The Role of Quantum Noise in Terahertz Receivers

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Abstract: We have revised and considerably extended our paper on quantum noise at the 13th ISSTT. In the present paper we first review general quantum mechanical limits on the sensitivity of heterodyne receivers. We introduce the ideal broad band mixer (IBBM), which has a receiver noise temperature of zero Kelvin. Based on the hot-spot model of a real HEB mixer, we model it as an IBBM in series with a passive resistance. An expression for the HEB receiver noise temperature, including optical input loss is then derived. We find that the predicted DSB receiver noise temperature agrees well with three sets of measured data. The result suggests that quantum noise and classical HEB noise contribute about equally at low terahertz frequencies while at higher terahertz frequencies quantum noise dominates.

1. INTRODUCTION

Hot Electron Bolometer (HEB) heterodyne detectors for the THz frequency range use devices fabricated from thin films of low temperature superconductors, such as NbN. They have recently given rise to a radical re-evaluation of our ideas of this frequency range, which has traditionally been regarded as one in which no very sensitive heterodyne detectors exist. The sensitivity of HEB heterodyne detectors ('mixers') has become so good, i.e. the receiver noise temperature has become so low, in fact, that it is worthwhile to discuss if Quantum Noise will influence the receiver noise temperature of THz HEB receivers. Our theoretical analysis in this paper indicates that at frequencies of about 2 THz quantum noise is equal to the "classical" HEB noise, while at higher THz frequencies, quantum noise represents a dominant fraction of the total noise of HEB mixer receivers. We present a detailed analysis of quantum noise in HEB receivers. The analysis represents a substantial extension and revision of our first, preliminary paper on this subject given at the 13th ISSTT [1]. We introduce the **I**deal **B**road **B**and **M**ixer (IBBM), which shows no other noise than quantum noise (QN). Our basic assumption in the analysis is that the IBBM model applies to an IDEAL HEB heterodyne detector. We then continue to use the IBBM concept to discuss a more realistic HEB "hotspot" model, and derive an expression for the expected receiver noise temperature of HEB mixer receivers as a function of frequency. Finally, we show that available experimental data of receiver noise temperature at frequencies up to 5.3 THz can be fitted to this expression with good agreement. A considerably expanded and more detailed version of this paper will be submitted to a journal shortly [2].

2. QUANTUM NOISE AND THE IDEAL BROADBAND MIXER

It is important to emphasize that "Quantum Noise" is a concept, which fundamentally expresses the limit in our ability to perform a measurement of an electromagnetic field, imposed by the quantum mechanical nature of this field. Callen and Welton [3] showed in their generalization of the Nyquist theorem that fluctuations (noise) are intimately connected to the process of power dissipation. They calculated the average energy density of an electromagnetic field, in equilibrium with an environment at a temperature, T_0. They obtained two terms, one of which yields the Planck blackbody radiation formula. This term, when applied to a single mode transmission line case, produces the familiar Nyquist noise expression. The second term yields an energy of $hf/2$, which represents the vacuum (zero-point) fluctuations of the field. Formally we might find the power emitted due to the second term into a single mode transmission line in the same way as done by Nyquist. The total power radiated into a single mode in a band B at frequency f then becomes:

$$P_{CW}(T_0) = \frac{hfB}{\exp\left(\frac{hf}{kT_0}\right) - 1} + \frac{hfB}{2} = P_{Planck}(T_0) + \frac{hfB}{2} \tag{1}$$

The first term in this expression is the single-mode form of the Planck law. The thermal "Planck" noise power term rapidly goes to zero for frequencies higher than kT/h, and when this happens, the second term in Eq. (1) begins to dominate.

How are we to interpret the second term in (1)? It cannot represent exchangeable power, since it is impossible to extract power from the vacuum fluctuations. However, if we imagine an electromagnetic field with a power given by (1) at the input of a heterodyne detector with large photon number gain, it can be shown that *the minimum noise fluctuations at the output* of an ideal such detector can be regarded as having been produced by the second term in (1), which we will call the "quantum noise" term [4-9]. A general heterodyne detector generates an output at a very low frequency (the "IF") by down-converting radiation near the local oscillator. Using quantum mechanics Marcuse [4], and later Haus [6], rigorously analyzed such a detector (an ideal photo-detector mixer), with no frequency dependence of its properties close to the local oscillator frequency. In microwave terminology we would call this a "*broadband mixer*", or '*BBM*', i.e. a mixer with equal response in both sidebands. We will initially use this photo-detector model to discuss heterodyne detectors and later show that it applies to ideal HEB mixers. Haus chose a balanced mixer, which has the advantage that the fluctuations in LO power cancel to first order at the IF output. The noise temperature of a balanced mixer should be the same as that of a single ended mixer if the mixer devices are equivalent.

