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Low Noise in a Diffusion-Cooled Hot-Electron Mixer at 2.5 THz

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The noise performance of a Nb hot-electron bolometer mixer at 2.5 THz has been investigated, The devices are fabricated from a 12 nm thick Nb film, and have a 0.30 μm×0. 15 μm in-plane size, thus exploiting diffusion as the electron cooling mechanism. The rf coupling was provided by a twin-slot planar antenna on an elliptical Si lens. The experimentally measured double sideband (DSB) noise temperature of the receiver was as low as 2750+ 250 K, with an estimated mixer noise temperature of ≈ 900 K. The mixer bandwidth derived from both noise bandwidth and IF impedance measurements was ≈1.4 GHz. These results demonstrate the low-noise operation of the diffusion-cooled bolometer mixer above 2 THz.

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A number of on-going astrophysical and atmospheric programs arc aimed at spectroscopic exploration of the terahertz (THz) frequency range. There is an urgent need here for low-noise mixers for heterodyne receivers. Currently available S1S mixers and Schottky-diode mixers exhibit significant degradation in noise performance above 1 THz. A unique superconducting hot-electron bolometer (HEB) mixer has been proposed [1,2] as an alternative to address these high-frequency needs. Theory 3 predicts the HEB mixer noise temperature duc to intrinsic noise mechanisms to be as low as ≈ 100 K, which is of the order of the quantum limit at THz frequencies. Also the required local oscillator (LO) power can be made very low (less than 100 n W for Nb devices) if the device size and sheet resistance are appropriately chosen. However, there is some concern about a high-frequency limitation for a diffusion-cooled HEB mixer. The relatively frequency independent absorption of rf radiation in a superconductor above the gap frequency can provide a good impedance match to an antenna-coupled microbridge device; up to visible light frequencies, in principle. On the other hand, the relaxation of highly excited electrons can be complicated by cascade processes of emission and absorption of phonons competing with the inelastic (ie: energy sharing) electron-electron interactions. The escape of high-energy phonons from the microbridge can reduce the efficiency of the mixing mechanism in the bolometer. Also, the use of purer material for the bolometer appears to be preferable to increase the sharpness of the superconductive transition in the film, which should improve mixer performance[3]. However, since the electron-electron relaxation time τ_{ee} -- R_{sq}^{-1}[4] (R_{sq} is the film sheet resistance), for a very short device the hot-electrons may diffuse out the microbridge more quickly than they interact with each other.

Recent experiments [5,6] have partly addressed the above issues showing no significant degradation of the mixer noise temperature between 0.5 and 1.2 THz. In this work we developed and tested at 2.5 THz a quasioptical diffusion-cooled HEB mixer made from a pure Nb film (2.5 THz is a frequency important for practical applications).

The bolometer device used in this experiment consists of a 0.30 μm long by 0.15 μm wide microbridge made of a 12 nm thick Nb film sputtered-deposited on a high-resistivity ($\rho \approx$ 4-5 kΩ cm) silicon substrate. The length of the bridge was defined by the gap between the 150 nm thick gold contact pads using a unique self-aligned fabrication process 7. The surrounding mixer embedding circuit and planar antenna arc fabricated from 300 nm thick gold. The critical temperature of the device was 6.5 K, the transition width was 0.2-0.3 K, and the sheet resistance was 11-13

Ω/sq. The critical current density at 4.2 K was measured to be 1.5x 107 A/cm^2. Figure I shows the completed device. More details of the device fabrication arc given elsewhere[7]

The mixer rf embedding circuit was made using a twin-slot antenna and coplanar waveguide transmission (CPW) line[8] located at the second focus of an elliptical Si lens of 12.7 mm diameter [9](sec Fig. I). The rf impedance presented to the HEB device at the feed point was designed to be 70 Ω, and was strongly determined by the gap (nominally 0.5 μm) in the CPW line. A 250 μm thick Si chip carrying the twin-slot antenna and rf choke-filter was glued to the lens and wire-bonded to a coplanar waveguide IF circuit on Duroid™ substrate which provided the first section of the DC and IF signal path.

