IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 5EB03 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)
The published version of this manuscript appeared in *IEEE Transactions on Applied Superconductivity* **19**, No. 3, Part 1, 274-277 (2009)

# Analysis of NbN Hot Electron Bolometer Receiver Noise Temperatures above 2 THz with a Quantum Noise Model

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***Abstract*— This paper summarizes our receiver noise temperature data of NbN HEB mixers obtained at a number of local oscillator frequencies between 1.9 to 4.3 THz in order to verify the role of quantum noise. The experimental data show that the receiver noise temperature increases roughly linearly with frequency. At 4.3 THz, we measured a receiver noise temperature of 1300 K, which is about 6 times ($hf/k_B$). The noise data at different frequencies are compared to a prediction of a noise model including the contribution of quantum noise and making use of a hot-spot model for mixing. We draw a preliminary conclusion that at 4.3 THz roughly 30% of the receiver noise temperature can be ascribed to the quantum noise. However, more dedicated measurements are required in order to further support the quantum noise model for HEB mixers.**

*Index Terms*—**heterodyne receiver, superconducting hot electron bolometer mixer, THz mixer, terahertz, quantum noise.**

## I. Introduction

Superconducting NbN hot electron bolometer (HEB) mixers are so far the most sensitive detectors for heterodyne spectroscopy at frequencies above 1.5 THz. Today HEB mixers are considered to be a rather mature technology when operated below 2 THz as they are used in the HIFI instrument on the Herschel space observatory [1]. Future space instruments will move to higher frequencies, e.g. a range between 2-6 THz, which holds crucial information on astronomical objects as well as on the chemical composition of Earth's atmosphere.

However, the noise contribution of a HEB mixer at such high frequencies is not well understood. It has been suggested that the quantum noise (QN) becomes increasingly important as the frequency goes up and that it can play a dominant role at frequencies beyond 3 THz [2].

Reports on terahertz HEB receivers often state the measured DSB receiver noise temperature ($T_{rec}^{DSB}$) as a factor times the minimum *system* single side band (SSB) noise temperature due to quantum noise, which is $hf/k_B$ [3]. A recent measurement of an NbN HEB mixer has shown a $T_{rec}^{DSB}$ of 1300 K at 4.3 THz, whose relative value in units of $hf/k_B$ is the lowest ever measured for any HEB mixers reported in the literature. This result renews the interest of the contribution of quantum noise. Here we summarize our noise temperature results at several frequencies between 1.9 and 4.3 THz. The noise data after corrections of known optical losses are compared to predictions of a noise model that includes the contribution of QN and is essentially based on a hotspot model for the mixing process. We also attempt to quantify the contribution of the QN to the total noise.

## II. HEB Mixer and Heterodyne Measurement Setup

A single HEB mixer was used for the measurements at 2.8, 3.4 and 4.3 THz (Fig. 1). It consists of a 2 μm wide, 0.2 μm long, and 5.5 nm thick NbN bridge on a highly resistive Si substrate, integrated with spiral antenna with expected upper cut-off frequency of about 6 THz [4]. The details of the device fabrication process are discussed in Ref. [5]. Although other mixers were used at 1.9 and 2.5 THz, they are all similar and therefore their performance is comparable at these frequencies. More details on the parameters of these devices can be found in Ref. [5-10].

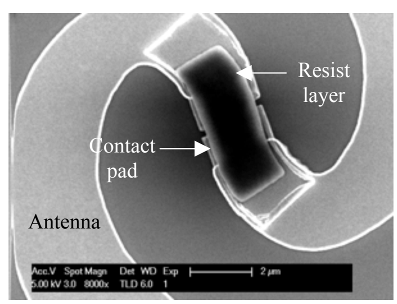


Fig. 1. Scanning Electron Microscopy (SEM) picture of a spiral antenna coupled NbN HEB mixer.

