New Results for NbN Phonon-Cooled Hot Electron Bolometric Mixers Above 1 THz

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ABSTRACT—**NbN Hot Electron Bolometric (HEB) mixers have produced promising results in terms of DSB receiver noise temperature (2,800 K at 1.56 THz). The LO source for these mixers is a gas laser pumped by a CO_2 laser and the device is quasi-optically coupled through an extended hemispherical lens and a self-complementary log-periodic toothed antenna. NbN HEBs do not require submicron dimensions, can be operated comfortably at 4.2 K or higher, and require LO power of about 100-500 nW. IF noise bandwidths of 5 GHz or greater have been demonstrated. The DC bias point is also not affected by thermal radiation at 300 K. Receiver noise temperatures below 1 THz are typically 450-600 K and are expected to gradually approach these levels above 1 THz as well. NbN HEB mixers thus are rapidly approaching the type of performance required of a rugged practical receiver for astronomy and remote sensing in the THz region.**

I. Introduction

The ongoing development of Hot Electron Bolometric (HEB) mixers is motivated 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. 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. Furthermore, the parasitic capacitance associated with SIS devices is eliminated by using HEB mixers. Fig. 1 shows receiver noise temperatures for existing receivers. We chose to work with NbN films which have the potential for achieving IF bandwidths up to 10 GHz [1]. NbN HEB mixers can also operate well in the convenient temperature range of 4K to 6K and are not easily saturated by broadband thermal radiation. The bandwidth of NbN mixers is determined by a phonon cooling mechanism [2].

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The first published results in [3] demonstrated mixing using a "direct-coupled" NbN device at 2.5 THz. The first receiver noise measurements for an NbN HEB mixer at 2.5 THz have been demonstrated by [4]. The approach taken in this investigation utilizes an "antenna-coupled" device which would require LO power of less than 1 μW and a noise temperature goal of ten times the quantum limit. Bandwidths from about 2 GHz to 4 GHz have been demonstrated so far with NbN devices by a number of groups. The IF bandwidth of any HEB mixer is a function of the relaxation time constant (τ), which depends on the thickness, critical temperature, and quality of the NbN films. IF noise bandwidth of 5 GHz (potentially 8 GHz) has been demonstrated as well [5].

II. Device Design and Fabrication

NbN films are DC magnetron sputtered on substrates of silicon. Typical films on silicon have T_c of about 10 K for a thickness t = 5 nm and 9 K for t=3.5 nm. The transition width is about 0.5 K to 1.0 K, and surface resistance values for the films vary from 300 Ω/square to 600 Ω/square.

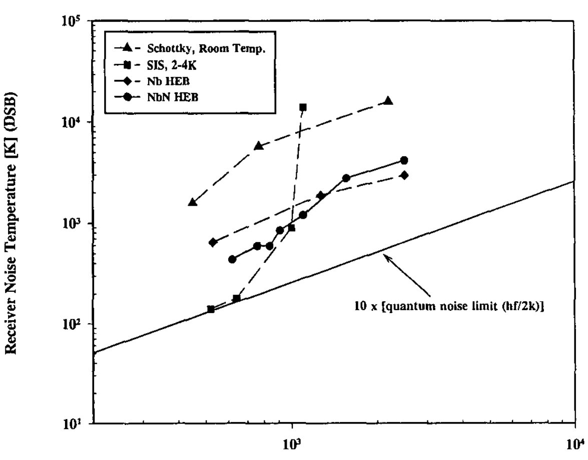

Fig. 1. Receiver noise temperature for receivers in the THz frequency range.

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An extended hemispherical silicon lens and a self-complementary log-periodic toothed antenna were integrated with the device in order to couple the THz radiation (Fig. 2). The lens and the antenna were scaled from a lower frequency design [6]. Two different sizes of antennas were employed, with estimated maximum frequencies of 1.25 THz and 2.5 THz. These antennas are designated Antenna A and Antenna B, respectively. Both antennas have seven teeth on each half. A 13 mm diameter lens with a matching layer was used in the experiments below 1 THz as described in [5]. A 1.3 mm diameter lens without a matching layer was used in the measurements of the device at 1.56 THz. The devices could be shaped either into several parallel strips or a single wide strip. The dimensions and some other data for the devices reported on here are given in Table I.

