QUANTUM NOISE CONTRIBUTION TO THE RECEIVER NOISE TEMPERATURE OF HEB THZ HETERODYNE RECEIVERS

Erik Kollberg
Microwave Electronics Laboratory, Department of Microelectronics, Chalmers University of Technology, Gothenburg, Sweden

and

Sigfrid Yngvesson
Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003, USA

Abstract

In this paper we discuss the quantum limit of bolometric mixer receivers. The importance of the optics attenuation is emphasized. Based on a simple bolometer model we predict that the *system* and *receiver* quantum noise limits referred to the input of a double-sideband hot-electron bolometer mixer receiver are, respectively, $2(hfB)$ and $1(hfB)$. The quantum limit to the DSB receiver noise temperature is $hf/2k$, in agreement with what has previously often been assumed. We suggest that an image-rejection single-sideband version of the HEB mixer would have a system quantum noise limit of $1(hfB)$. We also suggest that at a frequency of several THz the quantum noise may indeed be responsible for about half the total receiver noise temperature in a typical HEB receiver system.

1. Introduction

Quantum noise is the well-known ultimate limiting noise of any receiver system and has been treated by many authors [1, 2, 3, 4, 5]. Essentially, a perfect receiver will at the output show fluctuations even if the input is just terminated by a matched load at zero Kelvin. Referred to the receiver input, this output noise power fluctuation is equal to (hfB). Of course, quantum noise is of particular importance at THz frequencies. For example, the minimum quantum noise power corresponds to a noise temperature of 48 K at 1 THz.

In this paper we discuss how to analyze the noise performance (including quantum noise) of a THz receiver, which has optical coupling losses, as well as a lossy circuit between the antenna and a Hot-Electron Bolometer (HEB) mixer. Experimental HEB mixer receivers have been described as having total DSB receiver noise temperatures of the order of ten to twenty times the quantum noise limit, defined as $hf/2k$ (see e.g. [6,7]). Using a simple model we predict in this paper that at the higher THz frequencies (about 5 THz) as much as one half of the receiver noise temperature may be traced to the quantum noise.

2. Quantum noise from the input circuit

The total noise power from a matched load including the quantum-noise equivalent power according to Callen-Welton [1] is

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

Referring to Fig 1, this is the noise "power" from a source delivered to a matched load. Notice that even if T_0=0, the source will radiate a noise power of $(hfB)/2$. Since this power will be radiated as well by the load at zero Kelvin this means that the quantum noise part, $(hfB)/2$, cannot be extracted as a real power [3].

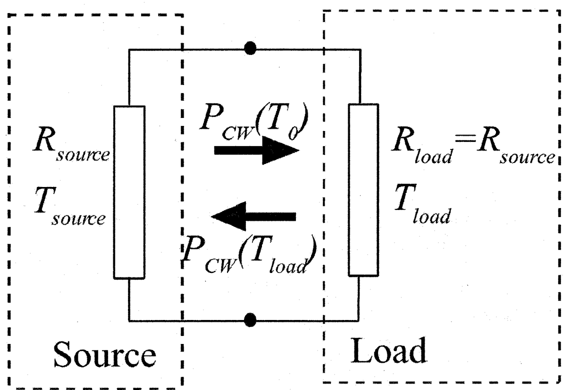

Fig. 1. Noise from a matched load (i.e. "Source") according to Callen-Welton [1]

The noise power of Eq. (1) can be transformed into an equivalent noise temperature

$$T_{CW}=T_0\cdot\left[\frac{\frac{hf}{kT_0}}{\exp\left(\frac{hf}{kT_0}\right)-1}\right]+\frac{hf}{2k}=\left(P_{Planck}(T_0)+\frac{hfB}{2}\right)\cdot\frac{1}{kB} \tag{2}$$

However, it is most convenient to perform our calculations in terms of noise power, and then convert this to noise temperature as the final step.

3. System noise vs Receiver noise

In order to analyze the bolometer mixer receiver, we have to make clear the difference between **System** (T_{syst}), **Receiver** (T_{Rec}), **Mixer** (T_{mixer}) and **IF amplifier** (T_{IF}) noise (see Fig. 2).

