Noise temperature of a 4.3 THz HEB receiver

Pourya Khosropanah*[a], Wouter M. Laauwen[a],
Jian-Rong Gao[bc], Merlijn Hajenius[bc], J. Niels Hovenier[c], Teun M. Klapwijk[c]

[a]SRON Netherlands Institute for Space Research, Landleven 12, 9747 AD, Groningen, the Netherlands;
[b]SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA, Utrecht, the Netherlands;
[c]Kavli Institute of NanoScience, Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ, Delft, the Netherlands

ABSTRACT

We have characterized a heterodyne receiver based on an NbN hot electron bolometer integrated with spiral antenna as mixer and an optically pumped FIR ring laser at 4.3 THz as local oscillator (LO). We succeeded in measuring the receiver output power, responding to the hot/cold load, as a function of bias voltage at optimum LO power. From the resulted receiver noise temperature versus the bias voltage, we found a DSB receiver noise temperature of 3500 K at a bath temperature of 4 K, which is a minimum average value. This is the highest sensitivity reported so far at frequencies above 4 THz.

Keywords: Hot electron bolometer, HEB, heterodyne receiver, THz, NbN.

1. INTRODUCTION

Hot electron bolometer mixers become the chosen technology for heterodyne receivers at frequencies far above 1 THz. They have been used for the two highest frequency bands in the Heterodyne Instrument for Far Infrared (HIFI) on the Herschel Space Observatory, covering a frequency range of 1410-1910 GHz [1]. For future space missions, 2-6 THz high resolution spectroscopic surveys are highly desirable for astronomical and atmospheric studies. However, 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 [2,3].

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 [4,5]. To separate the problems associated with either HEBs or QCLs, we use an optically pumped FIR laser, commonly used in the laboratory, as a local oscillator at 4.3 THz to characterize the HEB mixers.

2. HEB MIXER

The HEB used here is a 2 μm wide, 0.2 μm long and 5 nm thick NbN bridge on a high resistive Si substrate. We applied NbTiN/Au bilayer pads to contact the NbN bridge to a spiral antenna. Previously we have demonstrated excellent receiver sensitivities at 1.6, 2.5 and 2.8 THz using mixers with the same contact structures [5-8]. The HEB has a room temperature resistance of 80 Ω, a critical temperature of 10 K, and a critical current of 180 μA at 4.2 K. It is integrated with a spiral antenna, with a tight winding design close to the HEB. The antenna is circular polarized and has a very wide RF bandwidth allowing the detection of radiation up to 6 THz [9]. Fig. 1 shows an SEM micrograph of a similar HEB mixer. Details of the device fabrication and DC characterization can be found elsewhere [10].

*P.Khosropanah@sron.nl; phone +31 (0)50 363 3465; fax +31 (0)50 363 4022; sron.nl

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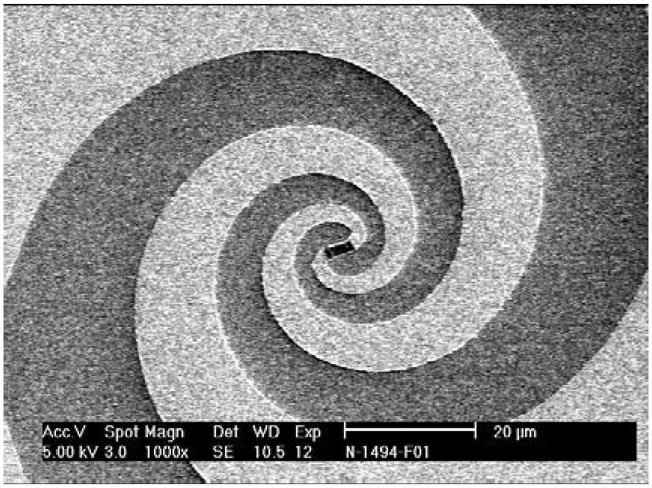

Fig. 1. SEM micrograph of a spiral antenna coupled NbN HEB

3. HETERODYNE MEASUREMENT SETUP

Fig. 2 shows a schematic view of the measurement setup. THz radiation is coupled to the mixer using a standard quasi-optical technique. The Si chip with the HEB is glued to the backside of an elliptical, anti-reflection coated Si lens. The coating on the lens is 14 µm thick Parylene C and optimized for 3.5 THz. Because of this, it improves the coupling efficiency only by about 10% at 4.3 THz in comparison to an uncoated one. The lens is placed in a metal mixer block, thermally anchored to the 4.2 K cold plate.