TABLE I
DEVICE DIMENSIONS AND PROPERTIES

Dev. #	t [nm]	l×w[a] [μm]	I_c [μA]	P_{LO} [nW]	BW [GHz]
1	3.5	1x(0.6×10)	425	500	3[b]
2	3.5	3×(0.6×1)	200	240	n/a
3	5	1×(0.6×5)	950	1500	1.6[c]

[a] l = device length, w = device width; [b] the BW is the gain bandwidth measured at 620 GHz; [c] the BW is the gain bandwidth measured at 94 GHz.

The gain bandwidth at the IF of NbN HEB devices cannot be easily measured at THz frequencies. Thus, the mixer gain bandwidth for the devices was measured at lower frequencies as indicated in Table I. SEM photographs of the actual device and the gold log-periodic toothed antenna are shown in Fig. 3.

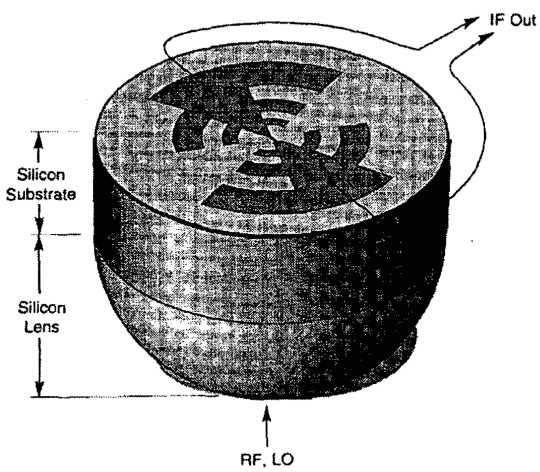

Fig. 2. Log-periodic toothed antenna fabricated on an extended hemispherical silicon lens (1.3 mm in diameter).

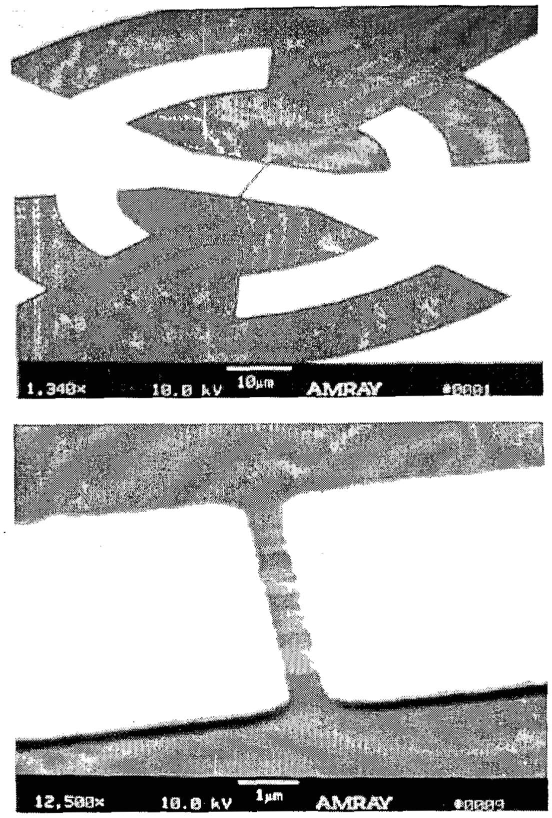

Fig. 3. SEM photographs of the NbN device.

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/lens registration accuracy be within ±20 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 when viewed with an IR mask aligner. These alignment marks are then used to photolithographically define a window in a plasma deposited layer of silicon dioxide. The etched oxide window serves as an accurately registered frame within which the silicon lens is affixed. The optimum extension of the hemispherical lens (about one third of the lens radius [6]) is accomplished by pre-thinning the silicon substrate on which the device sits.