In the ***System noise*** is included the noise power from the source (R_{Source}), which is $[P_{Planck}(T_{source})+hfB/2]$ at each sideband. Concerning the minimum ***System noise*** **temperature** for a mixer receiver, references [2,3,5] are in agreement with the following statements:

*For a linear amplifier and for a mixer used in SSB measurements, using either SSB or DSB receivers, the **minimum** system noise temperature is hf/k.*

For broadband continuum measurements using a DSB receiver the ***minimum*** *(DSB) system noise temperature is hf/2k.*

The ***Receiver noise*** does not include the noise from the source. It does, however, include noise from the **optics**, the **mixer** and the **IF** amplifier. The **mixer** noise is generated in the bolometer at both RF and IF. Until now only the contribution from the IF side (Johnson noise and thermal fluctuation noise) has been included as shown in all standard treatments of HEB noise [8,9].

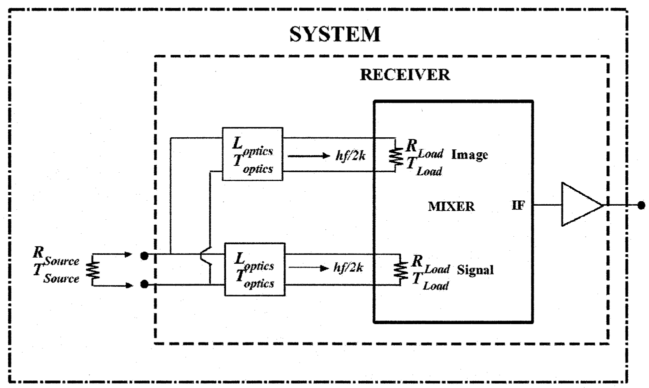

Fig. 2. Definition of Mixer, Receiver, and System.

4. The noise introduced by the optical losses

To analyze the noise from the optics we first consider one channel only (upper or lower sideband). The optics circuit is represented by a two-port matched to both the antenna and to the receiver (Fig. 3). We will now let the "**Load**" in Figure 1 represent one sideband of the *mixer*; specifically the mixer terminals are the terminals of an antenna, which couples the input optics quasi-optically to the mixer. The optical circuit introduces an attenuation L_{optics} and has the physical temperature T_{optics}. If $T_{Source}=T_{optics}$ the noise power transmitted to the mixer (P_{in}) must then be identical to the noise power $P_{CW}(T_{Source})$ from the source. The situation is described in Fig. 3

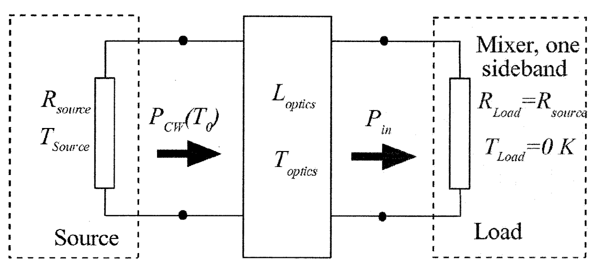

Fig. 3 A simplified model circuit for a THz mixer receiver, one sideband.

Next consider $T_{Source}?T_{optics}$. Then referring to Eq. (3) below, the contribution to P_{in} from the source is $P_{CW}^{source}(T_{source})\cdot 1/L_{optics}$ whereas the contribution from the lossy two-port must be $P_{CW}^{optics}(T_{optics})\cdot\left(1-1/L_{optics}\right)$. Adding these, we have:

$$\begin{aligned} P_{in} &= P_{CW}^{source}(T_{source})\cdot\frac{1}{L_{optics}} + P_{CW}^{optics}(T_{optics})\cdot\left(1-\frac{1}{L_{optics}}\right) = \\ &= P_{Planck}(T_{source})\cdot\frac{1}{L_{optics}} + P_{Planck}(T_{optics})\cdot\left(1-\frac{1}{L_{optics}}\right) + \frac{hfB}{2} \end{aligned} \tag{3}$$

