OPTICAL COUPLING AND CONVERSION GAIN FOR NbN HEB MIXER AT THz FREQUENCIES

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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; and others], 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 a conversion gain bandwidth of 3 GHz were measured by [Ekström et al., 1997]. The LO power required is typically 100 nW, which makes NbN HEB mixers suitable for use with future solid state tunable THz sources. However, the LO power is not at such a low level, as to cause the device to saturate by thermal radiation. This paper describes the development of a 2.5 THz HEB mixer, employing NbN, and our first results from measurements with this mixer.

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, 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 [Cherednichenko et al., 1997]. The films used for the devices we have tested so far have T_c = 7.5 - 9 K and the transition width is about 1 K.

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 1), as successfully demonstrated and analyzed at 250 GHz and 500 GHz by [Filipovic et al, 1993]. 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 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 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.

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 liftoff is performed. The NbN strips are then defined and etched using Reactive Ion 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 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 100nm. The lens is attached to the silicon substrate using purified bees wax. The final dimensions of the device strips 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 2 shows an SEM picture of a device with four strips, recently fabricated at UMASS/Amherst.

III. EXPERIMENTAL SETUP

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. A 1 mil mylar beam splitter acts as a diplexer between the LO and a chopped hot/cold noise source. The cooled IF amplifier has a bandwidth from 1250 to 1750 GHz, with noise temperature less than or equal to 10K. In order to measure the conversion gain directly, we employed two lasers at UMASS/Lowell. The active medium was difluoromethane, and the frequency 1.56 THz. The lasers were slightly detuned and produced an IF of 600 kHz. 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 sideband generator, which produces a tunable sideband from a fixed laser frequency. Future such measurements are being planned with a source of this type at UMASS/Lowell.

IV. RESULTS AND DISCUSSION

Laser Measurements

The best device available for the preliminary measurements was one fabricated at MSPU, which was integrated with a regular spiral antenna. Figure 3 shows three IV-curves for this device. The physical temperature was 4.73 K and T_c 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 6.8 K (a resistive 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; 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 no 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 these data we can estimate the 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 2.5 THz laser power absorbed by the device, by utilizing the IV-curves. The power absorbed at what would be a typical optimum operating point was in the range 100 nW to 800 nW. The measured laser power after the paraboloid mirror was 2.5 mW. The ratio of these numbers gives an estimate of the total optical coupling loss of 35 dB. FTS measurements indicate that much of this loss may be due to the frequency response of the spiral antenna; similar measurements on the log-periodic spiral antenna show that its response is expected to reach 2.5 THz. We are continuing our experiments to obtain a measurement of the mixer noise temperature. We also expect to improve the optical coupling. We have tested the 1.25 THz version of our log-periodic antenna/device at 620 GHz at Chalmers University of Technology, using a different lens (12.5 mm diameter). The DSB receiver noise temperature was 1000 K, with similar performance at least up to 750 GHz. Fourier Transform Spectrometer measurements of the direct detection response near T_c for the same device indicate broadband coupling from 300 GHz to 1.2 THz, as expected. Our antenna design and device fabrication technology have thus been validated up to 1.2 THz so far.

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 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).

V. CONCLUSIONS

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 (as low as 100 nW) has been verified. We have also demonstrated conversion gain of an HEB mixer device at 1.56 THz, for a 600 kHz IF frequency, and measured a DSB receiver noise temperature of 1000K at 620 Ghz.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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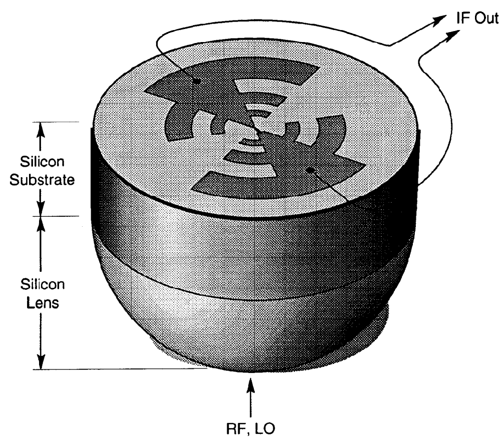

Figure 1: Log-Periodic antenna fabricated on an extended hemispherical silicon lens.

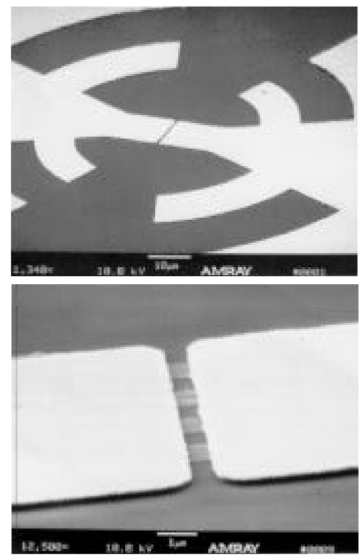

Figure 2: SEM photographs of the NbN device.

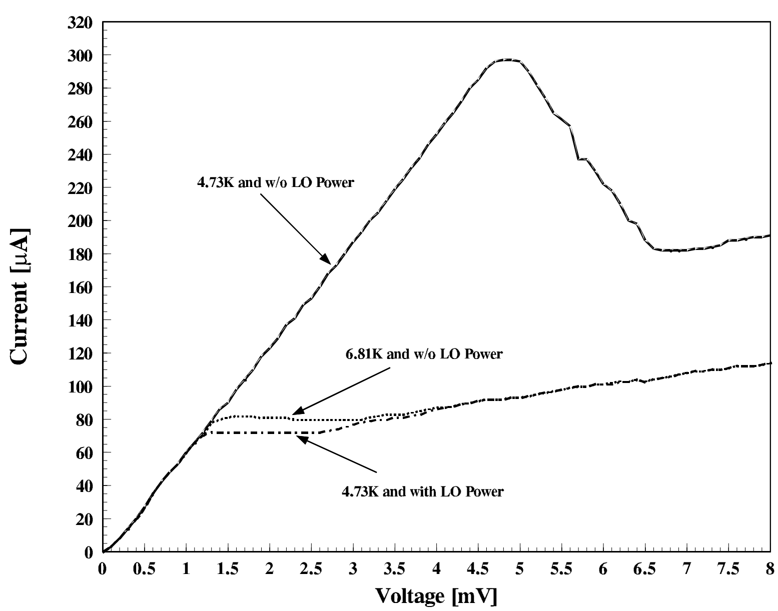

Figure 3: I-V Characteristics of a quasi-optically coupled NbN device.