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NbN Hot Electron Bolometric Mixers - A New Technology for Low Noise THz Receivers

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ABSTRACT—**New advances in Hot Electron Bolometer (HEB) mixers have resulted in record low receiver noise temperatures at THz frequencies recently. We have developed quasi-optically coupled NbN HEB mixers and measured noise temperatures up to 1.56 THz, as described in this paper. We project the anticipated future performance of such receivers to have even lower noise temperature and LO power requirement as well as wider gain and noise bandwidths. We introduce a proposal for integrated focal plane arrays of HEB mixers which will further increase the detection speed of THz systems.**

I. Introduction

The emerging technology of low noise receivers operating well into the terahertz regime has a number of important applications including in plasma diagnostics, in remote sensing of the atmosphere from both airborne and ground based instruments, and in astronomy for observing molecular clouds. Examples of astronomical observing platforms which are presently being implemented for these applications are SOFIA (airborne) and FIRST (orbiting). The technology which has traditionally been available for this purpose utilizes Schottky-barrier diode mixers pumped by gas laser local oscillators. The noise temperature of such receivers has essentially reached a stationary limit of about 80 x hf/k (the quantum noise limit of the double sideband (DSB) noise temperature for heterodyne receivers is hf/2k or 25 K at 1 THz).

In the last few years, the maturing technology of Hot Electron Bolometric (HEB) mixers with an active medium of thin film superconductors [1] has introduced an alternative to Schottky-barrier diode technology. HEB mixers have significantly lower noise temperature and require three or four orders of magnitude less LO power. The frequency dependence of the receiver noise temperature for HEBs is also much less steep than for other types of receivers, as shown in FIG. 1. This behavior can be explained by the fact that HEBs act as resistive absorbers with very low (inductive) reactance to the THz radiation, while SIS devices and Schottky-barrier diodes have a capacitive reactance, which leads to a rapid rise of the noise temperature with frequency. SIS mixers also work well only below the bandgap frequency (700 GHz for Nb), whereas HEBs absorb radiation even better above this frequency. HEB mixers are therefore expected to work well into the IR regime in which the charge carrier inertia decreases the absorption. A reasonable es-

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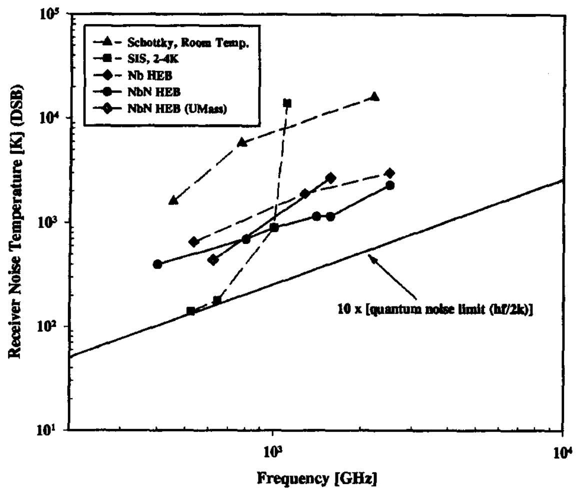

FIG. 1. Noise temperatures as a function of frequency for receiver in the terahertz regime.

timate of the potential future DSB receiver noise temperature for HEB mixer receivers is 10 x hf/k. This value of noise temperature is a very substantial improvement which will decrease the observing time required for a given level of detection by the square of the ratio of the noise temperatures (i.e. by almost two orders-of-magnitude).

II. DEVICE DESIGN AND FABRICATION

A typical HEB device [2][3] is made from a thin (3 to 4 nm) film of NbN deposited on a substrate of silicon or quartz by DC magnetron sputtering. Thinner films are desirable in order to achieve wider IF bandwidth. The critical temperature of the NbN film is about 10 K and efficient mixing occurs at about half that temperature. Above the superconducting bandgap frequency (roughly 1 THz for these films), terahertz radiation sees a resistance roughly equal to the normal resistance, which is 300 Ω/square to 600 Ω/square. A device with an aspect ratio (length to width) of from 1:5 to 1:10 will therefore match a typical antenna impedance of 80 Ω. The critical current of a device is a few hundred μA and the optimum operating point may occur at about 20% of this current. A typical DC bias voltage is between 1 mV to 2 mV. Since the device acts as a bolometer, the absorbed LO power is measured by the device itself and is computed from its I-V curve. As a rule of thumb, the LO power required is five times the DC power and, thus, of the order of 100 nW to 1 μW, depending on the device area and thickness. Our devices have a length of 1 μm and LO power close to 1 μW.