As expected, the ideal receiver still receives the same quantum noise equivalent power of $(hfB)/2$. Adding noise power from the "load" itself, P_{Load} (including all mixer and IF contributions) the total noise power entering the "load" is:

$$P_{total,in} = \frac{1}{L_{optics}}\left[P_{Planck}(T_{source}) + P_{Planck}(T_{optics})\cdot\left(L_{optics}-1\right) + L_{optics}\cdot\frac{hfB}{2} + L_{optics}\cdot P_{Load}\right] \tag{4}$$

The noise power within the parenthesis […] is the total noise power referred to the source. To determine the receiver noise referred to the source, we measure the Y-factor in the ordinary way by using two physical temperatures of the source, T_{Hot} and T_{Cold}. The Y-factor is measured as

$$Y = \frac{P_{total,in}^{Hot}}{P_{total,in}^{Cold}} \tag{5}$$

where

$$P_{total,in}^{Hot} = \left\{P_{Planck}(T_{Hot}) + \frac{hfB}{2}\right\} + P_{Planck}(T_{optics})\cdot\left(L_{optics}-1\right) + \left(L_{optics}-1\right)\cdot\frac{hfB}{2} + L_{optics}\cdot P_{Load} \tag{6}$$

and

$$P_{total,in}^{Cold} = \left\{P_{Planck}(T_{Cold}) + \frac{hfB}{2}\right\} + P_{Planck}(T_{optics})\cdot\left(L_{optics}-1\right) + \left(L_{optics}-1\right)\cdot\frac{hfB}{2} + L_{optics}\cdot P_{Load} \tag{7}$$

We obtain the ***receiver noise temperature*** as

$$T_{Rec} = \left\{\left(P_{Planck}(T_{optics}) + \frac{hfB}{2}\right)\cdot\left(L_{optics}-1\right) + L_{optics}\cdot P_{Load}\right\}\cdot\frac{1}{kB} = \frac{T_{CW}^{Hot} - Y\cdot T_{CW}^{Cold}}{Y-1} \tag{8}$$

If there is no attenuation in the coupling circuit, i. e. $L_{optics}=1$, the quantum noise contribution to the receiver noise temperature

$$P_{QN,Rec} = \left\{L_{optics}-1\right\}\cdot\frac{hfB}{2} \tag{9}$$

disappears. This term includes only the quantum noise (QN) contribution from the optics and not the QN from the source (hot and cold loads). In reference [4] it is argued that the QN should be referred to the source and not to the receiver. However, in this case when optics losses are part of the receiver we need the QN contribution from the optics according to Eq. (9) in order to meet the requirement that the "receiver" should see a matched source emitting QN of *(hfB)/2*. So far we have also not considered the QN from the bolometer itself.

5. RF noise from the bolometer

Let us first try analyzing RF noise generated in the bolometer itself. The device in the hot-electron bolometer (HEB) mixer is essentially a temperature dependent resistance, which should add noise not only at the IF, which has normally been assumed, but also at the input frequency.

Since we assume that the RF frequency is well above the superconducting bandgap frequency in the entire bolometer, the bolometer should appear uniformly resistive to the RF power. However, the IF resistance change for a small change in RF absorption is not necessarily the same along the bridge. In Fig 3 an approximate model accounting for such a situation is described by two resistances (compare Merkel et al.[10]). R_P represents the passive RF resistance zones of the bolometer, and R_A the zones, which are actively converting RF power to IF power. We expect that we can use Eq. (1) to predict the amount of RF noise produced by any part of the bolometer. Only the active zones of the bolometer convert RF power (including noise power) to the IF, however, and we must therefore consider the active and the passive zones separately in our noise analysis. The passive zones are not only the central Hot-Spot zone, but also the zones between the hot-spot and the contacts that are superconducting and have essentially zero resistance at lower frequencies. The active zones are located at the transition from the central hotspot to the "low frequency" superconducting regions. Adding these two resistances together we get R_P+R_A=R_N, i. e. the normal resistance of the device.

