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Low noise NbN hot electron bolometer mixer at 4.3 THz

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We have studied the sensitivity of a superconducting NbN hot electron bolometer mixer integrated with a spiral antenna at 4.3 THz. Using hot/cold blackbody loads and a beam splitter all in vacuum, we measured a double sideband receiver noise temperature of 1300 K at the optimum local oscillator (LO) power of 330 nW, which is about 12 times the quantum noise ($h\nu/2k_B$). Our result indicates that there is no sign of degradation of the mixing process at the superterahertz frequencies. Moreover, a measurement method is introduced which allows us for an accurate determination of the sensitivity despite LO power fluctuations.
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Superconducting mixers[1] play a key role in astrophysics at terahertz frequencies, where the early universe radiates strongly. The availability of low noise superconductor-insulator-superconductor (SIS) mixers and hot electron bolometer (HEB) mixers has made the realization of highly sensitive spectrometers on ground, airborne, and space telescopes possible. An example of this is the heterodyne instrument for far infrared on the Herschel space telescope,[2] to be launched in 2008, where the heterodyne spectrometers are operated up to 1.3 THz using SIS mixers and further up to 1.9 THz using HEB mixers. For the next generation of space telescopes, it becomes highly desirable to demonstrate sensitive mixers in the frequency range between 2 and 6 THz. HEB mixers, which are currently the only devices suitable for this frequency range, have been reported up to 5.3 THz.[3–5] However, only few experiments have so far been done at the frequencies above 3 THz, namely, superterahertz frequencies, and the performance is relatively poor.[3,4]

The noise temperature of a receiver is a crucial parameter that defines the ultimate sensitivity of the heterodyne spectrometer and the observation time. To achieve the low noise at superterahertz, several challenges are expected either in the mixer itself or in the testing technique. First, it is unclear whether the performance of HEBs will degrade. The relaxation of highly excited electrons due to increased photon energy can be complicated by cascade processes of emission and absorption of phonons. This can compete with the electron-electron interaction and thus may decrease the mixing efficiency.[6] Also, there is a concern of the quantum noise.[7] Second, it becomes more difficult to couple terahertz radiation to the HEB. Third, there is lack of local oscillators (LOs). Optically pumped far infrared (FIR) gas lasers are commonly used, but achieving stable output power is cumbersome. Terahertz quantum cascade lasers[8] (QCLs) are promising, stable solid-state LOs,[9] but still in a development stage. Finally, there is an increase in the air loss due to the absorption of terahertz radiation by water vapor, which can increase the receiver noise temperature and may also cause instability.

In this letter, we report the measurement of a quasioptical NbN HEB mixer at 4.3 THz using a hot/cold load built in vacuum and demonstrate low noise performance at this frequency, which is nearly a factor of 4 better than the previously reported.[3,4] In addition, we introduce a characterization method which allows for the determination of the noise temperature accurately despite LO power fluctuations.

The HEB mixer is shown in the inset of Fig. 1. It consists of a 2 μm wide, 0.2 μm long, and 5.5 nm thick NbN bridge on a highly resistive, natively oxidized Si substrate.[10] The bridge is connected to the antenna by NbTiN (10 nm)/Au (50 nm) bilayer contact pads. Prior to the deposition of the pads, the surface of the NbN layer is cleaned *in situ* by rf Ar^+ etching. Previously, we have demonstrated excellent receiver sensitivities of 950 K at 2.5 THz (Ref. 11) and 1200 K at 2.8 THz (Ref. 12) using the mixers with similar contacts. The antenna is an on-chip spiral antenna made of a 170 nm thick Au layer. It has a tight winding design with an inner "diameter" of 6.6 μm close to the NbN bridge (see Fig. 1). Based on a design rule given in Ref. 4 and our