III. QUASI-OPTICAL COUPLING

Quasi-optical coupling is very convenient at the very high THz frequencies, where waveguides become increasingly difficult to manufacture. Although quasi-optical antennas have been well developed in the millimeter wave range, these same techniques have only rarely been demonstrated at THz frequencies. More efficient quasi-optical coupling is one of the main improvements which we believe will lead to much lower receiver noise temperatures for HEB mixers in the near future. We couple our devices through a 1.3 mm (in diameter) extended hemispherical silicon lens and a log periodic self-complementary toothed antenna. This design is scaled from the millimeter wave design in [4] and is illustrated in FIG. 2 (other antennas under investigation are spiral antennas and twin dipole/slot antennas). Two sizes of the log-periodic toothed antenna were designed with

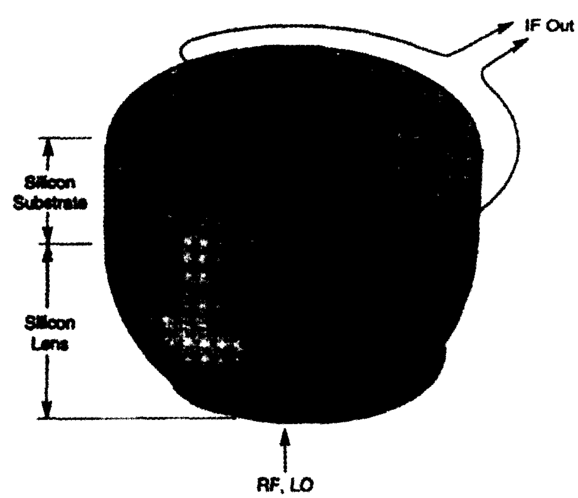

FIG. 2. Log-periodic toothed antenna fabricated on an extended hemispherical silicon lens (1.3 mm in diameter).

maximum frequencies of 1.2 THz and 2.4 THz, respectively. This antenna design has a 4:1 bandwidth, which makes it convenient to measure the performance at a wide range of frequencies with the same device. The antennas were fabricated from a gold film using lift-off lithography. We measured the response of the antenna/lens combination with a Fourier Transform Spectrometer (FTS). The antenna response as a function of frequency for both parallel and perpendicular polarizations is plotted in FIG. 3. The polarization dependence of the response was in agreement with measured spectra seen at millimeter waves in [5]. This feature is not of major concern, since the polarization of the LO beam can easily be switched with the help of wire grids. At the moment, we use no reflection matching for the silicon lens (ε_r = 11.8). optical losses should decrease by 2 to 3 dB once a suitable material for such coatings in the THz range becomes available.

IV. Optical Setup

Devices have been measured with the above two antennas at 620 GHz and 1.56 THz, respectively. A BWO was used as LO at the lower frequency and a CO_2 laser pumped difluoromethane gas FIR laser at the higher frequency. The LO was injected via a TPX lens through a thin (3 or 6 μm) Mylar beam splitter. The noise temperature was measured by inserting a

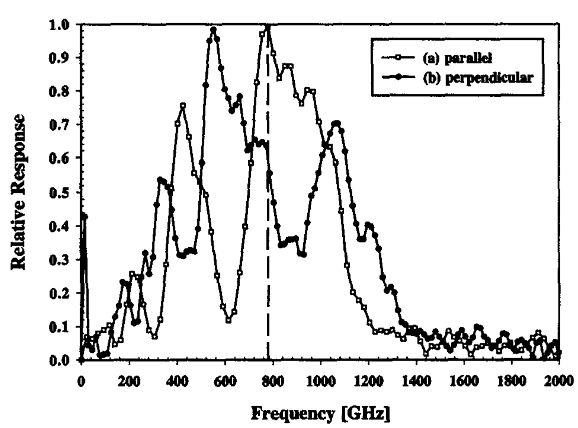

FIG. 3. FTS spectra of the device with the larger antenna for (a) device orientation parallel to the FTS polarization, and (b) perpendicular to the FTS polarization.

hot/cold blackbody source into the beam. The beam splitters have only a few percent of loss and thus have a very small effect on the measured noise temperature. A polyethylene window (0.75 mm thick) and a Zitex thermal filter were used in the dewar. Cooled isolator-coupled HEMT amplifiers were employed as the first stage of the IF chain.

