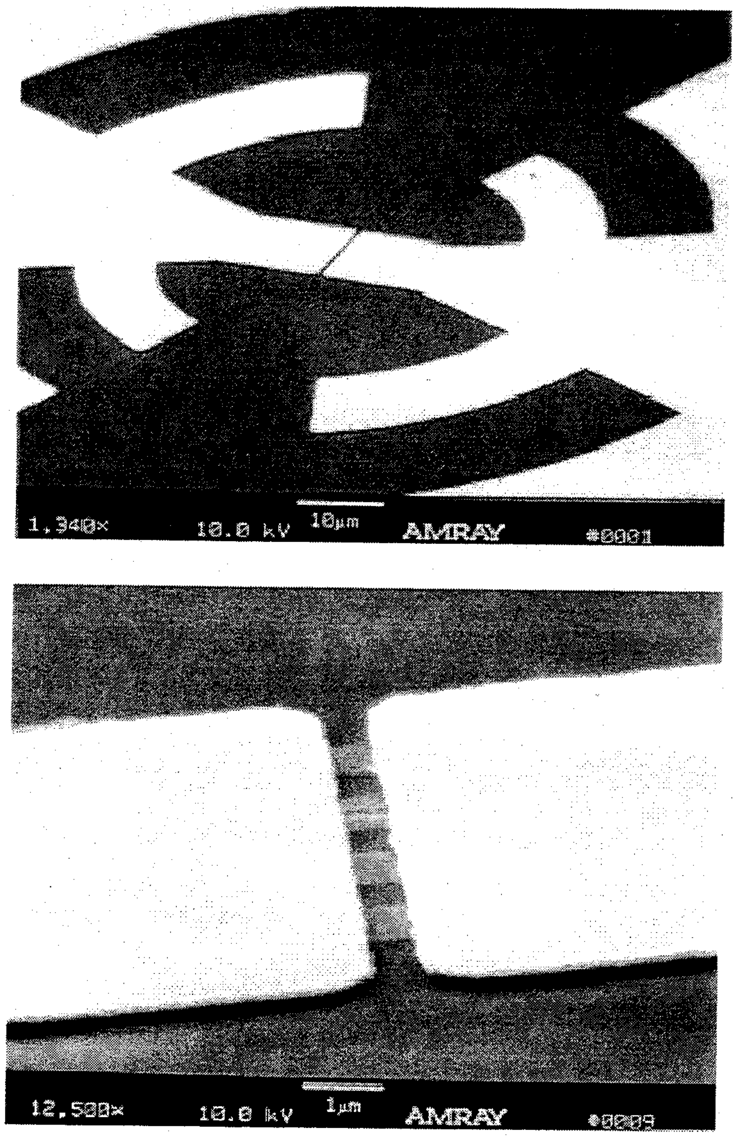

Figure 4: SEM photographs of the NbN device.

are about 0.6 µm long by 1.0 µm wide. The number of strips is from one to three. The mask also has a different pattern for which the smallest teeth, which determine the highest frequency of the antenna, are twice as large, i.e. the highest frequency is 1.25 THz. This antenna can have up to five strips. Figure 4 shows an SEM picture of a device with four strips recently fabricated at UMASS/Amherst. Finally, the holding frame and the device are mounted onto a copper post which is attached 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.

The contact resistance of good devices is less than 1 Ω. The normal resistance of the device should be matched to the antenna impedance (100 Ω). The devices fabricated so far have a normal resistance as low as 200 Ω. A better match could be obtained if a thicker film were used but with a tradeoff for somewhat narrower bandwidth.

III. EXPERIMENTAL SETUP

Optical Setup

The optical coupling loss as well as the receiver noise temperature are measured using a laser setup shown in Figure 5. An FIR methanol laser is pumped by a CO_2 laser and reflected by a 1 mil mylar beam splitter. The laser beam is then focused by an off-axis paraboloidal mirror through a 0.75 mm polyethylene window onto the device. Shorter IR wavelengths are further attenuated by a sheet of cooled Zitex. The beam splitter allows radiation from a hot-cold load to be directed into the beam path. This blackbody radiation is obtained 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 30 dB gain and about 10 K noise temperature (including isolator losses). The IF system bandwidth is 1250 to 1750 MHz. In some experiments we used a room temperature IF amplifier with a noise temperature of 150 K. After further amplification, the IF power is measured with a microwave detector connected to a lock-in amplifier with its reference obtained from the chopper. The setup is aligned by using the HEB device itself as a detector and observing the depression of the device current due to the laser power.