The fabrication technique developed here begins with the deposition of 3.5-5 nm NbN on a silicon wafer by magnetron sputtering. The gold log-periodic toothed antenna is fabricated using liftoff. 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 the alignment window for the lens on the other side of the substrate is then defined and etched. The substrate is mounted on a specially designed holding frame made of OFHC copper. The antenna is contacted through indium wires. The lens is attached to the silicon substrate using purified bee wax. 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.

III. Optical Setup

A single laser setup enables us to measure optical coupling loss as well as receiver noise temperature. The optical setup is shown in Fig. 4. An FIR gas laser is pumped by a CO_2 laser. The laser beam is then focused by a TPX lens, reflected by the beam splitter, and transmitted through a 0.75 mm polyethylene window into the dewar. Shorter IR wavelengths are further attenuated by a sheet of Zitex at 4.2 K. The LO source at 1.56 THz was a sealed difluoromethane dielectric waveguide laser. Its invar-supported structure was designed with thermal compensation to maintain constant cavity length. In order to obtain a high power single mode output, uniform output couplers consisting of wire grids deposited on a silicon substrate (also coated for high reflectivity from 9 - 11 μm) were used. The laser beam was measured to have a Gaussian spatial output profile with the first sidelobes 20 dB down. This FIR laser was pumped by an extremely stable, two meter long, grating-tuned CO_2 laser, with available power of up to 200 W [7]. The amplitude stability of the 1.56 THz laser source, measured over periods of minutes, with a relatively fast (0.1 s) integration time, was ±0.3 %. Mylar beam splitters with thickness of 6 μm were used as the diplexers between the LO and a hot/cold noise source, which can either be operated by hand or chopped mechanically. 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 13 K noise temperature (including isolator losses). The IF system bandwidth is limited by the isolator to 1250 - 1750 MHZ. After further amplification, the IF power is measured with a microwave power meter. The setup is aligned by using the HEB device itself as a detector and observing the signal through the bias port on the I-V curve. Additional noise measurements were also performed at 620 GHz using a BWO as the LO source [5].

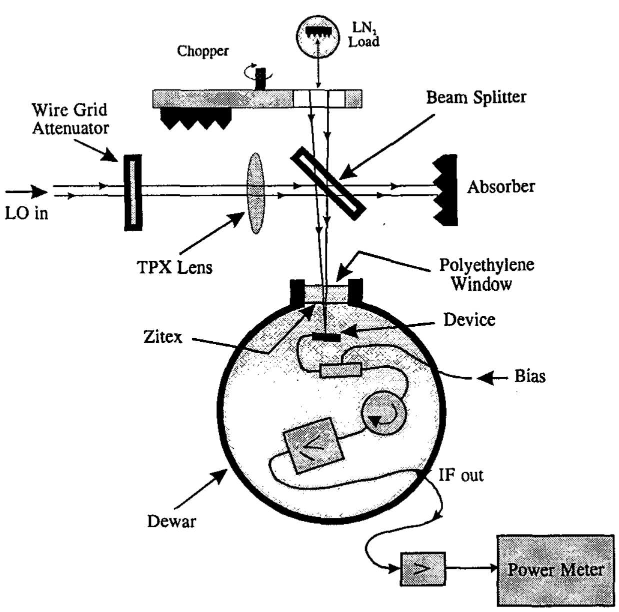

Fig. 4. Optical layout for noise measurements.

IV. Experimental Results

Fourier Transform Spectra (FTS) were obtained by employing the device as a direct detector at a temperature close to T_c in order to evaluate the frequency and polarization response of the antenna/lens system. These responses had previously only been measured at much lower frequencies, up to 250 GHz [6], for this type of antenna. FTS results of the frequency and polarization response in [8] for Antenna A (see Fig. 5) are in good agreement with those of [6] and [9]. At 1.56 THz, the optimum polarization is roughly parallel to the contact pads (marked "IF out" in Fig. 2). Furthermore, the frequency for maximum response occurs in the center of the band which extends from 300 GHz to 1.2 THz for Antenna A, and from 600 GHz to 2.4 THz for Antenna B. In the experiment with Device #3 at 1.56 THz, 8.5 mW were available before the beam-splitter, which reflects 0.8 % of the LO power. The power absorbed by the device was calculated from the I-V curve [5] to be 1.5 μW. Therefore, an LO coupling loss of about 16.5 dB after the beamsplitter is achieved (the coupling loss to the hot/cold source is estimated to be much lower, see below). The Y-factor values are averages of about ten measurements, which were then converted to noise temperature (T_{DSB}) as given in Table II.

