IMPROVED CHARACTERISTICS OF NbN HEB MIXERS INTEGRATED WITH LOG-PERIODIC ANTENNAS

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I. INTRODUCTION

Hot Electron Bolometric (HEB) mixers have recently demonstrated the lowest receiver noise temperatures ever measured in the THz frequency region. HEB receivers have become the most promising approach for applications such as high-resolution heterodyne spectral measurements of astronomical objects from airborne or space-based platforms at frequencies above 1 THz. At most frequencies the lowest noise temperatures attained so far have used NbN Phonon-cooled HEB (PHEB) mixers. We have developed NbN PHEB devices and have improved their characteristics very substantially since our paper at the Ninth STT Symposium. We report total DSB receiver noise temperatures of 485 K at 620 GHz (440 K when the device was cooled to 3 K), 1,000 K at 1.56 THz, and 2,200 K at 2.24 THz. 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. We have measured a conversion gain bandwidth of 3 GHz at 620 GHz for one of our devices and calculated the receiver noise bandwidth to be 6.5 GHz with a sufficiently wideband IF amplifier. The lowest LO power required is 500 nW which makes NbN PHEB 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 our NbN PHEB mixers and discusses device fabrication and optical coupling issues as well as our measurement setup and results.

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 surface resistance of the films is from 300 Ω/square to 600 Ω/square. The devices fabricated during the last year have shown an improvement of T_c from 7.5-9 K to 10-10.5 K (11 K for the 5 nm device). The transition width is still about 1 K and the critical current density can be as high as 3×10^6 to 4×10^6 A/cm^2 for the 3.5 to 4 nm devices.

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 still use an extended hemispherical silicon lens coupled to a self-complementary log-periodic toothed antenna (see Figure 1), as successfully demonstrated and analyzed at 250 GHz and 500 GHz by [Filipovic et al, 1993]. The log-periodic toothed antenna is convenient since it can be used over a very wide frequency range; later versions will employ other antennas tuned to smaller frequency bands, which may possibly have higher efficiency. For our original design, 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

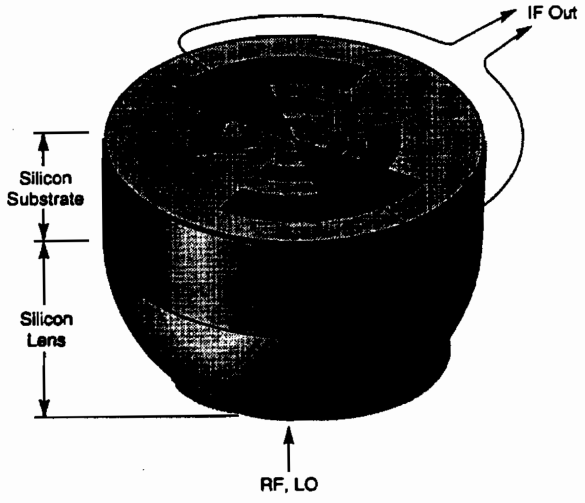

Figure 1: Log-periodic antenna fabricated on an extended hemispherical lens.

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 at this stage. The beamwidth of this lens at 1.56 THz is 8 degrees, which is sufficiently narrow for the beam to clear the dewar window. Recently, we have also used an elliptical lens with a base diameter of 4 mm. The elliptical lens is less critical in terms of alignment and does not require the substrate thickness to be adjusted. The device is then mounted at the foci of the lens.

Device Fabrication

Devices were fabricated at UMASS/Amherst. The gold log-periodic antenna is fabricated using liftoff. After the pattern has been defined in the photoresist, 20 nm of Ti and 100 nm of Au are deposited by E-beam evaporation and the lift-off is performed. The NbN strips (strip) are then defined and etched using Reactive Ion Etching (RIE). In the most recent fabrication run, we tested wet etching of the NbN as an alternative technique with excellent results. All devices fabricated since the beginning of 1998 have had a configuration of a single wide strip which results in the lowest normal resistance and thus the best match to the antenna. For the device used with the 1.3 mm lens, 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 100nm. The lens is attached to the silicon substrate using purified bees wax. The final dimensions of the device strips for the original design are about 0.6 μm long by 1.0 μm wide. The single strips have the same length and are either 5 μm or 10 μm wide. Two different sizes of antennas with maximum frequencies of 1.2 THz (Antenna A) and 2.4 THz (Antenna B), respectively, were employed. Figure 2 shows an SEM picture of a device of the older type with four strips.