The result of Haus' analysis is that the fluctuations in the IF output with no external signal present is equivalent to a signal power corresponding to an expectation value for the photon number $\langle n_s \rangle$ per observation time, of one photon. Since the observation time τ is the inverse of the bandwidth, B, of the system then $P_s \cdot \tau = \langle n_s \rangle hf = hf$, and the equivalent noise power becomes hfB. This defines the minimum noise power one can have, the quantum noise. We thus have the following important conclusion:

The minimum output noise of an IBBM SYSTEM corresponds to an input noise power of *hfB* (2)

Based on Eq. (1) we see that the sum of the minimum input noise powers for the signal and the image which we can ascribe to the input source is also hfB. Since the vacuum input fluctuations already explain the output fluctuations, *there is no extra contribution required from the IBBM itself to satisfy the minimum system noise level. A second important conclusion is then*

The noise power added by an IBBM is ZERO (3)

The detailed analysis in Haus shows that the output fluctuations arise due to the properties of the commutator of the signal and image field operators, respectively. As Haus notes, "one may interpret this result as fluctuations induced by the signal (and image) zero-point fluctuations in the charge (or current) generated by the local oscillator photons."

In the ideal model for an HEB mixer, the IF current can be given a completely equivalent expression [9] to that for the photodetector case: $I_{IF} \propto \sqrt{P_s P_{LO}}$. Formally, the two types of mixers produce output currents which are equivalent functions of the input photon fluxes, and we can thus directly apply the results of the analysis in Haus to an (ideal) HEB mixer:

The noise power added by an Ideal Broadband HEB mixer is ZERO (4)

The same minimum noise output power as in Eq. (2) was also derived for a general linear amplifier by Caves [5] and many others. Wengler and Woody [7] showed that an optimum double sideband (DSB) SIS mixer operates in a manner similar to an ideal photodetector, and approaches the same minimum output noise power. SIS mixers require additional quantum considerations of the quantized charge in the device [9], which turn out in the ideal case to result in zero added noise, as in the photo-detector mixer case discussed above. Reference [8] stated the same conclusion as in (2), (3) and (4); that reference built on earlier papers analyzing quantum noise primarily in SIS mixers. Reference [7] concludes *that the only remaining noise source in an ideal SIS mixer is the process of "photon absorption".* This reference added to previous analyses of SIS mixers a fully quantized model of the external circuit to which the mixer input was connected. The above references thus are unanimous in reaching the same conclusion as the one we stated in Eqs. (2), (3) and (4). We see that the limiting *total* noise power is the same for *any* coherent, phase-insensitive, receiver, whether an amplifier or a mixer, as expected on general quantum-mechanical grounds.

An ideal broadband receiver will consist of an IBBM with large photon number conversion gain, an IF amplifier, and a power detector, as shown in Figure 1. Due to the relatively low IF frequency (a few GHz), a THz mixer will always have a large photon number gain. Also, noise directly emitted at the IF (see below for details) should show negligible quantum effects due to the low IF frequency. Apart from quantum noise, a real mixer may show other (classical) noise sources, $T_{CL,MIX}^{out}$. Also, the IF amplifier has a noise temperature, T_{IF}. We will disregard these classical noise sources for the moment, and discuss them later. This is done since we are first trying to identify the absolute minimum value which is allowed by quantum mechanics for the noise temperature. We further want to define the <u>*system noise temperature*</u> and the <u>*receiver noise temperature*</u> of the circuit in Figure 1. In doing so we use the convention that noise temperature is proportional to noise power [8], through