Our mixer test system consisted of a CO_2-pumped methanol FIR laser as an LO source, and a vacuum box containing two blackbody loads with similar emissivities for Y-factor measurements of the receiver noise temperature. The box is connected to the LHe vacuum cryostat, allowing operation without a pressure window in the signal path. The box and cryostat are evacuated to remove the effects of atmospheric absorption which are significant at 2.5 THz. The signal from the hot and cold loads was switched by a mechanical chopper with a reflecting blade at a rate typically around 100 Hz. The first-stage of the IF system consisted of a cooled broadband HEMT amplifier with a bandwidth 1.5-3.0 GHz and a noise temperature of ≈ 9 K. This was followed by room-temperature amplifiers, a narrow bandpass filter (a set of different filters with bandwidths ranging from 25 to 300 MHz was used), and a commercial crystal detector. The average IF response, V_{dc}, (i. e., the dc voltage across the IF crystal detector) and the change in IF response synchronous with the chopper, ΔV, were simultaneously measured using a voltmeter and a lock-in amplifier. The Y-factor is then given by $(V_{dc}+\Delta V/2)/(V_{dc}-\Delta V/2)$, and the DSB mixer noise temperature, TM, is $T_M=(T_{Hot}-T_{Cold}Y)/(Y-1)$, where T_{Hot} and T_{Cold} are the effective Planck temperatures of the hot and cold loads.

The antenna frequency response was measured using a fourier transform spectrometer. For this measurement, the device operating temperature was set to a value near T_c, and the bias voltage was adjusted to obtain a large direct-detection response in the bolometer. The detector response was corrected for the calculated frequency dependence of the beamsplitter in the spectrometer. The remaining frequency dependence is dominated by the antenna response and is centered at 1900 GHz with the 3-dB bandwidth of ≈ 1.1 THz. These results conform with the expected performance for twin-slots [8] and demonstrate that this type of antenna functions well above 2 THz. Previously, twin-slot antennas have been successfully demonstrated only slightly above 1 THz [10]. The center frequency is offset by almost 25% from the desired 2.5 THz center frequency, and results in an apparent 50% decrease of the optical efficiency. We have investigated the antenna rf performance, attempting to understand this discrepancy. A model simulation [1 revealed a significant dependence of center frequency on the HEB device resistance. The theory predicts approximately 1.5 dB of impedance mismatch loss at the LO frequency of 2.522 THz for a 23 Ω HEB (the resistance of the experimental device). More details of the modeling and discussion are given in Ref. 11.

Mixer experiments were performed with two very similar devices, and both demonstrated comparable performance. Only the data for one are discussed here. The coupling efficiency of the bolometer to the radiation was measured using the direct detection response of the HEB to the hot and cold loads *(i. e.,* without any LO applied). Plot ting the two current-voltage (IV) characteristics ("hot" and "cold'), one can calculate the absorbed radiation power, P_{abs}, assuming the rf power heats the device in the same fashion as the dc bias Joule heating. Here, $P_{abs} = P_{dc}(hot) - P_{dc}(cold)$, applied for a constant resistance line (P_{dc} is the Joule power) and the coupling efficiency is $\eta = P_{abs}/\Delta P_{inc}$, where ΔP_{inc} is the difference between the powers of black body radiation from the hot and cold loads, integrated over the rf bandwidth of the mixer. This yields $\eta \approx$ -7.2 dB. The same technique allows one *to* find the LO power (P_{LO}) absorbed in the bolometer. Within the uncertainty of this simple method, $PLO \approx 80$ nW was obtained.

