Sensitivity of a hot electron bolometer heterodyne receiver at 4.3 THz

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***Abstract*— 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 super-THz frequencies. Also, a measurement method is introduced where the hot/cold response of the receiver is recorded at constant voltage bias of the mixer, while varying the LO power. We argue that this method provides an accurate measurement of the receiver noise temperature, which is not influenced by the LO power fluctuations and the direct detection effect. Moreover, our sensitivity data suggests that one can achieve a receiver noise temperature of 1420 K at the frequency of [OI] line (4.7 THz), which is scaled from the sensitivity at 4.3 THz with frequency.**

I. Introduction

Superconducting mixers play a key role in astrophysics at terahertz frequencies, where the early universe radiates strongly [1]. 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 these is the Heterodyne Instrument for Far-Infrared (HIFI) 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 future space missions, 2-6 THz high resolution spectroscopic surveys are highly desirable for astronomical and atmospheric studies. Our long-term research goal is to develop sensitive heterodyne receivers operating at the super-THz frequencies using NbN HEBs as mixers and quantum cascade lasers (QCLs) as local oscillators [3,4].

There are concerns about using HEB mixers at high frequencies. 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 [5]. Also there is a study showing that quantum noise can become a dominant factor as frequency increases [6].

The performance of HEB mixers at frequencies above 3 THz, namely super-THz frequencies, has not been measured extensively and only few studies have so far been reported [7-9]. This is mainly due to availability of suitable local oscillators. Although QCLs are very promising, they are still in developing stage. The high power consumption and the beam shape of these lasers make it difficult to use them as LO. The optical pumped FIR lasers are commonly used in laboratories but stabilizing these gas lasers at high frequencies is cumbersome and therefore the measured results suffer from LO power fluctuations. Besides, the losses in the air and the window of the cryostat are higher at these frequencies which add to the optical loss of the receiver.

Addressing some of these issues, considerable efforts have been put into stabilizing the output power of our gas laser at 4.3 THz. A new measurement setup is used where the hot/cold load calibration sources and the beam splitter are in vacuum and directly attached to the mixer cryostat. We report the measurement of a quasi-optical NbN HEB mixer at 4.3 THz using this vacuum setup and compare that with the outcome of usual setup in the air. We achieved low noise performance at this frequency, which is nearly a factor of 4 better than previously reported [7,8]. Furthermore, we introduce a characterization method that allows for the determination of the noise temperature accurately despite LO power fluctuations.

II. HEB Mixer

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 and 1200 K at 2.8 THz using the mixers with similar contacts [11,12]. 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. 8 and our previous results [9,11] using a design with a diameter of 15 µm, an expected upper cut-off 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.

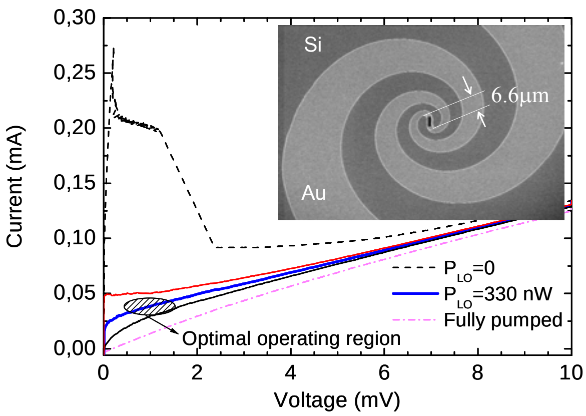

Fig. 1. A set of current-voltage curves of an NbN HEB mixer at 4.2 K at different LO power, where the optimum operating region is indicated. The inset shows a SEM micrograph of an HEB integrated with a spiral antenna with an inner diameter of 6.6 µm.

III. Heterodyne Measurement Setup

Our key results have been achieved in a quasi-optical setup, schematically shown in Fig. 2. The HEB is glued to the backside 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 anti-reflection 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 a narrow-bandpass filter [15] (both are at 4.2 K). All these components are in vacuum, therefore the radiation does not suffer from absorption due to air. 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 laser. It consists of a CO2 laser made by DEOS and a FIR ring laser developed by Max Planck Institute for Radio Astronomy in (MPIfR) Bonn, Germany. An earlier version of this ring laser has been flown successfully as a local oscillator on the Kuiper Airborne Observatory (KAO). The frequency of the pump laser is stabilized by piezoelectrically fine movement of the output mirror, controlled by an external optical feedback, which is a confocal Fabry-Perot etalon. The combination of the 9P34 line of the CO2 laser and methanol in the FIR ring laser emits 3 mW of power at 4.252 THz (λ ≈ 70.5 µm). The LO power, which is the 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 HDPE window on the HEB cryostat. The rest of the setup is kept unchanged. The latter is referred as the air setup.