$$P_n = kT_nB \tag{5}$$

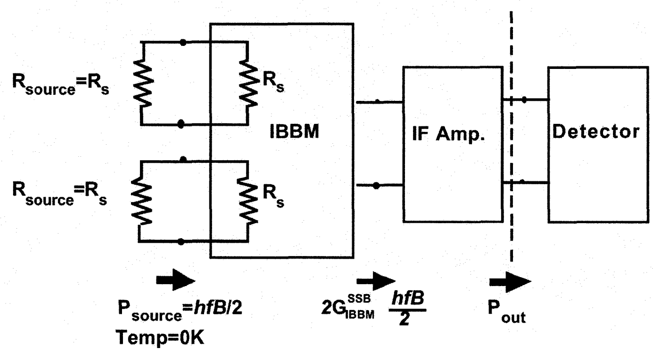


Figure 1. An IBBM receiver.

The system noise temperature is derived from (5) based on the noise power output of the entire system, including both the receiver and the input sources. If we can neglect all other noise sources except the quantum noise, we find from Fig.1 that

$$T_{sys,SSB} = \frac{hf}{k} \tag{6}$$

This is the quantum-limit for the *system* noise temperature of a broadband mixer receiver when performing narrow-band measurements (within a single sideband) [8]. If we instead perform broadband (continuum) measurements, the desired signal will be twice as large, and the ideal system noise temperature will be

$$T_{sys,DSB} = \frac{hf}{2k} \tag{7}$$

When calculating the *receiver* noise temperature, we will follow the usual convention [8] and subtract the noise power of the input source(s) from the total system noise output. For the ideal receiver in Fig. 1, we have (for both types of measurements)

$$T_{rec,DSB} = 0 \tag{8}$$

The results (6), (7) and (8) agree with those given in a recent paper by Kerr, Feldman and Pan [8]. These authors discussed a similar diagram as Fig. 1, and several others like it.

3. MEASUREMENTS OF THE NOISE TEMPERATURE OF HETERODYNE DETECTORS, INCLUDING QUANTUM NOISE

A standard Y-factor measurement involves measuring the ratio of the output powers obtained from the receiver when two input loads at different temperatures T_{hot} and T_{cold} are inserted at its input. As proposed by Kerr et al.[8], we use the CW expression (1) in the Y-factor expression to find the noise temperature.

$$T_{Rec,DSB} = \frac{T_{CW}^{Hot} - Y \cdot T_{CW}^{Cold}}{Y-1} \tag{9}$$

Using Eq. (9) as written gives the total noise power *added* by the receiver, including QN, correctly. To find the system noise temperature for DSB measurements, we add *hf/2k* plus any thermal input noise temperature in the particular system configuration:

$$T_{sys,DSB} = T_{Rec,DSB} + \frac{hf}{2k} + T_{Planck}(in) \tag{10}$$

4. MODEL FOR THE BROADBAND HEB RECEIVER

In what follows in this paper, we will make use of both the Callen-Welton expression, and the concept of an IBBM, in order to estimate the minimum noise temperature of a broadband HEB receiver. The HEB device basically acts as an absorber of the radiation (LO plus signal plus image), and has no shot noise. As explained earlier, we will assume that an ideal, matched, broadband HEB receiver will approach the noise performance of the ideal heterodyne detector, i.e. its noise output, referred to its input, will be given by Eq. (2), and the limit for its receiver noise temperature is zero K, as stated in Eq. (8).

Any HEB mixer also necessarily produces noise output due to the fact that the HEB is a resistive device with finite heat capacity and finite temperature. There are two "classical" noise sources to take into account because of this: (1) Thermal fluctuation noise (T_{FL}) and (2) Johnson noise (T_J). The total is :

$$T_{CL,MIX}^{out} = T_{FL} + T_J \tag{11}$$

We use the subscript 'CL' ('classical') for this noise contribution. The typical magnitudes are $T_{FL}\approx$50-100 K, and $T_J\approx T_c$, which is about 10 K for NbN. We also need to include the noise temperature of the IF amplifier, T_{IF}, typically about 5 K or less. Assuming now that the circuit properties of the upper and lower sidebands are identical (which they are if $f_{IF} << f_{LO}$) and that we add signals at the upper and lower sideband respectively, we have a situation as indicated in Fig. 2: This figure summarizes the noise power flow for an ideal HEB mixer receiver, and the concepts we have introduced so far. We have also introduced input RF losses, which will turn out to be very important for the receiver and system quantum noise; these losses are actually the most important topic of this paper and will be discussed in detail next.