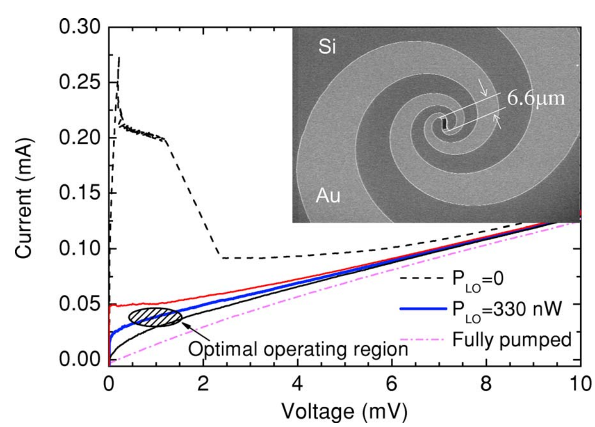

FIG. 1. (Color online) A set of current-voltage curves of an NbN HEB mixer at 4.2 K at different LO power, where the optimum operating region is indicated. The inset shows a SEM micrograph of an HEB integrated with a spiral antenna with an inner diameter of 6.6 μm.

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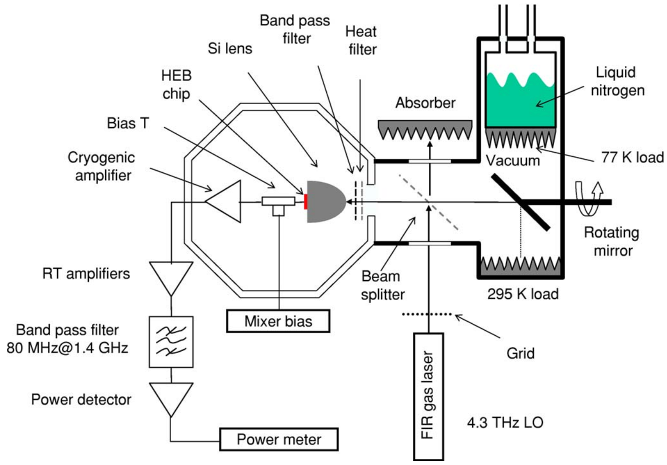

FIG. 2. (Color online) Schematic picture of the measurement setup, where the hot/cold loads and the beam splitter are built in a vacuum unit, directly attached to the HEB cryostat. Switching between the hot and cold load is done by rotating a mirror.

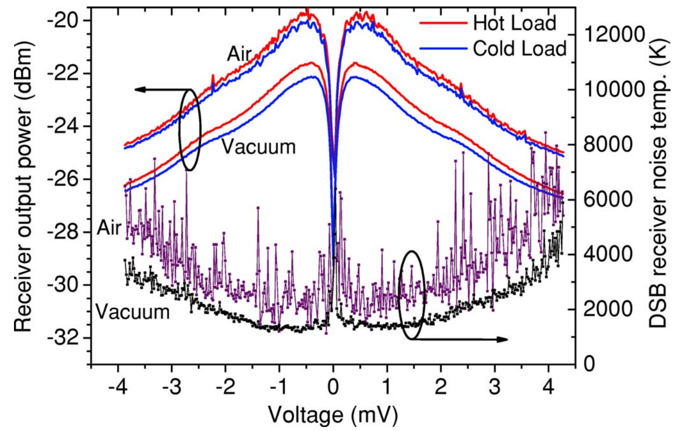

FIG. 3. (Color online) Measured receiver output power (left axis) responding to the hot and cold load at optimal LO power as a function of bias voltage. One set of data are measured using hot/cold loads in the vacuum setup and another set using the air setup. The resulted DSB receiver noise temperatures are also plotted vs bias voltage (right axis).

previous results[9,11] using a design with a diameter of 15 μm, an expected upper cutoff frequency of this antenna is 6 THz. The HEB has a room temperature resistance of 80 Ω, a critical temperature of 10 K and a critical current of 275 μA at 4.2 K.