Figure 2 shows both unpumped and optimally LO-pumped IV characteristics at 4.3 K. Normally, only small or no negative resistance region was observed in the optimal IV curve. The bias dependencies of both V_{dc} and $A V$ are given in the same figure. One can see than the IF output power starts to rise when approaching the dropback point at the IV curve, indicating the onset of strong mixing performance (at this point the dynamic resistance becomes very large and the self-heating effects increase). This behavior was also observed at 1.5 K, where both the position of the operating point and the mixer noise temperature were almost the same as at 4.3 K. The only difference was a somewhat larger amount of LO power required to pump the mixer at 1.5 K. Also, for bias voltages in the negative differential resistance region, the generat ion of oscillations in the device were observed. This bias region was avoided for mixer measurements.

In order to estimate the IF bandwidth, f_{3dB}, of the mixer, the device IF impedance was measured over a 0.05-4 GHz frequency range. It has been demonstrated experimentally for phonon-cooled Nb[12,13] and NbN[14] devices that the HEB impedance changes from a high differential resistance value at low frequencies to a lower ohmic resistance R at high frequencies. The crossover occurs at the frequencies related to the mixer bandwidth. Thus, a measurement of the HEB impedance versus frequency allows f_{3dB} to be determined.

For these measurements, the S_{21} parameter of a 0.3 μm long test device (made of the same film) with small contact pads wire-bonded into a microstrip test circuit was measured using a vector network analyzer. The analyzer's rf power level was greatly attenuated to avoid any influence of the test signal on the device resistive state. Calibrations were done with the HEB device in the superconductive state (Z= O) and normal state ($Z = R_n$). This allowed the HEB IF impedance, $Z(f)$, to be de-imbedded from the microstrip test fixture. Figure 3 shows the Z(t) dependence (both real and imaginary parts) along with the fitted curves from theory[3]. The associated mixer bandwidth is found to be f_{3dB} = 1.4 GHz. This quantity is in good agreement with recently reported bandwidth measurements on diffusion-cooled Nb devices of the same length[5,15].

The experimental values of the DSB receiver noise temperature are plotted vs IF in Fig. 4. The different points correspond to the different bandpass filters used. A best receiver noise of 2500-3000 K was measured at IF's of 1.4 GHz and below. The noise bandwidth is consistent with the mixer bandwidth implied by the impedance measurements. If wc remove the IF system noise and correct for the measured 1.5-dB loss in the off-resonant antenna, an upper limit of about 900 K is obtained for the mixer noise temperature. This performance is comparable to that for similar diffusion-cooled HEB mixers at 533 GHz[5] and at 1.2 THz[6], and demonstrates the relative frequency-indcpcndcnce of the mixer performance. It should be noted that this receiver performance is 3-to-5 times better than competing Schottky-diode receivers at 2.5 THz, and the required LO power is at least four orders of magnitude lower.

In conclusion, excellent performance of a diffusion-cooled Nb hot-electron bolometer mixer has been demonstrated at 2.5 THz. A DSB receiver noise temperature of ≤ 3000 K has been measured at f_{IF} ≤ 1.4 GHz, along with only 80 nW absorbed LO power. The mixer performance is expected to improve by at least 1 .5-2 dB with better antenna design and impedance match. This demonstrates that diffusion-cooled HEB mixers can work above 2 THz with no significant degradation in performance. This is a major improvement for heterodyne sensor technology and is expected to be extremely useful for numerous astrophysical and atmospheric applications.

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Figure Captions

Fig. 1. Planar mixer circuit consisting of the twin-slot antenna and coplanar waveguide transmission line. The inset shows the SEM photo of the 0.30 μm by 0.15 μm Nb HEB device between the gold contacts. The SiO passivation protects against oxidation.

Fig. 2. Current-voltage characteristics and the dc (V_{dc}) and ac (ΔV) components of the IF output power. V_{dc} and ΔV are arbitrary scaled in reference to each other.

Fig. 3. HEB IF impedance for a 0.3 μm long microbridge. The dashed line represents the best fit by the theory of Ref. 3.

