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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. © 2007 American Institute of Physics.
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Superconducting mixers¹ 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 lasers⁸ (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. 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 $T_{N,\text{rec}}$ 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 ($P_{\text{out}}-I$ 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 $P_{\text{out,hot/out,cold}}$ are comparable for both the air and vacuum setups, suggesting that this measurement method is not sensitive to the LO power fluctuations.

The $T_{N,\text{rec}}$ calculated from the fitted curves for both the vacuum and the air setup are also shown in Fig. 4. The lowest $T_{N,\text{rec}}$ 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 $T_{N,\text{rec}}$ 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 $P_{\text{out}}-I$ curve. Furthermore, with this method, the Y factor and thus the $T_{N,\text{rec}}$ are not influenced by the direct detection effect because the $P_{\text{out,hot}}$ and $P_{\text{out,cold}}$ 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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²<http://herschel.esac.esa.int/>

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¹⁴The 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.

¹⁵The 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.

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