The HEB is incorporated in a quasi-optical receiver, schematically shown in Fig. 2. The mixer chip is glued to the backside of an elliptical Si lens and mounted in a 4.2 K L-He cryostat. The lens is not coated except for the 2.8 and 4.3 THz

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measurements, where a layer of Parylene C is used to act as an anti-reflection coating at these particular LO frequencies. The radiation from the hot/cold (295/77 K) load is combined with that from the LO by a 3 µm Mylar beam splitter, passes through the cryostat window (1 mm HDPE), a heat filter [11] and then a narrow-bandpass filter (both are at 4.2 K). For 2.5 and 2.8 THz no narrow-bandpass filters are used. At 4.3 THz we also performed a measurement using a vacuum unit that houses the hot/cold calibration loads and a beam splitter [10]. Since this unit is directly attached to the HEB cryostat there is no need for an optical window.

The mixer output at intermediate frequency (IF) goes through an isolator, 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 about 80 dB and a noise temperature of 7 K. At 1.9, 2.5 and 4.3 THz an optically pumped FIR laser is employed as LO. At 2.8 and 3.5 THz, quantum cascade lasers are used [8,9].

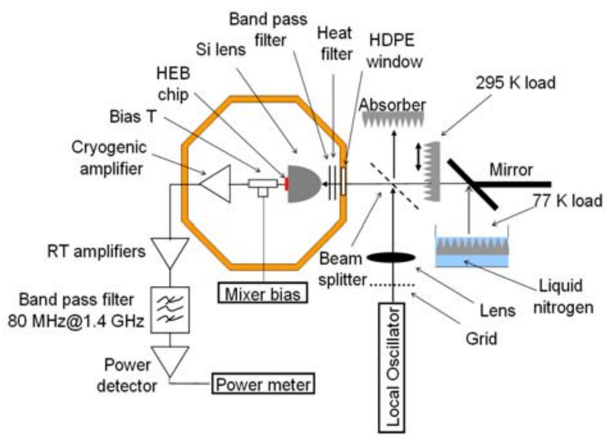


Fig. 2. Schematic picture of the heterodyne measurement setup. There is an isolator between the HEB mixer and the low noise amplifier, which is not shown. The LO power is regulated by a rotating wire grid.

## III. Heterodyne Measurement Results

Fig. 3 shows a typical set of current-voltage (*I-V*) curves of a HEB pumped from zero to fully pumped power level of a local oscillator. At the indicated optimum operating region, the sensitivity is within 5% of the best value.

To obtain $T_{rec}^{DSB}$ we measured the receiver output power responding to the hot and cold loads ($P_{rec}^{hot\&cold}$) under the optimum LO power and bias. To derive $T_{rec}^{DSB}$ we use the standard *Y*-factor method,

$$T_{rec}^{DSB} = \frac{T_{CW}(295) - YT_{CW}(77)}{Y-1} \qquad (1)$$

where $Y = P_{rec}^{hot} / P_{rec}^{cold}$, and $T_{CW}$ (295) and $T_{CW}$ (77) are the equivalent temperatures of a blackbody according to the Callen-Welton definition [3] at 295 K and 77 K, respectively. In the 3.5 and 4.3 THz measurements we employed a particularly accurate version of the *Y*-factor method that relies on measurements of the output power of the mixer as a function of bias current by changing the LO power [9,10]. The other key parameter is the so-called *U*-factor, which is the ratio between the receiver output power when the HEB mixer is at the operating point (with a hot load in front), and in the superconducting state (no bias and no LO heating). Since there is an isolator between the HEB mixer and the low noise amplifier, inserting a superconducting short at the IF chain input does not change the noise temperature or gain of the IF amplifier and the *U*-factor can be written as:

$$U = \frac{T_{MXR}^{out} + T_{IF}}{T_{bath} + T_{IF}} = \frac{T_{CW}(295) + T_{rec}^{DSB}}{T_{bath} + T_{IF}} \times \frac{1}{L_{DSB}} \qquad (2)$$

where $T_{bath}$ is the bath temperature (4.2 K), $T_{IF}$ is the noise temperature of the IF chain and $L_{DSB}$ is the DSB receiver conversion loss including the optical losses. By measuring the *U*-factor and using Eq. (2) we can calculate the receiver conversion loss. Deducting the optical loss from this value yields the DSB conversion loss of the mixer ($L_{MXR}^{DSB}$).