Microwave Measurements

The microwave measurements were performed by utilizing a dipstick setup. The dipstick apparatus used in these measurements consists of a device mounting block immersed in LHe or positioned just above the LHe surface and a low loss, thermally insulated, cable. The impedance characteristics were recorded on a network analyzer operated at a very low power level. Calibration was accomplished in part by using the device at zero volt bias as a superconducting short. The parasitic characteristics of the device mount were taken into account by simulating the mount in Sonnet *em* and by performing one further meas-

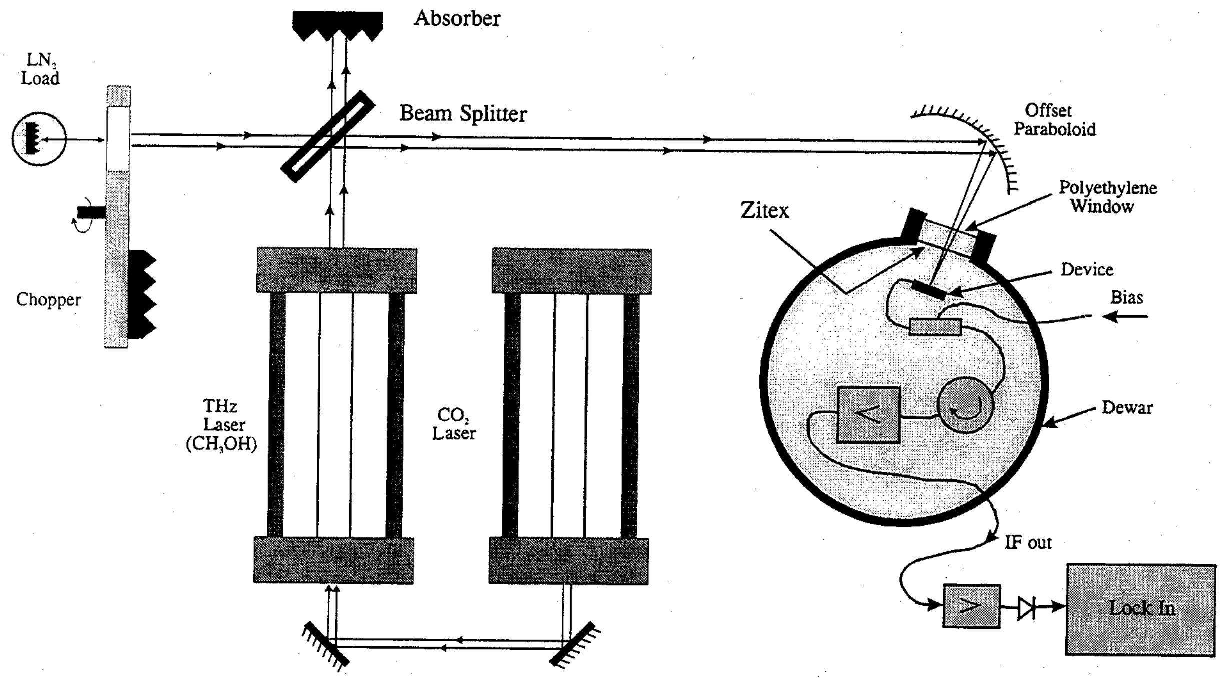

Figure 5: Optical layout for noise measurements.

urement with the device replaced with an indium wire short. The subsequent calibration calculations were done with the Hewlett-Packard MDS package.

We have previously measured the bandwidth of an earlier generation of NbN devices at about 15 GHz. It is sometimes difficult to interpret these measurements due to the very low frequency. However, measurements at 140 GHz have been shown to correlate well with measurements in the 600 GHz range [8]. We have therefore started to perform measurements of mixer bandwidth at 94 GHz in a dipstick waveguide setup.

IV. RESULTS AND DISCUSSION

Laser Pumping of the Device

The best device available for the preliminary measurements was one fabricated at MSPU integrated with a regular spiral antenna. The device substrate was thicker than required for the 1.3 mm diameter lens and was instead waxed to a 2 mm lens. After alignment of the device to the laser beam, we were able to obtain sufficient suppression of the device current due to the laser power as depicted in Figure 6. The device temperature was 4.73 K and the critical temperature was 7.5 K. In the particular case shown, the LO power produced an IV-curve which is almost identical to one recorded at an elevated temperature of 6.81 K (a heater was then used to heat the device). The significance of this observation is that the device is heated to an electron temperature close to T_c by the laser power as required for optimum mixer operation. The near coincidence of the two curves is expected since the LO radiation is at a frequency much higher than the superconducting gap frequency and LO heating effects should then produce results close to those due to thermal heating.