Our key results have been achieved in a quasioptical setup, schematically shown in Fig. 2. The HEB is glued to the back side of an elliptical Si lens and mounted in a mixer unit that is placed in a 4.2 K L–He cryostat. The lens is coated with an 11 μm thick parylene C layer, which acts as an antireflection coating optimal for 4.3 THz. As calibration radiation sources, a blackbody (a coating layer of a mixture of SiC grains in black Stycast epoxy)[13] at 295 K is used as the hot load and another one at 77 K as the cold load. The two loads can be selected by rotating a mirror. The radiation from the hot/cold load is combined with that from the LO by a 3 μm mylar beam splitter. Before reaching the HEB, the radiation passes through a heat filter[14] and then through a narrow-bandpass filter[15] (both at 4.2 K). All these components are in vacuum, therefore the radiation does not suffer from the absorption due to air.[6] The use of the bandpass filter is essential to overcome a direct detection effect,[16] which becomes significant due to a combination of the lossless hot/cold blackbody radiation in the vacuum and the wide rf bandwidth of the antenna.

The LO is an optically pumped FIR ring laser, operated at 4.252 THz ($\lambda \approx 70.5$ μm). The LO power (power absorbed by the HEB) is regulated by a rotating wire grid.

The mixer output at the intermediate frequency (IF) is amplified first using a cryogenic low noise amplifier and then followed by room-temperature amplifiers. This signal is filtered at 1.4 GHz in a band of 80 MHz. The entire IF chain has a gain of about 80 dB and a noise temperature of 7 K.

The just described setup is referred as *the vacuum setup*. For comparison, we also performed measurements in a commonly used setup, where hot/cold loads and a beam splitter are in air, and a 1 mm thick high-density polyethylene (HDPE) window on the HEB cryostat. The rest of the setup is kept unchanged. The latter is referred as *the air setup*.

Figure 1 shows a typical set of current-voltage (I-V) curves of the HEB pumped from zero to a fully pumped power level. At the indicated optimum operating region, the sensitivity is within 5% of the best value (see below), the LO power in the HEB is about 330 nW, the bias voltage is 0.5–1.4 mV, and 30–45 μA.

To obtain the double sideband (DSB) receiver noise temperature ($T_{N,\mathrm{rec}}$) we measured the receiver output power, $P_{\mathrm{out,hot}}$ and $P_{\mathrm{out,cold}}$, responding to the hot load and cold load in the vacuum setup as a function of bias voltage under the optimum LO power. The results are plotted in Fig. 3. To derive $T_{N,\mathrm{rec}}$, we use a standard Y-factor method, where $Y = P_{\mathrm{out,hot}}/P_{\mathrm{out,cold}}$, and the expression[17]

$$T_{N,\mathrm{rec}} = \frac{T_{\mathrm{eff,hot}} - YT_{\mathrm{eff,cold}}}{Y-1},$$

where $T_{\mathrm{eff,hot}}$ and $T_{\mathrm{eff,cold}}$ are the equivalent temperatures of a blackbody at 295 and 77 K, respectively, which are 307 and 118 K at 4.3 THz according to the Callen-Welton definition.[17] The calculated $T_{N,\mathrm{rec}}$ as a function of bias voltage is also plotted in Fig. 3. The $T_{N,\mathrm{rec}}$ shows a broad minimum in its voltage dependence around 0.8 mV, where the lowest $T_{N,\mathrm{rec}}$ value is 1350±160 K. The ±12% uncertainty (±160 K) is attributed partly (±7%) to the fluctuations in the laser output power and partly (±5%) to the drifting. The latter was reflected by the slightly asymmetrical $T_{N,\mathrm{rec}}$-V curve. The receiver conversion loss is about 16.5 dB including all the optical losses.