TABLE II
SUMMARY OF NOISE DATA

f [THz]	Dev.# / Ant.	T_{out} [K]	T_{DSB} [K]	$L_{c,tot}$ [dB]	$L_{c,i}$ [dB]
0.62	#1/A	77	485[a]	12.7	7.7
1.56	#2/B	10	5,800	27	18-20
1.56	#3/B	44	2,800	20	11-13

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

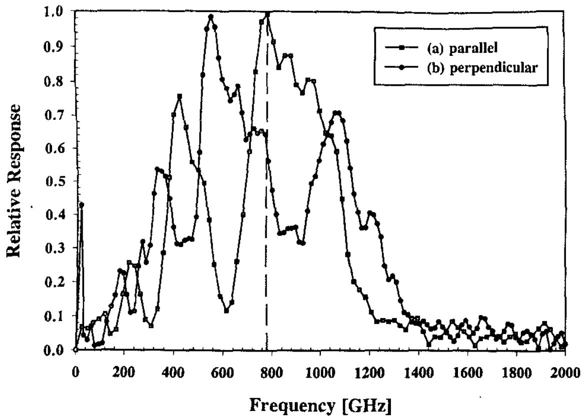

Fig. 5. FTS spectra of the device of Antenna A for (a) device orientation parallel to the FTS polarization, and (b) perpendicular to the FTS polarization.

V. Discussion

The total conversion loss of the mixer ($L_{c,tot}$) was calculated by using,

$$T_{R,DSB} + 290 = \frac{L_{c,tot}}{2} \times \left(T_{out} + T_{IF}\right) \quad (1)$$

Here, T_{out} is the output noise temperature of the device at the operating point with LO on. T_{out} was measured by comparing the IF chain output noise level when the device bias was varied from low voltage (superconducting state) to high (normal state) voltage [5]. T_{IF} is the IF amplifier chain noise temperature, which had been measured separately. The total optical coupling losses (L_{opt}) from the hot/cold source to the antenna were estimated to be about 7-9 dB [8] (5 dB at the lower frequency). The remaining conversion loss is the intrinsic mixer conversion loss ($L_{c,i}$), including IF mismatch. The analysis of the noise data is summarized in Table II. We achieved the lowest receiver noise temperature at 1.56 THz by using Device #3. It has a normal resistance of 85 Ω and is well matched to the antenna impedance of 74 Ω. We derived a noise bandwidth of 7 GHz for Device #1 and 4 GHz for Device #3 by using the method in [5]. At zero IF, Device #3 would have a receiver noise temperature of 2,600 K and a mixer noise temperature of 2,250 K. The intrinsic conversion loss for zero IF would be 8-10 dB, which is close to that of device #1 at a lower frequency and also close to that predicted by HEB theory from the I-V curves [8]. Device #2 gave a higher noise temperature than Device #3 primarily because of the higher intrinsic conversion loss. We attribute this result to inferior device quality which can be inferred from the lower critical temperature when compared with the best devices with this thickness (3.5 nm). Device # 1 was measured in the lower frequency band and has smaller optical losses.

It is clear that it should be possible in the near future to decrease the receiver noise temperature of NbN HEB mixers at frequencies from 1 through several THz further to the neighborhood of 1,000 K (note the noise temperature of 485 K measured for Device #1 at 620 GHz). For example, matching the lens will decrease the optical coupling losses by 2 to 3 dB. We can also optimize the device configuration, film fabrication, and film thickness. A film thickness between 3.5 and 5 nm may be optimum and also result in an even wider noise bandwidth similar to the bandwidth of 8 GHz shown to be feasible in measurements at lower frequencies [5]. The measured performance reported here and the potential for improvement along with absorbed LO powers of the order of 100 nW to 1 μW indicate that the NbN HEB mixer provides a strong alternative to the Nb diffusion cooled mixer for ultra low noise THz applications.

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