The IF power in a 50 MHz bandwidth was measured for three conditions: (i) device superconducting at V=0; (ii) with optimum DC bias but without LO power; (iii) with optimum DC bias and the LO power on. The change in IF power from (i) to (iii) amounted to 8 dB. From this we can estimate the device

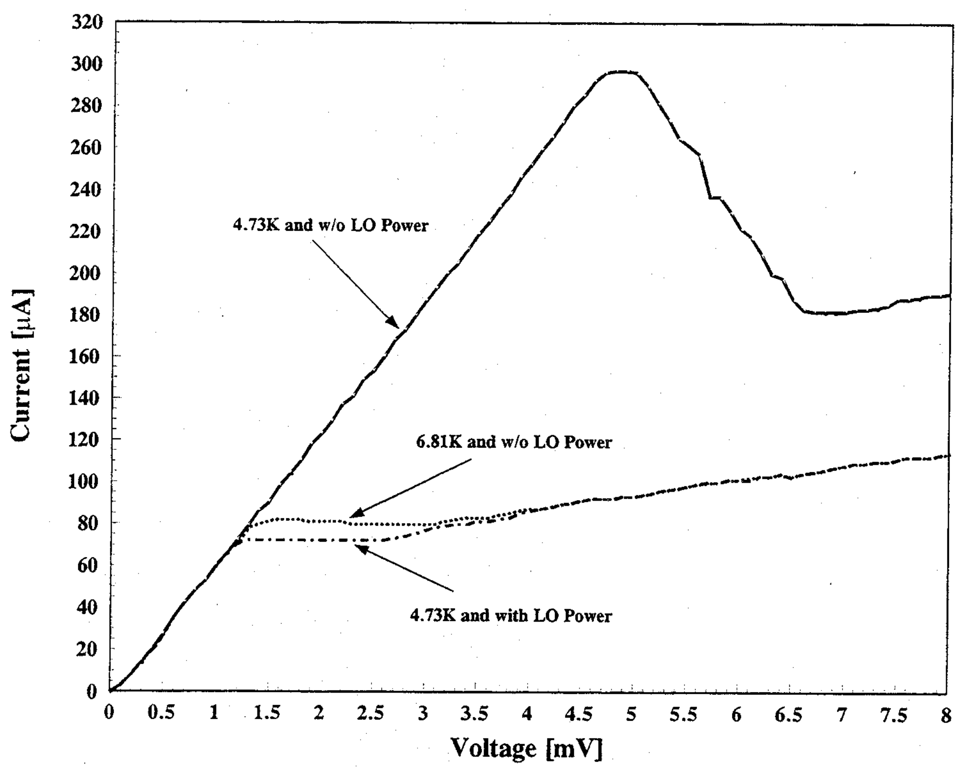

Figure 6: I-V characteristics of quasi optically coupled NbN device.

output noise temperature (T_{out}) to be in the range 40-80 K. The uncertainty is due to our incomplete knowledge of the amplifier noise temperature. This value of T_{out} is in the expected range.

We were also able to measure the amount of laser power absorbed by the device utilizing the IV-curves. The power absorbed at what would be a typical optimum operating point was 800 nW. Note the very small LO power which can be made even smaller in future devices with somewhat smaller device dimensions. The measured laser power after the paraboloid mirror was 2.5 mW. The ratio of these numbers gives an estimate of the optical coupling loss of 35 dB. Such a high value is not uncommon in quasi-optical HEB experiments so far since the gaussian modes are rarely perfect; nor are they well matched between the laser and the antenna/lens combination. These problems will need to be attended to before sources such as the photomixer, with available power at best in the microwatt range, can be utilized. We are continuing our experiments to obtain a measurement of noise temperature. We also expect to improve the optical coupling by using the optimum antenna/lens combination which was not available before the conference[2].