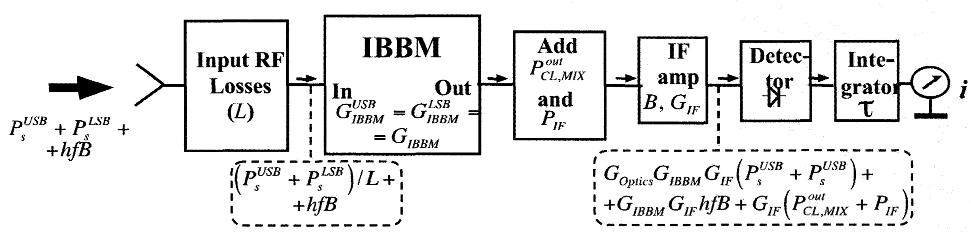


Fig. 2 Noise power flow in the HEB mixer receiver. The noise powers can all be translated into noise temperatures by using Eq. (5).

5. NONIDEAL HEB DEVICE: INFLUENCE OF "SERIES RESISTANCE"

It is obvious that the traditional model for the HEB mixer, where the device is assumed to be a dimension-less temperature dependent resistance, is a simplification of reality. It has recently been emphasized that it is important to take the contact resistance into account [13,14,15], and this will add a non-active series resistance. Even more important are the consequences of the hot-spot model [16], which suggests that the device at DC and IF frequencies is essentially a normal conductor in a central "hot spot" region and superconducting near the contacts. It turns out that the sensitivity to radiation absorption along the bolometer bridge is strongest near the boundary between the hot-spot and the superconducting regions. In a forthcoming paper [2] we will present a more detailed discussion of the influence of these effects on the QN, while in this paper we discuss a simple model which takes into account the contact resistances and the division of the bolometer into active and passive regions.

In the simplified model, we assume that the bolometer at THz frequencies is composed of two resistors in series, R_A (active resistance) and R_p (passive resistance). Recent modeling work [16] indicates that R_A may be of the order of 30 % of the full bolometer normal resistance, $R_B = R_A+R_p$. We assume that

(1) R_A represents the actual mixer, modeled as an IBBM, which also provides a "classical" IF noise output as given by (11),

(2) R_p is modeled as a passive resistor in series with R_A. We use the Callen-Welton expression to calculate the THz noise generated in R_p.

(3) The ratio $R_B/R_A = \beta$.

We insert an ideal circulator (Fig. 3) into our HEB model in order to take into account the fact that the active part, R_A, is also radiating Callen-Welton noise into the input circuit (from port 2). The circulator emphasizes that R_A is the

IBBM input impedance and nothing else. We assume that the IBBM has zero receiver noise temperature, and acts as a resistive load to the circuit to the left. In Fig. 3 we indicate that at the output of the HEB mixer to the IF circuit we must also include the "classical" HEB noise according to Eq. (11), i.e.:

$$P_{IF,out} = 2P_{in}G_{IBBM} + kT^{out}_{CL,MIX}B \tag{12}$$

Note that G_{IBBM} is the conversion gain from R_A to the output port of the mixer device, see Fig. 3, and not the total mixer gain. We next calculate the noise power entering the IBBM in *one sideband*, and then refer it to the source. We get after some calculations [2]:

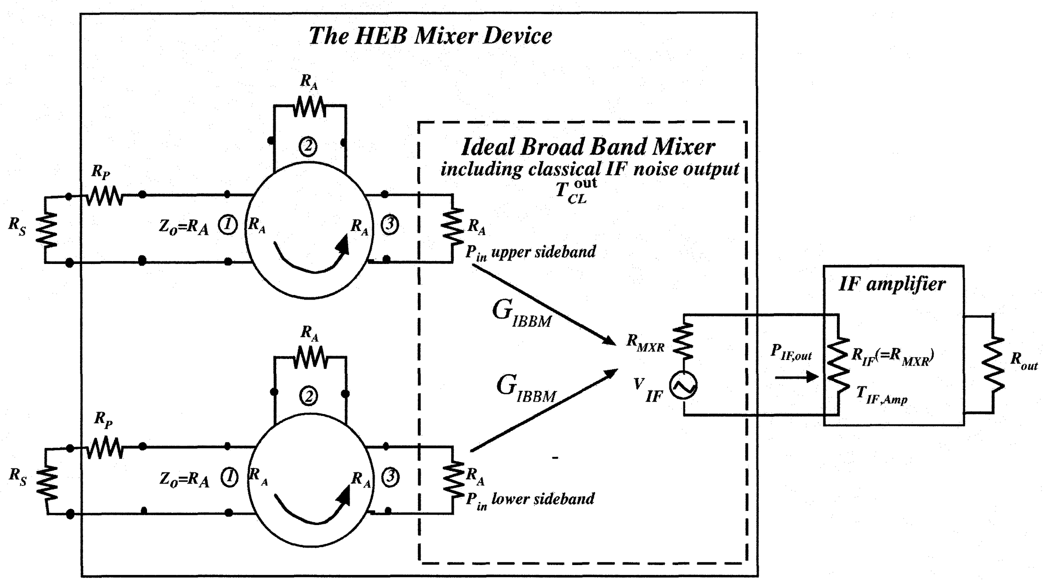


Figure 3. Model for the broadband HEB mixer only; optics not included.

$$P_{Source} = P_{Planck}(R_s) + \frac{R_p}{R_s}P_{Planck}(R_p) + \frac{(R_s + R_p - R_A)^2}{4R_sR_A} \cdot P_{Planck}(R_A) + \frac{hfB}{2}\frac{(R_s + R_B)^2}{4R_sR_B}\frac{R_B}{R_A} \tag{13}$$

The first three different contributions in this expression are Planck noise related to respectively R_s, R_p, and R_A, while the last term is the quantum noise contribution. Notice that the $hfB/2$ is multiplied by a term always larger than one. Also notice that R_p is part of the reasons for the existence of input losses (compare Fig.2).

Incidentally, non-ideal photodetectors are often characterized by using a quantum efficiency, η [4]. Wengler and Woody also discuss the SIS mixer by introducing a quantum efficiency [7,17]. This is similar to our case; however, the increased insertion loss in the HEB is resistive, and then the CW expression should be used to calculate the modified noise properties.

6. RECEIVER AND SYSTEM NOISE TEMPERATURE FORMULAS FOR HEB THz MIXERS, INCLUDING OPTICAL INPUT LOSS

To analyze the noise due to ordinary attenuation in the optics we first consider the situation described in Fig 4. The optics part is represented by a two-port matched in both ends to R_s. The "characteristic impedance" of the optics is assumed equal to R_s, i.e. there are no reflections anywhere. The optical circuit introduces an attenuation L_{optics} and has a physical temperature of T_{optics}. If T_s=T_{optics} the noise power transmitted to the load (P^{Load}_{CW}) must be identical to the noise power $P_{CW}(R_s)$ from the source. Next consider $T_S \neq T_{optics}$. Then the noise contribution to P^{Load}_{CW} from the source is $P_{CW}(R_s) \cdot 1/L_{optics}$ whereas the contribution from the lossy two-port must be $P^{optics}_{CW}(T_{optics}) \cdot (1 - 1/L_{optics})$. Through similar calculations as performed above, we can now find the equivalent DSB receiver noise temperature for the case when both sidebands are matched. In order to facilitate comparison with experimental results it is

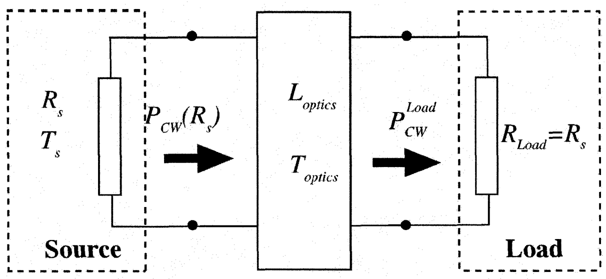


Fig. 4. A model for analyzing the equivalent noise from the quasi optical input circuit. Notice that both P_{CW}^{Load} and $P_{CW}(R_s)$ obviously include the same equivalent noise power due to the vacuum fluctuations, $hfB/2$.