The local oscillator is a CO2 pumped FIR ring laser, shown in Fig. 3. The combination of the 9P34 line of the CO2 laser and methanol in the FIR laser gives about 3 mW of power at 4.3 THz ($\lambda \approx 70$ µm). The laser beam is collimated with a HDPE lens and is further reflected to the HEB cryostat by a 3.5 µm thick Mylar beam splitter. The blackbody radiation from a slab of Eccosorb at 295 K (hot load) and 77 K (cold load) is used as a calibration source. This signal is combined with the laser beam by the beam splitter and passes through a 1 mm thick HDPE window at room temperature and a metal mesh heat filter (QMC Ltd.), mounted on the 4 K shield of the HEB cryostat.

The IF signal, resulting from mixing the hot/cold load signal with the LO, is amplified first using a cryogenic low noise amplifier and then 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 71 dB and a noise temperature of 7 K.

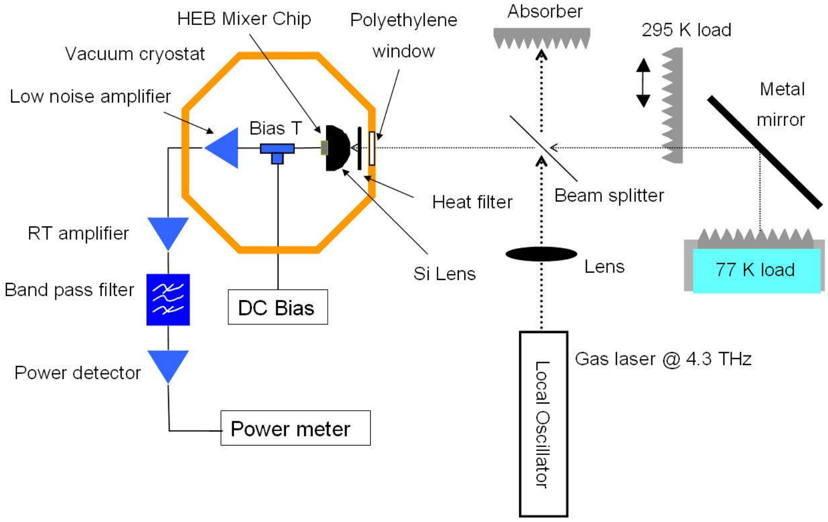

Fig. 2. Measurement setup

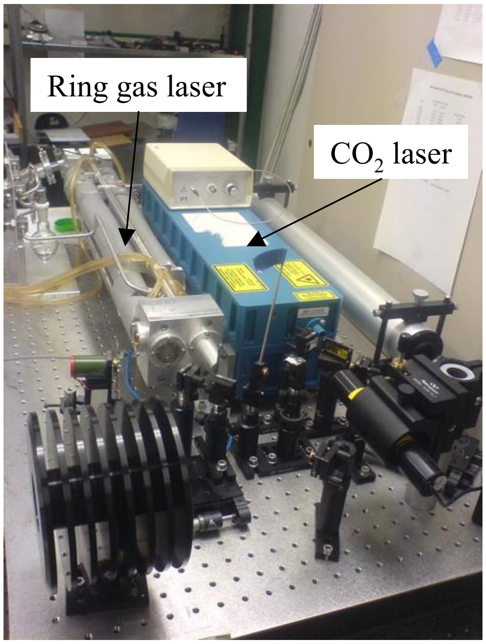

Fig. 3. Optically pumped FIR laser used as local oscillator. It consists of a CO_2 laser made by DEOS and a FIR ring laser developed by Max Planck Institute for Radio Astronomy in (MPIfR) Bonn, Germany. An earlier version of this ring laser has been flown successfully as a local oscillator on the Kuiper Airborne Observatory (KAO).