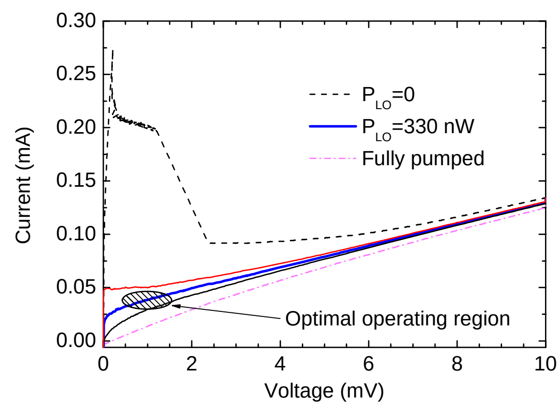


Fig. 3. A set of current-voltage curves of an HEB mixer at 4.2 K at different LO power, where the optimal operating region is indicated.

Table 1 summarizes our experimental results at several frequencies between 1.9 and 4.3 THz. At 1.9, 2.5 and 3.5 THz, because of using an uncoated Si lens, the optical losses are relatively higher. $L_{300}$ and $L_4$ are the optical losses in the warm (room temperature) optics including the loss in the air and at liquid helium temperature, respectively. The difference in the measured noise temperature with air and vacuum setups at 4.3 THz is due to additional optical losses in the air and the cryostat window.

## IV. Quantum Noise in HEB Mixers

We now investigate whether part of the measured noise temperature summarized in Table 1 can be ascribed to QN. To do so, we will make use of the QN model for a HEB mixer in Ref. [2]. An ideal broadband mixer (IBBM) has a $T_{rec}^{DSB}$ of 0 K, when QN is taken into account. In Ref. [2] it was shown that this applies to an ideal HEB mixer. It has also been shown that an ideal SIS mixer has zero DSB receiver noise temperature [12]. An ideal coherent amplifier, on the other hand, has a minimum receiver noise temperature due to QN of $hf/2k_B$ [13]. Note that quantum noise of $hf/2k_B$ is generated in both sidebands at the input of the ideal HEB mixer. Losses (*L*) between the receiver input and the "ideal mixer" means that the equivalent QN at the receiver input has to be multiplied by

$L$. We will give an expression for this below (Eq. (4)). For details see Ref. [2].

TABLE 1 SUMMARY OF MEASURED RESULTS

| **Frequency (THz)** | 1.9 | 2.5 | 2.8 | 3.5 | 4.3 | 4.3 |
|---|---|---|---|---|---|---|
| **Setup type** | Air | Air | Air | Air | Air | Vacuum |
| $T_{rec}^{DSB}$ (K) | 1250 | 1230 | 1150 | 2100 | 2000 | 1300 |
| $L_{300}$ (dB) | 1.7 | 1.5 | 1.5 | 2.3 | 2 | 0.4 |
| $L_4$ (dB) | 2.7 | 2.5 | 1.5 | 2.7 | 2.1 | 2.1 |
| $L_{total}^{opt}$ (dB) | 4.4 | 4 | 3 | 5 | 4.1 | 2.5 |
| $Y$ (dB) | 0.64 | 0.63 | 0.65 | 0.37 | 0.36 | 0.52 |
| $U$ (dB) | 8 | 7.5 | 8 | 8 | 8 | 8 |
| $L_{MXR}^{DSB}$ (dB) | 9 | 9.8 | 10 | 10.3 | 11 | 11.2 |
| $T'$ (K) | 346 | 373 | 444 | 523 | 617 | 627 |

All parameters are defined in the text.

A major point in Ref. [2] is that all present HEB mixers are not ideal broadband mixers, and thus the QN is expected to be enhanced by a factor $\beta$ that is of the order of 2-4. The basic explanation for this phenomenon is that an HEB mixer is not a uniform bolometer, but instead can be regarded as being composed of two superconducting regions next to the contacts, and a "hotspot" region in between, where the superconductor has gone normal[1]. The mixing function is confined to the hotspot. Effectively then, a real HEB mixer consists of an ideal mixer connected to the optics output through a lossy superconducting strip. The loss of the superconducting strip increases the receiver noise temperature and also increases the conversion loss of the HEB mixer, both by the same factor $\beta$. The quantitative treatment of this model in [2] assumes a distributed HEB broken up into many parts. The analysis then becomes more complicated, but the basic conclusions from the analysis support the above qualitative picture.