Impedance Measurements

We have pursued accurate measurement techniques for the device impedance in order to obtain useful information to characterize the device without the need to perform THz measurements. Mixing measurements at low GHz frequencies are often more difficult to interpret. Previous published data of the microwave impedance for NbN were obtained by [12] and [13]. We have tested our calibration techniques on an older 10 nm device as shown in Figure 7. The agreement with theory is better than in previous measurements: The real part follows the theoretical model closely whereas the imaginary part fits well above 200 MHz but shows an extra capacitive contribution at very low frequencies. We do not have a satisfactory explanation for the deviation of the imaginary part at low frequencies at this point, but note that other measurements [12][14] show a similar tendency. Data for a fairly large Nb device follow theory very well [15]. Future measurements on the newer generation of films will be performed with even more precise calibration. We will also obtain bandwidth measurements at 94 GHz for the new devices. A long-term goal is to measure

[2] The 1.25 THz version of our log-periodic antenna/device has since been tested at 650 GHz at Chalmers University of Technology and yields a receiver noise temperature of 1750 K. This design is thus validated at the lower frequency [Ekstrom, private communication].

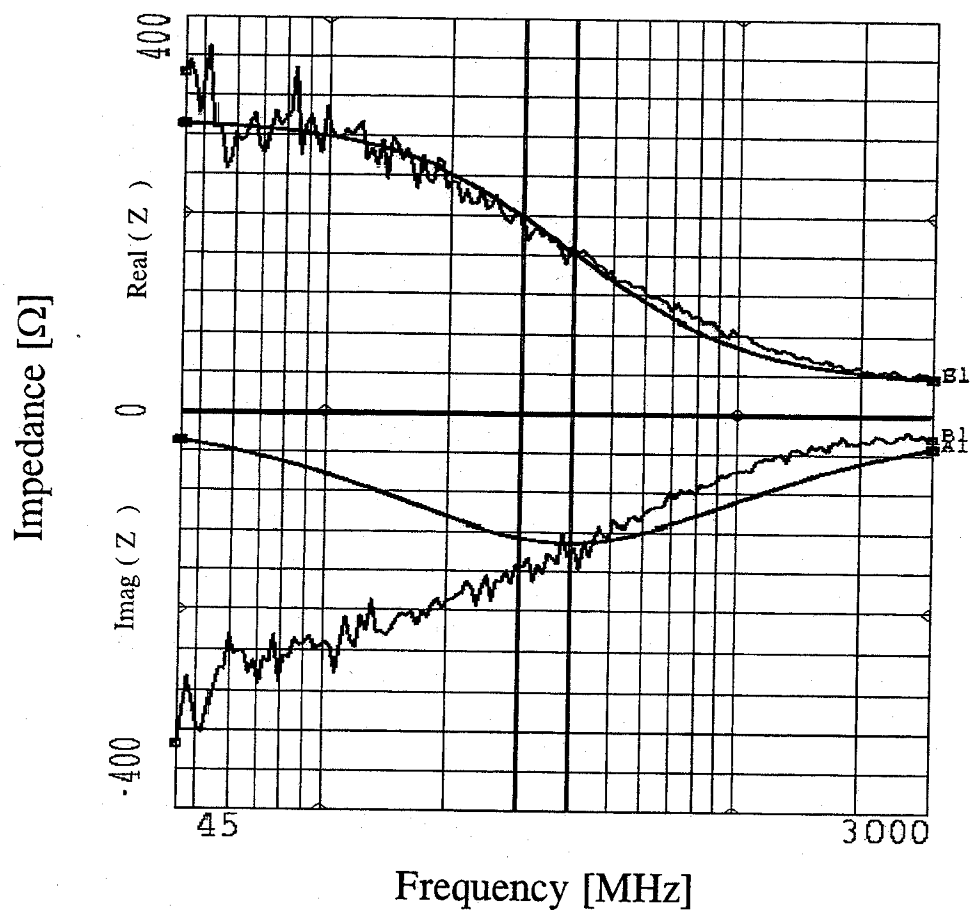

Figure 7: Theoretical and experimental impedances of a 10 nm NbN film.

the conversion gain bandwidth at THz frequencies utilizing a laser LO and a sideband generator as the RF source [7].

V. CONCLUSION

We have shown that lasers can be quasi-optically coupled at THz frequencies to NbN HEB mixer devices integrated with log-periodic or spiral antennas and small silicon lenses. The very small LO power to be expected from such devices when optimally matched (less than 1 microwatt) has been verified. We have also demonstrated improved measurements of the microwave impedance of the device. Noise temperature measurements will be performed in the near future.

VI. ACKNOWLEDGMENT

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