convenient to break L_{optics} up into contributions from components at room temperature, L_{300}, and at liquid helium temperature, L_4, respectively. We can then neglect Planck noise at 4 K, and finally obtain:

$$T_{RX}^{DSB} = (L_{300} - 1)\frac{P_{Planck}(300K)}{kB} + \frac{hf}{2k}[L_{300}L_4 \cdot \beta - 1] + \frac{L_{300}L_4}{2G_{MXR}}(T_{CL,MIX}^{out} + T_{IF,Amp}) \qquad (14)$$

7. COMPARISON WITH EXPERIMENTAL RECEIVER NOISE TEMPERATURE DATA

In comparing experimental receiver noise temperature data with our predictions we will use Eq. (14), which assumes that the bolometer is matched to the source, and that the sidebands have equal conversion loss. There is only one set of data which extends far into the THz frequency range, up to 5.3 THz, that of the DLR/MSPU collaboration ("DLR"), [18]. A recent paper at the 15th ISSTT gives two points, at 2.5 THz and at 3.8 THz, respectively ("MSPU"), [19]. All other data sets have as their highest frequency 2.5 THz, and we will use measurements performed by the Chalmers University group ("CTH"), [20], which presently represent the best measured values at these frequencies[1]. In order to compare these data with Eq. (14) we also need to know the optical losses, and these are available in the DLR and CTH references. For the MSPU data we use the same optical losses as for DLR. We found simple polynomial fits to the optical loss as a function of frequency, and used these in the calculations to be described below. We extrapolated the optical losses to 10 THz based on these functions, beyond the highest frequency measured.

Equation (14) has three terms: (TERM 1): The optical input loss (Planck) term. These losses are assumed to be at 300 K; TERM 1 is generally small.; (TERM 2): The QN term; (TERM 3): The Classical HEB mixer and IF amplifier noise terms.

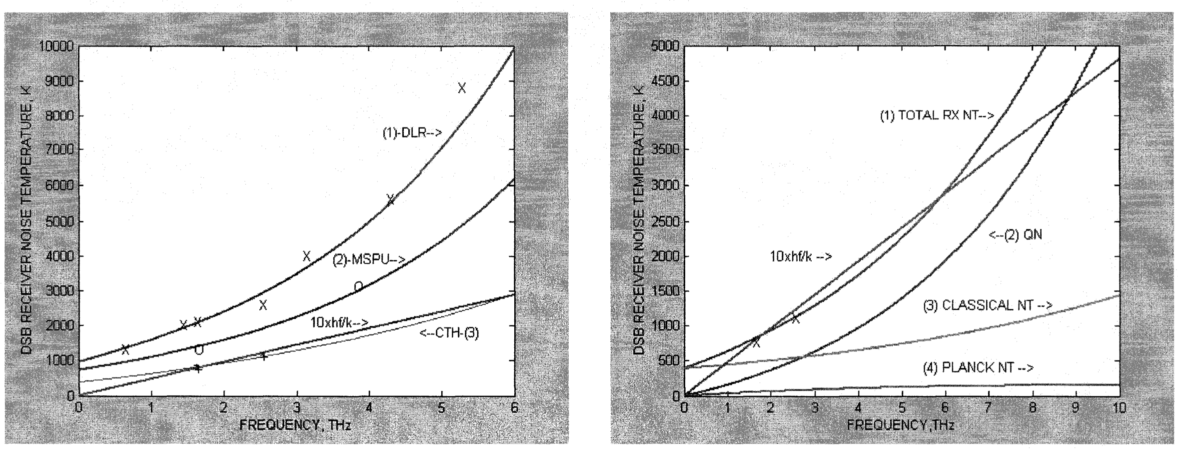
TERM 3 can be estimated from measurements at the lowest THz frequencies (1 to 1.5 THz), for which TERM 2 can initially be neglected as a first step in an iterative process. By calibrating the mixer output noise power compared with the case when the device is superconducting it is then possible to calculate $T_{CL,MIX}^{out}$, and $G_{MXR}^{tot} = G_{IBBM}/\beta$. The values of these two parameters also determine $T_{R,DSB}$. The IF amplifier noise temperature and the optical losses are measured or estimated separately. This general type of method is described in greater detail in [20]. Note that the classical HEB parameters are assumed to NOT depend on the frequency in the present paper. We can now determine a value of β which provides a best fit of $T_{R,DSB}$ calculated from Eq. (14) over the entire measured frequency range, by iteration. Figure 5a shows fits of the three sets of data mentioned above, obtained in this way. A straight line is also drawn for $T_{RX,DSB} = 10\times hf/k$.