The DSB receiver noise temperature of a HEB mixer was derived to be (compare with Eq. (39) in Ref. [2][2])

$$T_{rec}^{DSB} = \left(L_{300} - 1\right)\cdot T_{300} + L_{300}\cdot\left(L_4 - 1\right)\cdot T_4 + \\ + L_{300}\cdot L_4\cdot L_{MXR}^{DSB}\cdot\left(T_{CL,MXR}^{out} + T_{IF}\right) + T_{QN}^{DSB} \qquad (3)$$

where (see Eq. (40) in Ref. [2])

$$T_{QN}^{DSB} = \frac{hf}{2k_B}\left(L_{300}\cdot L_4\cdot\beta - 1\right) \qquad (4)$$

[1] An alternative more recent model by Barends et al can also be used [14]. It is expected to result in similar values for $\beta$ as those in [2].

[2] Eq. (39) in Ref. [2] has a typographical error: The $L_{300}$ factor is missing in the second term. We also use the notation $\beta/2G_{IBBM} \equiv L_{MXR}^{DSB}$ in the present paper. There were no optical losses at 77 K in the present experiments.

is the QN term, which depends linearly on frequency as expected. The classical noise term is based on standard HEB models. The remaining parameters in these equations have been defined in the text above, or will be defined shortly. Experimental values can be obtained for all the parameters in Eq. (3) using Table 1 except for $T_{CL,MXR}^{out}$ (classical output noise generated at the IF by the bolometer [2]) and $\beta$.

It is very challenging to verify the QN theory through measurements. One fundamental difficulty is that so few measurements exist at frequencies high enough that the QN term is a substantial fraction of the total measured noise temperature. Another difficulty is that all the measurements including the estimation of the optical losses must be performed with great accuracy, as it becomes clear in the following discussion. Here we apply a new method of analysis for accomplishing this goal. Using the measured data in Table 1, we calculate the following quantity,

$$T' = L_{MXR}^{DSB}\cdot T_{CL,MXR}^{out} + T_{QN}^{DSB} / L_{total}^{opt} \qquad (5)$$

$T'$ is given in the last row in Table 1. The first term in Eq. (5) represents the intrinsic DSB mixer noise temperature at the input of a HEB mixer due to classical noise sources. In order to estimate the QN term, we must know the value of $\beta$. This can be obtained by using the $T'$ data. We first make a guess of the $\beta$ values and calculate $T_{QN}^{DSB} / L_{total}^{opt}$ for different $\beta$. By subtracting this contribution from $T'$, we obtain a set of data for $T_{CL,MXR} = L_{MXR}^{DSB}\cdot T_{CL,MXR}^{out}$ and plot the classical mixer output noise $T_{CL,MXR}^{out} = T_{CL,MXR} / L_{CL,MXR}^{DSB}$ at different frequencies in Fig. 4. Note that this calculation only makes use of measured parameters except for $\beta$, plus the assumption that $T_{rec}^{DSB}$ can be written on the form given in Eq. (3), and that the QN term can be written on the form given in Eq. (4). Since the classical output noise term should be independent of frequency, we can find an appropriate $\beta$ value by taking the frequency independent curve in Fig. 4. This corresponds to the curve for $\beta$ = 2 or 3. We chose these two values because the output noise data are flat (independent of frequency) and also their values are reasonable compared to what we expect for the classical noise sources (typically 50 K).

The QN contribution referred to the receiver input can now be calculated by Eq. (4) using $\beta$ = 2 or 3. We plot this for these two $\beta$ values, together with two other higher $\beta$ values in Fig. 5, again referred to the HEB mixer input ($T_{QN,MXR} = T_{QN}^{DSB} / L_{total}^{opt}$). From Fig. 5 we can see that at 4.3 THz the QN contribution at the HEB mixer input is 148-251 K ($\beta$ = 2 or 3). If we refer this to the input of the receiver in the vacuum setup instead, we find 263-447 K, roughly 20-34% of the measured $T_{rec}^{DSB}$ of 1300 K.