4. HETERODYNE MEASUREMENT RESULTS

Fig. 4 shows a set of current-voltage curves of the HEB for different absorbed LO power levels. The optimum operating region, which gives the highest sensitivity is around 30-35 μA and 0.5-1.0 mV bias point. The optimum absorbed LO power in the HEB is about 230 nW, determined by using the isothermal technique [11].

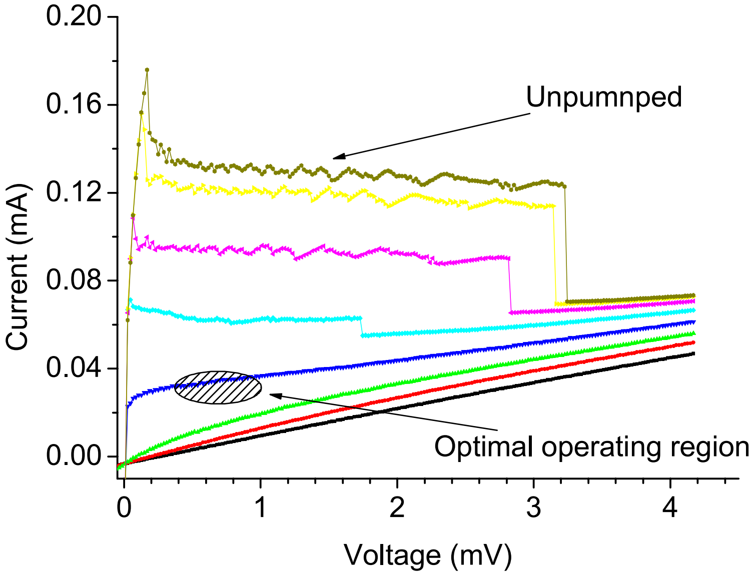

Fig. 4. Current-voltage curves of the HEB mixer for different pumping level, taken at 4.2 K. The optimum operating point is around 0.5-1 mV and 30-35 μA where the absorbed LO power in HEB is about 230 nW.

To obtain the receiver noise temperature we apply a standard Y-factor method, taking the ratio of the receiver output power responding to the hot/cold load. It is worthwhile to note that the equivalent temperature of a blackbody at such high frequencies is substantially different from its physical temperature. Using the Callen-Welton definition [12], at 4.3 THz the equivalent temperatures of a blackbody at 77 and 295 K are 118 and 307 K respectively.

Fig. 5 shows the measured receiver output power, responding to the hot/cold load, versus the bias voltage at optimum LO power. Fig. 6 gives the double sideband (DSB) receiver noise temperature, calculated using the data plotted in figure 5. If we focus on the noise temperature curves in Fig. 6, it is clear that the data is noisy. We attribute the noise to the fluctuations in the output power of the ring laser. It is known that the lasing in the cavity of a gas laser is sensitive to the fluctuations of temperature and gas pressure. Thus, stabilizing the gas lasers in general is cumbersome and therefore, it is difficult to record the IF output power versus bias voltage at constant LO. We succeeded in measuring such curves, suggesting that we have achieved reasonable power stability of the gas laser. However, the power is still not stable enough to accurately determine the Y-factor without averaging.

In our experiment we observed correlations between the fluctuations in the IF output power and those in the current of the HEB. The latter reflects the LO power fluctuations. To quantify the receiver sensitivity, we take the average value of measured Y factor and the receiver noise temperature at the optimum operating point. We found the highest Y-factor of 0.22 dB around 0.8 mV. This corresponds to a DSB receiver noise temperature of 3500 K in figure 6. To the best of our knowledge, this is the first published data, which shows the noise temperature of a HEB as a function of bias voltage using a gas laser as LO at the super-THz frequencies and the value of 3500 K is the highest sensitivity reported beyond 4 THz in the literature. Previously the best result reported was 4700 K at 4.3 THz [13].