The FIR laser was pumped by an extremely stable two meter long grating-tuned CO_2-laser. The available power from the CO_2-laser was 200 W [6]. The amplitude stability of the 1.56 THz laser source, measured over a period of minutes, with a relatively fast (0.1 s) integration time, was ± 0.3 %. About 50 mW of FIR power was available.

V. Experimental Results

With the device cooled to 4.5 to 5 K, we obtained a DSB receiver noise temperature of 485 K (16 x hf/k) at 620 GHz, using the larger antenna (440 K by cooling to 2.5 K), and 2,700 K (35 x hf/k) at 1.56 THz with the smaller antenna version. The measured 3 dB IF conversion gain bandwidth for one device was 3 GHz and it is estimated that the bandwidth over which the receiver noise temperature is within 3 dB of its minimum value is 6 GHz. Flat response of the receiver noise temperature up to 8-10 GHz is feasible in the future. The fact that the receiver noise temperature bandwidth is two or three times wider than the conversion gain bandwidth is a well-known feature of HEB mixers. This characteristic can be understood if one realizes that the main noise process in the device (temperature fluctuation noise) yields a noise output which falls at the same rate as the conversion gain, flattening the net receiver noise dependence on the IF frequency [7]. By analyzing the measured noise data for the 1.56 THz mixer [2], we can conclude that the optical coupling loss was about 7 - 9 dB and that the intrinsic conversion loss was 11-13 dB. This emphasizes the importance of further work on decreasing the optical coupling losses. The intrinsic receiver noise temperatures (at the mixer input terminals, excluding optical coupling loss) are 400 K for the 1.56 THz mixer and 250 K for the 620 GHz mixer. It is from these results that we can confidently predict that the receiver noise temperature can be decreased to 10 hf/k or less in the near future. In fact, other researchers have already demonstrated lower noise temperatures for NbN HEB devices using a similar approach [8].

VI. TERAHERTZ FOCAL PLANE ARRAY

Our quasi-optical approach lends itself particularly well to further developing the HEB receiver into focal plane arrays with tens of HEB mixer elements on a single silicon substrate (see FIG. 4). Such an arrangement will make real time imaging systems feasible in the THz region. Each pixel will contain an HEB device integrated with a lens and an antenna as well as a MMIC IF amplifier. The advantage of this "fly's eye" configuration is that the elements are more spread out than if one were to use a single larger lens. In addition, the number of elements which can be used with a single lens will be more limited due to lens aberration. A lens size of 1 to 2 mm will result in sufficient space for the IF amplifiers especially if MMIC versions of these are employed. The routing of transmission lines for the IF output, the amplifier, and the biasing of the HEB can be accommodated by using a spun-on dielectric such as polyimide or BCB. Focal plane arrays will represent the next generation

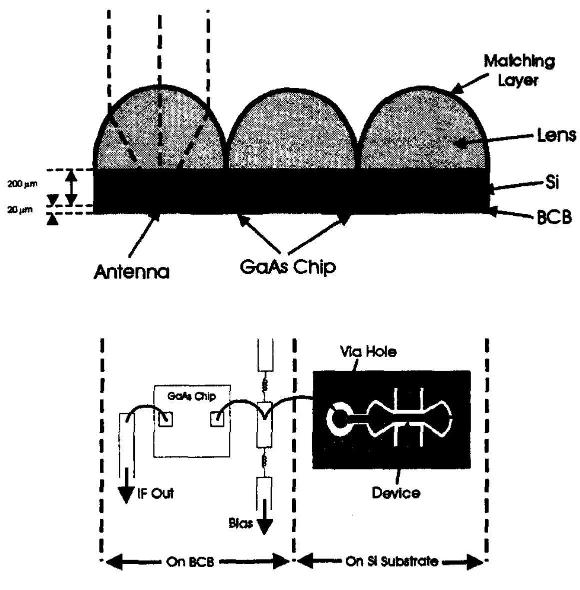

FIG. 4. A portion of an HEB terahertz focal plane receiver array.

detection system for THz receivers which will increase the detection speed by one further substantial step and may be considered for new applications of the NbN HEB receiver technology beyond astronomy and remote sensing.

VII. ACKNOWLEDGMENT

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