We want to comment on one further aspect of our results: We could take a $\beta$ as high as 5 based on the flatness of the output noise data in Fig. 4. Then, the contribution of QN to the $T_{rec}^{DSB}$ becomes more significant and nearly 50%. However, the absolute values of the output noise data are surprisingly low (~11 K). This is much lower than what typically estimated for HEB mixers.

The frequency dependence of the noise temperature data in [4] may be fitted to our Eq. (3) with an approximate value of $\beta$ = 4. We note, however, that the measured data in [4] (larger noise temperatures by factors of up to more than three) require larger corrections for optical losses to be known, compared with the data in the present paper. This makes it much more difficult to accurately determine the QN component.

The authors of Ref. [4] ascribe the increased receiver noise temperature at higher frequencies to frequency-dependent coupling losses between antenna and bolometer due to inhomogeneous current distribution caused by skin effect in the bolometer. In our QN analysis we intentionally do not take this into account for two reasons. First, we are uncertain about the presence of inhomogeneous current in the bolometer strip. Electromagnetic simulations using HFSS for the same geometry as our bolometer including gold contacts show a homogeneous current distribution up to 5 THz. The details of the simulation will be given elsewhere [15]. Second, there is lack of direct experimental data to confirm the role of the skin effect. In Ref. [4] a comparison between the experimental data and the model has been made. However, in this analysis the authors have to make additional hypotheses to explain the effect of bolometer size and the contact resistance on much higher receiver noise temperatures measured using narrow bolometers.

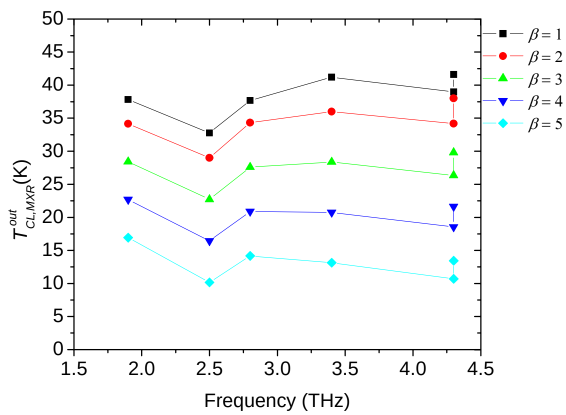


Fig. 4. Calculated classical mixer output noise $T^{out}_{CL,MXR}$ for $\beta$ = 1 to 5.

## V. Conclusions

The receiver noise temperatures of NbN HEB devices of comparable quality and the conversion losses have been measured for a wide THz frequency range. Such data should allow us to separate the quantum noise term (that depends linearly on frequency) from the total measured noise temperature. By estimating the $\beta$ parameter in the model, we find that at 4.3 THz the quantum noise contributes to roughly 30% of measured DSB receiver noise temperature. However, due to uncertainty in the estimation of optical loss at different frequencies and the use of different HEBs, it is hard to determine the $\beta$ parameter accurately and thus difficult to quantify the contribution of the quantum noise. To confirm the model, a new measurement method is proposed in order to obtain more accurate noise data. New measurements should be performed in a single HEB at all frequencies and all in the vacuum setup. The latter will minimize the optical losses, and the uncertainty in estimating them.

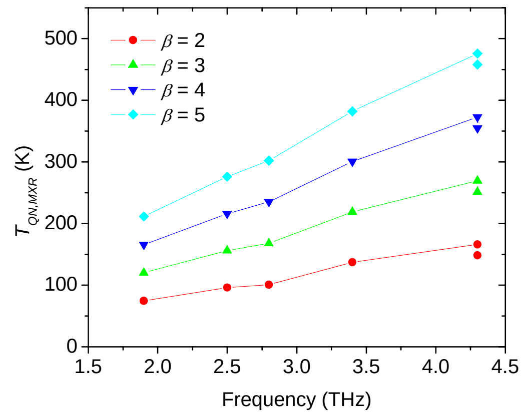


Fig. 5. Predicted quantum noise contribution, referred to the HEB mixer input versus frequency for $\beta$ = 2 to 5. $T_{QN,MXR} = T^{DSB}_{QN} / L^{opt}_{total}$.

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