For comparison, the same measurement is done using the air setup and the results are also included in Fig. 3. In contrast to those obtained in the vacuum setup, the $P_{\mathrm{out,hot/out,cold}}$ data are noisy, resulting in considerable fluctuations in the $T_{N,\mathrm{rec}}$ curve. By neglecting several exceptional high peaks, the lowest $T_{N,\mathrm{rec}}$ is 2300±650 K (±28%). Based on the data obtained in the vacuum setup, we expect that the ±12% of the fluctuations are caused by the instability of the laser. However, the remaining ±16% are likely due to the air turbulence and the microphonic vibration in the thin beam splitter. The difference in $T_{N,\mathrm{rec}}$ obtained with two setups is due to the additional optical losses in the air (0.8 dB) and the cryostat window (0.9 dB).

The LO power fluctuations caused by either the power fluctuations of the laser itself or by the air and beam splitter vibrations can have a significant impact on the stability of a

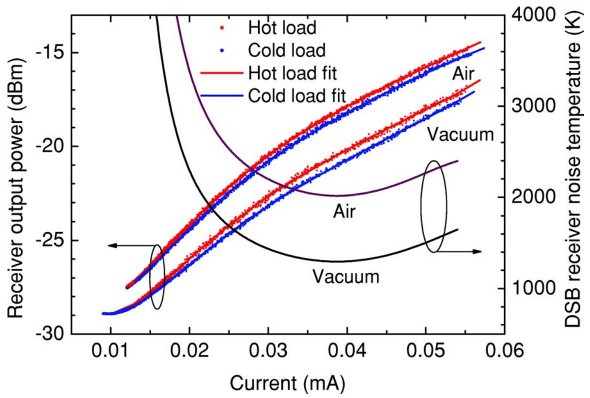

FIG. 4. (Color online) Measured receiver output powers at the optimum bias voltage of 0.8 mV (dots) and the polynomial fit (lines) responding to hot and cold loads in the vacuum and air setup as a function of the current of the HEB, which is varied by changing the LO power (left axis). The resulted DSB receiver noise temperature curves are also included as a function of the current of the HEB (right axis).

receiver. Here, we introduce a measurement method that can accurately determine the $T_{N,\mathrm{rec}}$ despite of LO power fluctuations.

At a constant bias voltage, we measure the HEB current and the receiver output power while changing the LO power from maximum to zero and vice versa. This will move the bias point from the fully pumped to the unpumped region, vertically on the *I*-*V* curves (see Fig. 1). The key plot is the receiver output power versus the HEB current (P_{out}-I curve). Two such curves are recorded, one responding to the hot load and the other to the cold load. Figure 4 shows the measured curves at 0.8 mV (the optimum bias voltage) using both the vacuum and the air setup. We observe that for a given current, the amplitude fluctuations in the $P_{\mathrm{out,hot/out,cold}}$ are comparable for both the air and vacuum setups, suggesting that this measurement method is not sensitive to the LO power fluctuations.

The $T_{N,\mathrm{rec}}$ calculated from the fitted curves for both the vacuum and the air setup are also shown in Fig. 4. The lowest $T_{N,\mathrm{rec}}$ are 1296 K in the vacuum setup and 2015 K in the air setup. Both are at 39 μA bias current. These values are in agreement with those in Fig. 3 measured in the standard manner. However, a clear advantage of this method is that the $T_{N,\mathrm{rec}}$ can be determined precisely and is not sensitive to LO power instability. In contrast to the standard manner, where the LO power is required to be fixed, here, it is used as a variable. Any data point at any LO power is a useful contribution to the P_{out}-I curve. Furthermore, with this method, the Y factor and thus the $T_{N,\mathrm{rec}}$ are not influenced by the direct detection effect because the $P_{\mathrm{out,hot}}$ and $P_{\mathrm{out,cold}}$ are taken at exactly the same bias point.