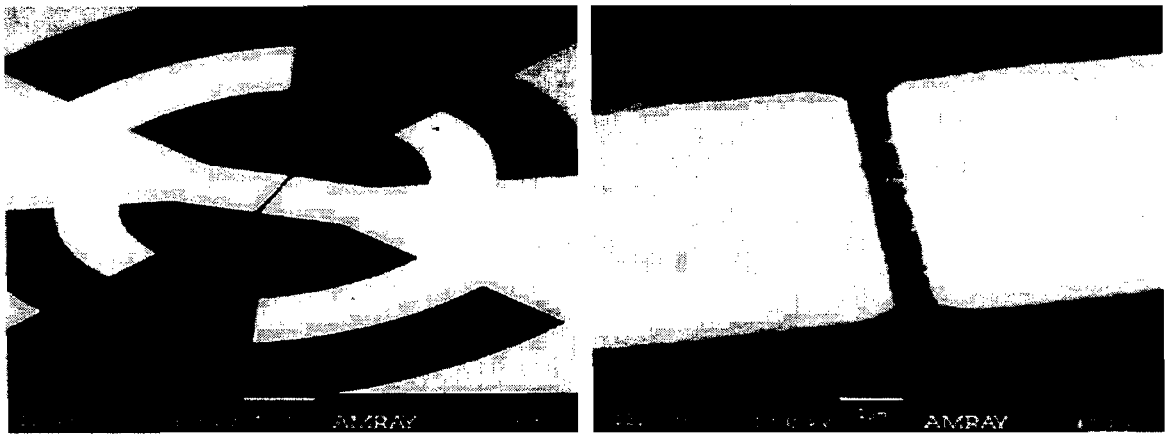

Figure 2: SEM photographs of the NbN device.

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 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. This IF amplifier has a bandwidth from 1250 to 1750 GHz with a noise temperature of about 13K except for in the most recent experiment in which we used an amplifier with 7 K noise temperature.

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

Optical Setup

The optical coupling loss as well as the receiver noise temperature are measured with a CO_2 laser pumped FIR gas laser as the LO source. The laser setup is illustrated in Figure 4. Mylar beam splitters with a thickness of 6 μm act as diplexer between the LO and a chopped hot/cold noise source. The LO radiation is focused by a TPX lens. The active medium of the FIR laser is difluoromethane and two output frequencies of 1.56 THz (wavelength 191 μm) and 2.24 THz (wavelength 134 μm), respectively, are available. 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. Noise temperature and bandwidth 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].

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.

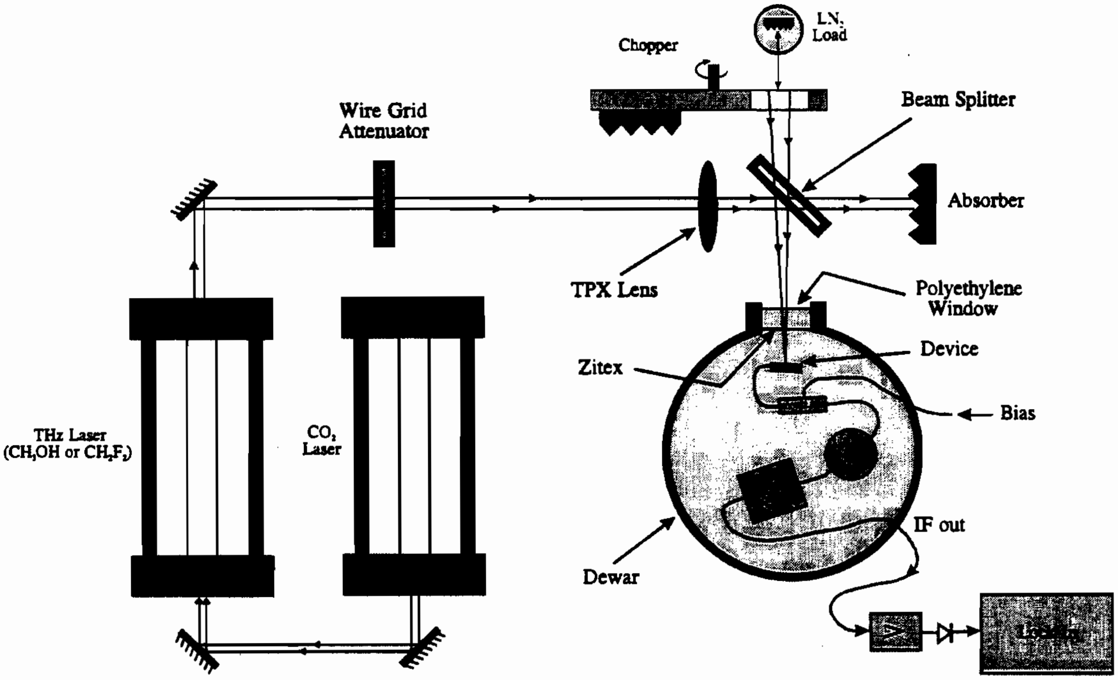

Figure 4: Optical setup for measurement of optical coupling loss and receiver noise temperature.

IV. RESULTS AND DISCUSSION

FTS Spectra of the Device Response

Figure 5 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. When utilizing 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 generally 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 2.24 THz.