We find the single sideband mixer conversion loss to be about 13 dB. In our case the total optical loss is estimated to be 5-6 dB in the optical path from the hot/cold load to the HEB, from which 1.7 dB is due to the cryostat window and 1 dB due to the air (at 40% relative humidity the loss in the air at 4.3 THz is about 4 dB/m). This suggests that the receiver sensitivity can be improved by reducing these losses.

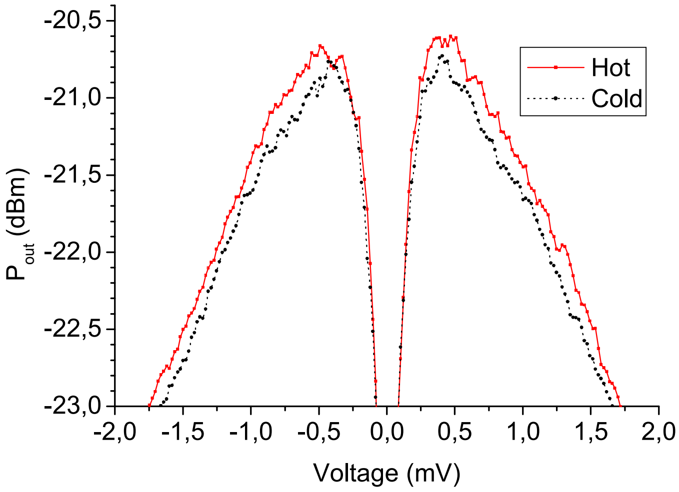

Fig. 5. Receiver output power responding to the hot (295 K) and cold (77 K) load as a function of bias voltage at optimum LO power. The difference in P_{out} between the two curves determines the receiver noise temperature. The fluctuations in the measured output power are caused by LO power fluctuations.

5. SUMMARY

In summary, we succeeded in characterizing a NbN HEB mixer at 4.3 THz using an optically pumped FIR ring laser as local oscillator. We measured the receiver output power, responding to hot/cold load, as a function of bias voltage of the HEB, which allows determining the receiver noise temperature at different bias voltages. The lowest averaged receiver noise temperature is 3500 K, which is uncorrected for any optical loss. Our experiment suggests that it is challenging to obtain accurate sensitivity data due to the power fluctuations of the gas laser at the super-THz frequencies. We believe that THz quantum cascade lasers can overcome this issue and have potential to replace currently used gas lasers.

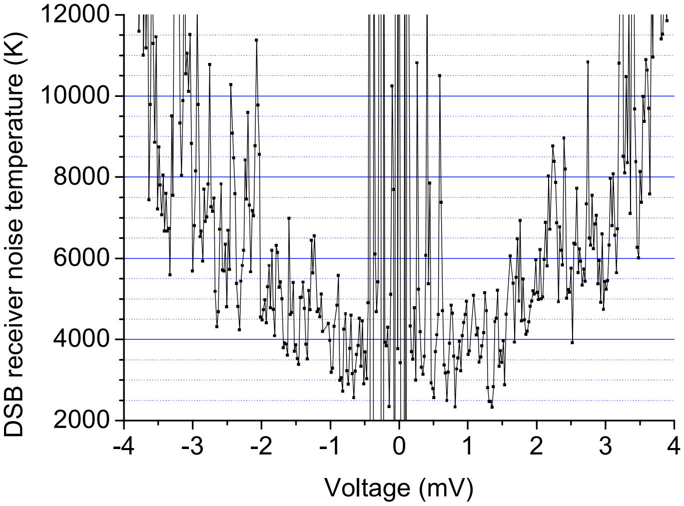

Fig. 6. Double side band (DSB) receiver noise temperature at optimum pumping level as a function of HEB bias voltage. The minimum receiver noise temperature is 3500 K, averaged and taken at 0.8 mV and 30 μA bias point. The fluctuations in the measured curve are caused by LO power fluctuations. The peaks near the zero voltage are due to unstable biasing area of the HEB and should be ignored. The LO frequency is 4.3 THz.

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