In summary, we have demonstrated a highly sensitive NbN HEB mixer at 4.3 THz by using the hot/cold blackbody loads and the beam splitter in vacuum. We introduced an accurate characterization method which is immune to the LO power fluctuations and drift. The lowest DSB receiver noise temperature was directly measured to be 1300 K using the vacuum setup. The value for the air setup is about 2000 K, which in comparison with our noise data at 2.84 THz (Ref. 12) or below shows an increased noise temperature, roughly scaled with frequency. However, there is no steep frequency dependence implying that there is no clear sign of degradation of the mixing process at the superterahertz frequencies.[6] Furthermore, based on the measured receiver noise temperature and the total receiver conversion loss, we obtain the mixer output noise to be about 50 K. Since this is the typical value found at lower frequencies and can be explained by classical noise sources in the HEB mixer alone, there seems to be no or negligible contribution of the quantum noise.[7]

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[1] J. Zmuidzinas and P. Richards, Proc. IEEE **92**, 1597 (2004).
[2] http://herschel.esac.esa.int/
[3] A. D. Semenov, H.-W. Hübers, J. Schubert, G. N. Gol'tsman, A. I. Elantiev, B. M. Voronov, and E. M. Gershenzon, J. Appl. Phys. **88**, 6758 (2000).
[4] H.-W. Hübers, A. Semenov, H. Richter, M. Schwarz, B. Günther, K. Smirnov, G. Gol'tsman, and B. Voronov, Proc. SPIE **5498**, 579 (2004).
[5] Y. B. Vachtomin, S. V. Antipov, S. N. Maslennikov, K. V. Smirnov, S. L. Polyakov, N. S. Kaurova, E. V. Grishina, B. M. Voronov, and G. N. Gol'tsman, Proceedings of the 15th International Symposium on Space Terahertz Technology, Northampton, MA, 27–29 May 2004 (unpublished), p. 236.
[6] B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc, Appl. Phys. Lett. **71**, 1567 (1997).
[7] E. L. Kollberg and K. S. Yngvesson, IEEE Trans. Microwave Theory Tech. **54**, 2077 (2006).
[8] See a review, B. S. Williams, Nat. Photonics **1**, 517 (2007).
[9] J. R. Gao, J. N. Hovenier, Z. Q. Yang, J. J. A. Baselmans, A. Baryshev, M. Hajenius, T. M. Klapwijk, A. J. L. Adam, T. O. Klaassen, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, Appl. Phys. Lett. **86**, 244104 (2005).
[10] A standard film provided by Moscow State Pedagogical University, Moscow, Russia.
[11] J. J. A. Baselmans, M. Hajenius, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Gol'tsman, Appl. Phys. Lett. **84**, 1958 (2004).
[12] M. Hajenius, P. Khosropanah, J. N. Hovenier, J. R. Gao, T. M. Klapwijk, S. Dhillon, S. Barbieri, P. Filloux, C. Sirtori, A. Ritchie, and H. E. Beere, Proceedings of the 17th International Symposium on Space Terahertz Technology, Paris, 10–12 May 2006 (unpublished), pp. 347–350.
[13] B. D. Jackson, G. de Lange, T. Zijlstra, M. Kroug, J. W. Kooi, J. A. Stern, and T. M. Klapwijk, IEEE Trans. Microwave Theory Tech. **54**, 547 (2006).
[14] The heat filter has an upper cutoff frequency of 5 THz and 0.32 dB loss at 4.3 THz and is made by QMC Ltd.
[15] The bandpass filter is centered at 4.3 THz with 0.35 dB loss and 15% 3 dB bandwidth and is made by Virginia Diodes, Inc.
[16] J. J. A. Baselmans, A. Baryshev, S. F. Reker, M. Hajenius, J. R. Gao, T. M. Klapwijk, Yu. Vachtomin, S. Maslennikov, S. Antipov, B. Voronov, and G. Gol'tsman, Appl. Phys. Lett. **86**, 163503 (2005).
[17] A. R. Kerr, IEEE Trans. Microwave Theory Tech. **47**, 325 (1999).