ABSTRACT—In recent years, improvements in device development and quasi-optical coupling techniques utilizing planar antennas have led to a significant achievement in low noise receivers for the edges of the submillimeter frequency regime. Hot Electron Bolometric (HEB) receivers made of thin superconducting films such as NbN have produced a viable option for instruments designed to measure the molecular spectra for astronomical applications as well as in remote sensing of the atmosphere in the THz regime. This paper describes an NbN HEB mixer with intrinsic DSB receiver noise temperature of at most five times the quantum noise limit at frequencies as high as 2.24 THz.

I. INTRODUCTION

New measurements with an NbN Hot Electron Bolometric (HEB) Mixer, which was described in detail at last year’s IMS [1] and in a subsequent IEEE Trans. MTT paper [2], have demonstrated Double SideBand (DSB) receiver noise temperatures which are one half of those reported at that time, and represent the lowest noise temperatures ever measured in the THz regime (see FIG.1). NbN HEB mixers with an active medium of thin film superconductors have introduced an alternative to Schottky-Barrier Diode (SBD) receiver technology [3]. The noise temperature of SBD receivers has essentially reached a stationary limit of about 150 x hf/2k (the quantum noise limit of the Double SideBand (DSB) noise temperature for heterodyne receivers is hf/2k or 24 K at 1 THz). 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. 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 SBD receivers have a capacitive reactance. SIS mixers also work well only below the bandgap frequency (700 GHz for Nb), whereas HEBs absorb radiation even better above this frequency.

II. DEVICE DESIGN AND FABRICATION

The HEB receivers were fabricated by conventional UV lithographical techniques on thin film (3 to...
4 nm) of superconducting NbN deposited on a substrate of silicon or quartz by DC magnetron sputtering. Thinner films are desirable in order to achieve wider IF bandwidth. A new approach for increasing the IF bandwidth is now being investigated by depositing the thin film NbN on MgO substrates. Preliminary measurements show a significant improvement in IF bandwidth without any deterioration of the noise temperature. 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

The devices are quasi-optically coupled through a small (4 mm diameter) elliptical silicon lens and a planar log-periodic self-complementary toothed antenna with maximum frequency response of 3.4 THz. Older devices were coupled through a 1.3 mm (in diameter) extended hemispherical silicon lens as shown in FIG. 2. It is very convenient at the very high THz frequencies to utilize quasi-optical coupling techniques based on earlier designs done for systems operating below 1 THz [4]. Recent developments in micro-machining will make waveguide coupling possible. 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. Three sizes of the log-periodic toothed antenna were designed with maximum frequencies of 1.2 THz (A), 2.4 THz (B), and 3.4 THz (C), 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. Different antennas under investigation in other laboratories are spiral antennas and twin dipole and slot antennas. We plan to study the performance of slot ring antennas. 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 polarization dependence of the response was in agreement with measured spectra seen at millimeter waves in [5]. At the moment, we use no reflection matching for the silicon lens. At the lower frequencies, silicon lenses have often used anti-reflection coatings, such as alumina-loaded epoxy, but above about 1 THz epoxy is known to be too lossy. A maximum improvement of 1.5 - 2 dB is feasible for an optimum AR coating. We have found a new material, parylene, which has close to the ideal refractive index and very low dielectric loss at THz frequencies [6]. We plan to use this material which is grown by Chemical Vapor Deposition (CVD) and produces a layer of uniform thickness in the near future.

IV. OPTICAL SETUP

A CO2-laser pumped difluromethane gas laser serves as the LO source. The LO power is attenuated.
using a wire grid, focused by a TPX lens, and then injected through a thin mylar beam splitter onto the device. The Y-factor was measured by inserting a 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. A cooled HEMT amplifier with a noise temperature of 7 K and a bandwidth of 500 MHz centered at 1.5 GHz was used as the first stage of the IF chain. Further amplification was needed at room temperature in order to monitor the signal. The measurement setup is shown in FIG. 3.

The FIR laser was pumped by an extremely stable two meter long grating-tuned CO₂-laser. The available power from the CO₂-laser was 200 W. 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

Total DSB system noise temperatures of 500 K at 1.56 THz and 1,100 K at 2.24 THz were measured (see TABLE I). The total system noise temperature is referred to a plane outside the mylar beamsplitter shown in FIG. 3. These results are 13 and 20 times the quantum noise limit at the respective frequency (as mentioned in the introduction, the DSB quantum noise limit (hf/2k) is about 24 K at 1 THz). We have estimated an optical coupling loss of 4.5 dB at 1.56 THz and 8 dB at 2.24 THz. This figure includes the dewar window and IR filter, as well as estimated losses due to the silicon lens and the antenna. Mismatch losses are also included. By dividing the measured total system noise temperature by this optical loss factor, we can obtain an estimate for the intrinsic receiver noise temperature at the input of the mixer element (including the IF amplifier contribution). We find a flat intrinsic receiver noise temperature of 180 K for both frequencies. This value for the intrinsic noise temperature corresponds to less than five times the quantum noise limit at 1.56 THz and less than four times the quantum noise limit at 2.24 THz. As advances in the optical coupling design are introduced, we expect the total system noise temperature to get closer to this intrinsic level. For example, the parylene anti-reflection coating for the silicon lens mentioned in section III will result in an improved optical loss by 1.5 to 2 dB.

Improved performance is also expected in terms of IF bandwidth and broadband matching to the IF amplifier. The IF conversion gain bandwidth for this type of HEB devices (phonon-cooled) is typically 3 GHz. It is a well-understood and experimentally proven characteristic of HEB mixers to have a receiver noise bandwidth which is about twice as wide as the conversion gain bandwidth (the receiver noise bandwidth is the IF frequency at which the total receiver noise temperature has increased by 3 dB compared with low IF frequencies). New investigations with NbN on MgO substrates [7] show an improved IF conversion gain bandwidth. IF noise bandwidths close to 10 GHz are expected in the near future. IF cooled-amplifiers with low noise temperature (5 K)

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FIG. 3. Measurement setup for noise temperature.
and wider IF bandwidth (4-8 GHz) are under development. The optimum value for the IF load impedance is also being investigated experimentally and theoretically.

The recent results reported here make the development of focal plane arrays for real-time imaging systems feasible in the THz region. Such arrays are expected to contain tens of HEB mixer elements on a single substrate. Each pixel will contain an HEB device, integrated with a lens and an antenna, as well as an MMIC IF amplifier. The quasi-optical coupling approach we employ for single elements lends itself well for use in a “fly’s eye” array as illustrated in FIG. 4. The slot-ring antenna allows an alternative method of very efficient LO injection through a wire grid. LO and signal radiation will be injected in orthogonal polarizations and the HEB device(s) will be fabricated in a position on the slotting which makes a 45° angle with both polarizations.

Focal plane arrays will represent the next generation detection system for THz receivers, which will increase detection speed by one further substantial step, and may be considered for new applications beyond astronomy and remote sensing.

VI. ACKNOWLEDGMENT

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VII. REFERENCES


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FIG. 4. HEB focal plane receiver array for THz frequencies using slot ring antennas.