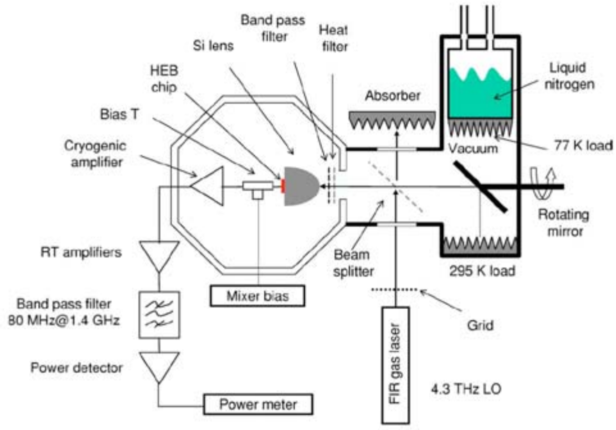

Fig. 2. Schematic picture of the measurement setup, where the hot/cold loads and the beam splitter are built in a vacuum unit, directly attached to the HEB cryostat. Switching between the hot and cold load is done by rotating a mirror.

IV. Heterodyne Measurement Results

Fig. 1 shows a typical set of current-voltage (*I-V*) curves of the HEB pumped from zero to 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 0.8-1.2 mV and the current is 35-45 µA.

To obtain the double sideband (DSB) receiver noise temperature ($T_{N,rec}$) we measured the receiver output power, $P_{out,hot}$ and $P_{out,cold}$, 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 $T_{N,rec}$ we use a standard Y-factor method, where $Y=P_{out,hot}/P_{out,cold}$, and the expression:

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

where $T_{eff,hot}$ and $T_{eff,cold}$ are the equivalent temperatures of a blackbody at 295 K and 77 K, respectively, which are 307 K and 118 K at 4.3 THz according to the Callen-Welton definition [17]. The calculated $T_{N,rec}$ as a function of bias voltage is also plotted in Fig. 3. The $T_{N,rec}$ shows a broad minimum in its voltage dependence around 0.8 mV, where the lowest $T_{N,rec}$ 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 $T_{N,rec}$-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 $P_{out,hot\ \&\ cold}$ data are noisy, resulting in considerable fluctuations in the $T_{N,rec}$ curve. By neglecting several exceptional high peaks, the lowest $T_{N,rec}$ 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 $T_{N,rec}$ obtained with two setups is due to 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 air and beamsplitter vibrations has a large impact on the total receiver stability. Obviously in a real astronomical instrument all measures are taken to ensure the stability of the LO. However, this is not the case in the laboratory environment. Here we introduce a measurement method that accurately determines the receiver noise temperature despite of LO power fluctuations.

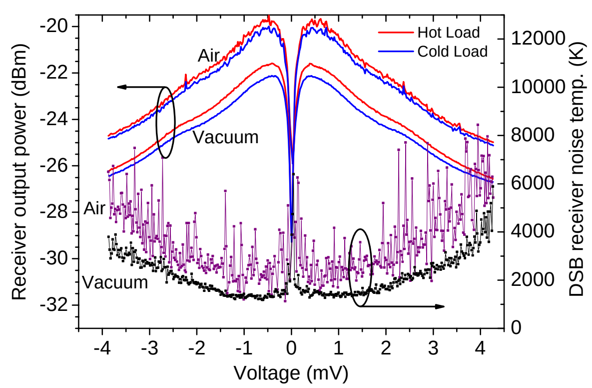

Fig. 3. Measured receiver output power (left axis) responding to the hot and cold load at optimal LO power as a function of bias voltage. One set of data are measured using hot/cold loads in the vacuum setup and another set using the air setup. The resulted DSB receiver noise temperatures are also plotted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

At a constant mixer voltage bias, we measure the mixer current and the receiver output power while changing the LO power from maximum to zero and vise versa. This will move the mixer bias point from fully pumped to unpumped curve vertically on the I-V curves on that constant voltage (see Fig. 1). The key plot is the receiver output power versus mixer current (P_{out}-I curve). Two such curves are recorded for every voltage bias, one for the hot load and the other for the cold load. Fig. 4 shows 10 such curves measured with the vacuum and the air setup at 5 different voltages. A computer control grid was used to systematically change the LO power. The presented data contains over 2000 point per curve which was collected while the grid was rotating 8 times.