Fig. 4. The receiver noise temperature vs inter-mediate frequency,

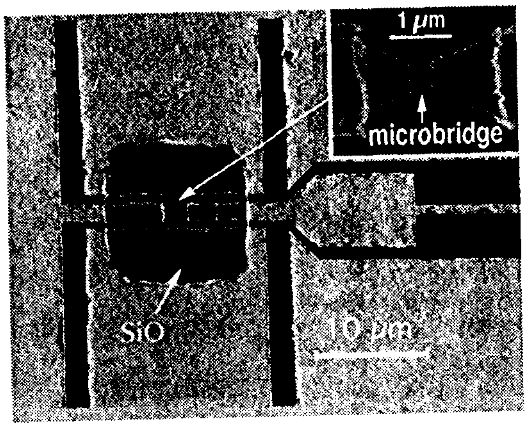

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Fig. 1

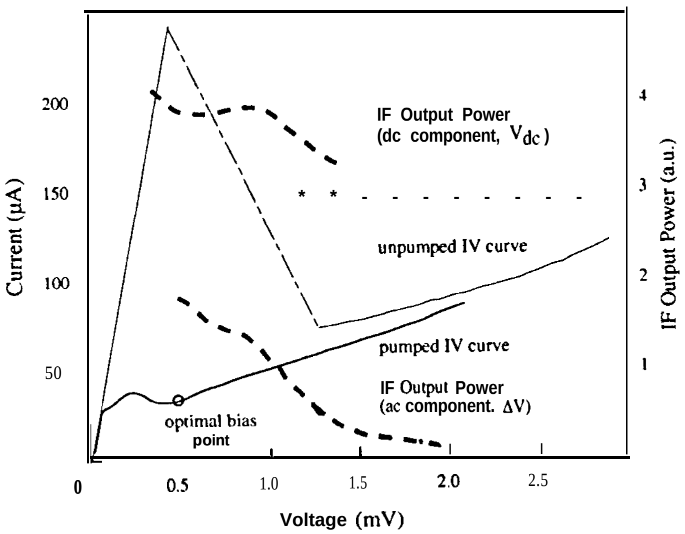

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Fig. 2

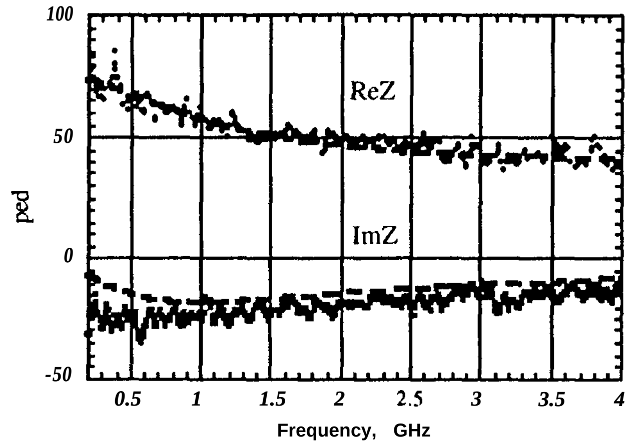

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Fig. 3

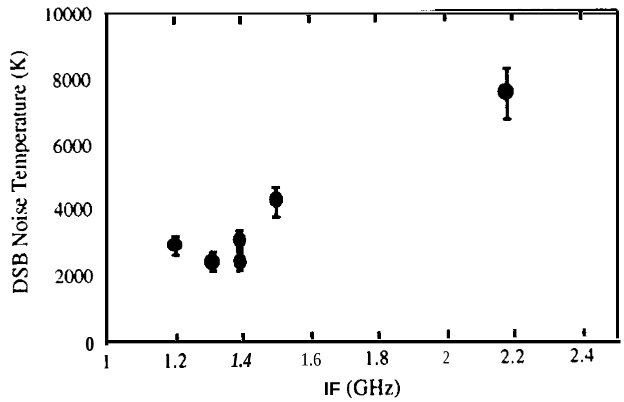

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Fig. 4