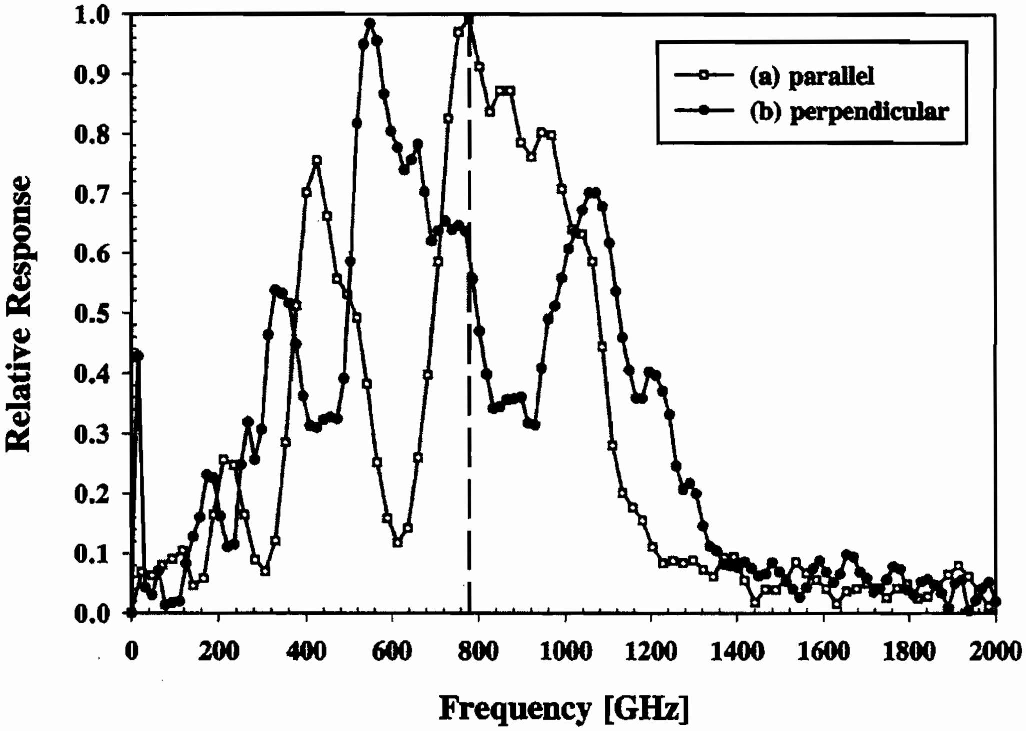

Figure 5: FTS spectra of the device for (a) device orientation parallel to the FTS polarization, and (b) perpendicular to the FTS polarization.

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 [THz]	Dev.# / Ant.	T_{out} [K]	T_{DSB} [K]	$L_{c,tot}$ [dB]	L_{opt} [dB]	$L_{c,i}$ [dB]
0.62	#1/A	82	485[a]	12.5	4	8.5
1.56	#2/B	10	5,800	27	8	19
1.56	#3/B	44	2,800	20	8	12
1.56	#4/B	43	2,700	20	8	12
1.56	#5/B	70	1,000	14.5	6	8.5
2.24	#5/B	70	2,200	18	9.5	8.5

[a] **440 K at a device temperature of 2 K.**

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 several individual Y-factor measurements were averaged. 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. In a separate test we measured the amplitude stability of the FIR laser at 1.56 THz with a relatively fast (0.1 sec) integration time over a period of several minutes. We found that the amplitude stability was ±0.3 %. The optimum operating point for the devices reported here is not very sensitive to variations in LO power or bias voltage. This is a distinct advantage compared to the DHEB Nb mixers which must be adjusted to a bias voltage very close to an unstable region of the IV-curve in order to optimize the receiver noise temperature. 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 with the 1.3 mm diameter lens and 2.5 degrees with the 4 mm diameter lens). The LO power absorbed by the device with the lowest noise temperature at 1.56 THz was 500 nW. 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 losses of the different components, such as the window, the Zitex thermal radiation filter, the reflection loss of the lens, etc.. The remaining loss is attributed to the mixer itself. **The intrinsic conversion loss, including IF output mismatch, is about 8.5 dB at all three frequencies (620 GHz, 1.56 THz, and 2.24 THz)** within the accuracy of the measurement and the error in our estimate of the optical losses is about ±2 dB. **This shows that the intrinsic receiver noise temperature does not depend on the frequency, up to 2.24 THz.** We measured both the receiver noise temperature and the output noise temperature for several devices. The intrinsic receiver noise temperature, the intrinsic conversion loss, and the output noise temperature were analyzed and compared with predictions of the standard model in a different separate paper at this symposium [Yngvesson and Kollberg]. The measured data agrees well with the theory. Both conversion loss and output noise temperature are relevant in establishing the receiver noise temperature. It should be clear, however, that receiver noise temperatures of NbN HEB mixers at THz frequencies are likely to progressively get lower. Specifically, we expect to be able to lower the optical coupling loss substantially in the future. We note that so far none of the HEB mixers above 1 THz have employed a matching layer for the lens.

V. CONCLUSIONS

We have demonstrated receiver noise temperatures of 485 K at 620 GHz, 1,000 K at 1.56 THz, and 2,200 K at 2.24 THz for a NbN HEB device, coupled through a silicon lens and a log-periodic toothed antenna. The very small LO power required by such devices when optimally matched (presently 500 nW) has been verified. We expect that measured receiver noise temperatures of NbN HEB mixers will continue their downward trend at frequencies above 1 THz in the future.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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