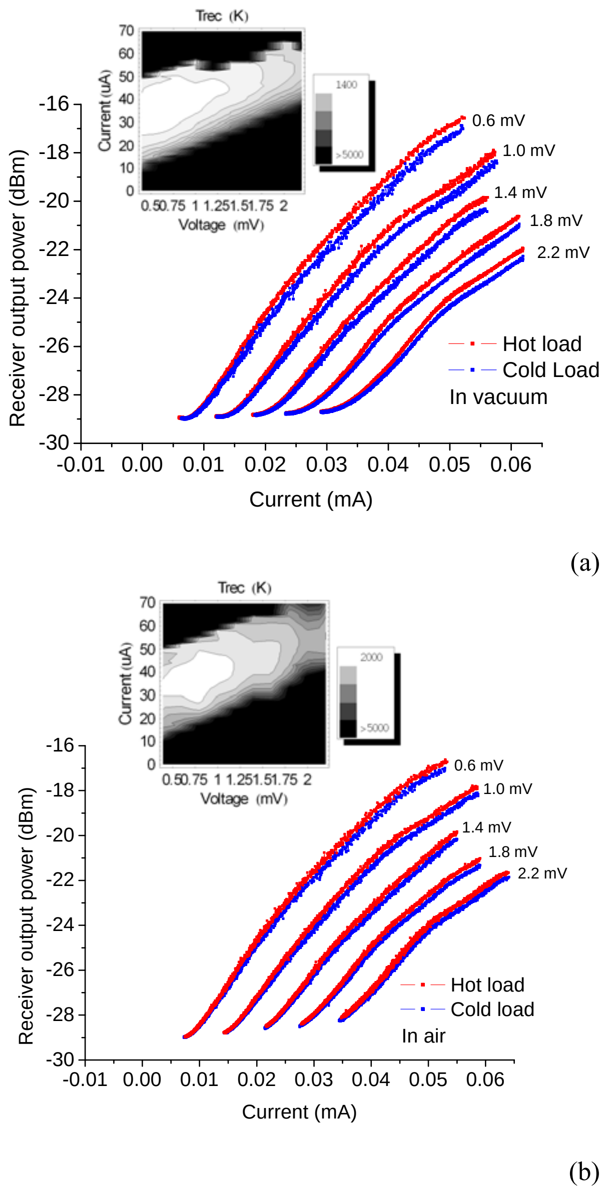

Fig. 4. Measured receiver output power responding to the hot and cold load while changing the LO power in (a) vacuum and (b) air setup at different mixer bias voltage as a function of bias current. The insets show the contour plots of the DSB receiver noise temperature, using the measured data between 0.4-2.2 mV bias voltages with 0.2 mV step.

The power difference between hot and cold load for every voltage determines the Y factor and the receiver noise temperature for that bias voltage and corresponding bias current.

A clear advantage of this method is that the accuracy of the measurement is not sensitive to LO power instability or drift. 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 $T_{N,rec}$ are not influenced by the direct detection effect if it is present because $P_{out,hot}$ and $P_{out,cold}$ are taken at exactly the same bias point, which is exactly the same bias voltage and bias current (and therefore exactly the same LO power). Comparison between the two methods can quantify the direct detection effect.

Fig. 5 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 $P_{out,hot\ \&\ cold}$ are comparable in both setups. The $T_{N,rec}$ calculated from the fitted curves for the vacuum and the air setup are also shown in Fig. 5. The lowest $T_{N,rec}$ are 1296 K in the vacuum 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.

SUMMARY

We have demonstrated a highly sensitive NbN HEB mixer at 4.3 THz by using 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, which is about 12 times the quantum noise ($h\nu/2k_B$). The value for the air setup is about 2000 K, which in comparison to our noise data at 2.84 THz or below (all measured in the air setup) 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 super-THz frequencies [5]. Such a HEB mixer in combination with THz QCLs offers a technology possibility to build highly sensitive solid-state heterodyne receivers at the super-THz frequencies for future space and airborne telescopes. 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 negligible contribution of the quantum noise [6]. However, to fully quantify the quantum noise contribution, more dedicated accurate measurements are required. Such an experiment can be the noise measurement of the same HEB mixer at several frequencies in our vacuum setup, which can reduce the uncertainties due to the window and the air loss at different frequencies.

ACKNOWLEDGMENT

The authors acknowledge P. van der Wal and J. Niels Hovenier for improving the gas laser, G. de Lange for providing the vacuum hot/cold unit, and H. Hoevers and W. Wild for their support. The work was partly supported by the EU through RadioNet and INTAS.

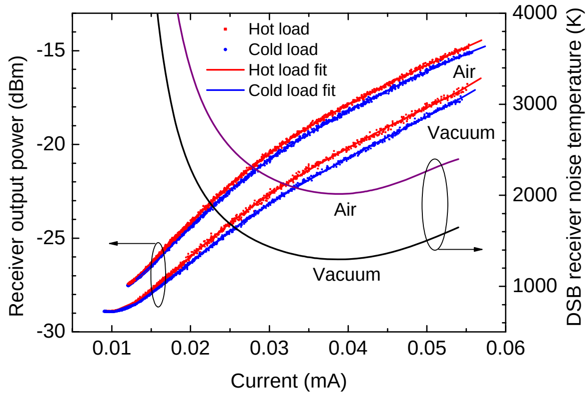

Fig. 5. Measured receiver output powers at the optimum bias voltage of 0.8 mV (dots) and the polynomial fit (lines), responding to hot and cold loads in the vacuum and air setup as a function of the current of the HEB, which is varied by changing the LO power (left axis). Also the resulted DSB receiver noise temperatures as a function of the current of the HEB (right axis).

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