A reasonable fit can be found. In particular, the steep frequency dependence of the DLR data at the highest frequencies is modeled well by our expression. We interpret the different noise temperatures obtained at the lower frequencies as being due to less efficient HEB operation because of such effects as contact resistance and a large value for R_p outside the hotspot, which are expressed by the parameter β (compare the discussion in Sec. 5 above).

To get further insight into the results in Figure 5a, we plot the three terms in Eq. (14) separately in Figure 5b. We use the CTH data. **Note that even for the lowest THz frequencies (already employed in ground-based HEB**

[1] Recent data from the Delft/ESRON group are about equal to those obtained by CUT, but we do not have optical loss data available for these.

receiver systems, and soon to be employed in the first HEB mixers in a space instrument, Herschel) the QN term and the classical HEB noise term are of comparable size! As the frequency increases further, the QN term is predicted to rapidly become completely dominant. The curve for the classical HEB noise term also shows a weak frequency dependence due to the optical losses which depend on frequency. The input Planck noise (TERM 1) is very small in comparison with both TERM 2 and TERM 3. Similar plots are obtained for the two other sets of data. It is also of interest to note that if our extrapolation to higher frequencies of the best receiver noise temperatures up to 2.5 THz, obtained so far, is correct, then **it may be possible to obtain DSB receiver noise temperatures of 10×*hf/k* (straight line in Figure 5b) or better, at least up to 6 THz, and with future improvements of the devices and the optical coupling up to 10 THz.** Our analysis also gives an indication that improvements in device performance over the entire frequency range can be obtained by finding ways of decreasing the value of β for the devices.



(a) (b)

Figure 5(a). Fits of Eq. (14) to measured DSB receiver noise temperature data versus LO frequency from three sources (the values used for β are given after the symbols used for the plots): (1) DLR [18] (x) (β=10); (2) MSPU [19] (o) (β=6); and (3) CTH [20] (+) (β=4). The straight line represents $T_{RX,DSB}$=10×*hf/k*.

Figure 5(b). Extrapolation of estimates of the three terms in Eq. (14) for the CTH data. The curves are (1) total receiver noise temperature; (2) the QN term; (3) the classical HEB and IF amplifier term; and (4) the Planck term of the optical input losses. The straight line again represents 10×*hf/k*.

10. CONCLUSION AND DISCUSSION

In this paper we derived an expression for the noise temperature of a "real" HEB receiver. This expression has two main terms, the QN term and the "classical" HEB noise term. The ratio of these two terms goes from about one at 2.5 THz to about five at 10 THz, as the quantum noise "takes over". By adjusting a single parameter, β, we can fit measured receiver noise temperatures as a function of frequency to this expression with good agreement. Since β represents resistive division between active and passive parts of the bolometer, high conversion loss at the lower THz frequencies is correlated with a more rapid increase of the receiver noise temperature at the highest THz frequency range. The values we obtain for β from our fitting procedure agree well with those derived from the latest hot spot model simulations. Although β is not determined with great accuracy (perhaps 20 %) the fact that a single value for β suffices to describe the behavior over a wide frequency range for at least two sets of measured data suggests that our model captures the basic features of the noise temperature variation with device quality and frequency. **Given this, one can be hopeful that HEB receivers in the reasonably near future can be developed up to 10 THz that will have receiver noise temperatures of 10×*hf/k* or better**. Such receivers, particularly in the form of focal plane arrays, are required for planned NASA projects in this frequency range such as SAFIR. Clearly, a much larger set of measured data is required to more definitely confirm or disprove the validity of the fundamental picture of HEB operation over a wide frequency range that we present. It appears possible to separate through more extensive measurements the two main terms in our noise temperature expression, and we plan to pursue such measurements and present the results in a future paper.

11. ACKNOWLEDGEMENT

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