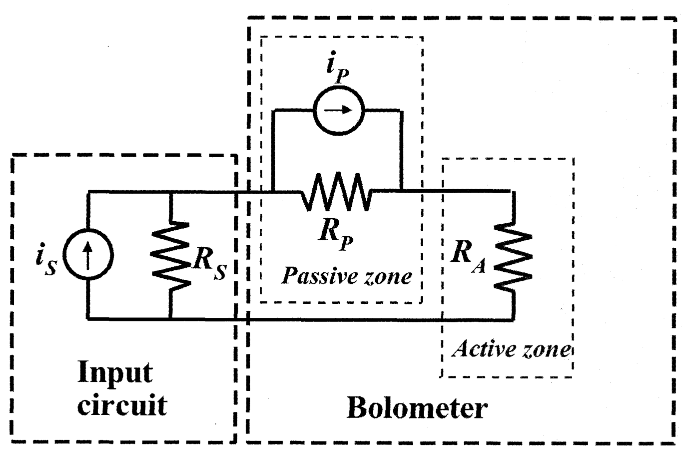

Fig 4 Equivalent circuit of a receiver including noise sources of R_P and R_S. Concerning the noise contribution from R_A, see the text below.

Referring to Fig. 4, noise currents are obtained as

$$\left(\frac{i_S}{2}\right)^2 \cdot R_S = P_{CW}(T_S) \qquad \left(\frac{i_P}{2}\right)^2 \cdot R_P = P_{CW}(T_P) \tag{10}$$

where $P_{CW}(T_S)$ etc. are the Callen-Welton noise powers according to Eq.(1). The thermal noise generated by R_A and dissipated in R_A is calculated by dividing R_A into a large number of series coupled elements ΔR_A ($\sum \Delta R_A = R_A$), which each contribute the same amount of noise current $\sqrt{\delta i_A^2}$ in the circuit viz.

$$\left(\frac{\delta i_A}{2}\right)^2 \cdot \Delta R_A = P_{CW}(T_A) \tag{11}$$

The currents i_S, i_P and all the $(\delta i_A)^2$ are completely uncorrelated. The noise current $i_{A,S}$ generated in the circuit by i_S and consequently also in the active part of the bolometer, R_A, is determined from

$$i_{A,S}^2 = i_S^2 \cdot \left(\frac{R_S}{R_S + R_P + R_A}\right)^2 \tag{12}$$

A similar noise current contribution is obtained from R_P as well as from R_A (the latter obtained as a summation of all contributions from ΔR_A). Each resistance in Fig. 4 contributes to the total noise current in the circuit and delivers noise power to R_A. Any ***signal*** from the antenna, which reaches the active zone of the bolometer, will mix with noise in the active zone. In particular, the local oscillator signal will mix with the RF-noise and produce noise power at the IF output.

We obtain the total noise power dissipated in R_A as

$$P_{tot,A} = \frac{4R_A}{(R_s + R_A + R_p)^2}\left[P_{CW}(T_s)\cdot R_s + P_{CW}(T_p)\cdot R_p + P_{CW}(T_A)\cdot R_A\right] \tag{13}$$

Considering that the bolometer mixer has two sidebands (Fig. 2) we notice that Eq. (13) applies to <u>each sideband separately</u>. It can be pointed out that Eq. (13) can also be derived using resistances in series with voltage noise sources $v^2 = 4R \cdot P_{CW}$, with the same result.

Let us investigate the case when the bolometer is matched at the RF, i. e. $R_P + R_A \equiv R_B = R_S$. We obtain

$$P_{tot,A} = P_{CW}(T_S)\cdot\frac{R_S R_A}{R_S^2} + P_{CW}(T_P)\cdot\frac{R_P R_A}{R_S^2} + P_{CW}(T_A)\cdot\frac{R_A R_A}{R_S^2} \tag{14}$$

which for the quantum noise part yields

$$P_{QN,A} = \left(\frac{R_S R_A}{R_S^2} + \frac{R_P R_A}{R_S^2} + \frac{R_A R_A}{R_S^2} \right) \cdot \frac{hfB}{2} = hfB \cdot \frac{R_A}{R_S} \tag{15}$$

Referring this noise to the *bolometer input terminals*, we multiply (15) by R_S / R_A, and obtain

$$P_{QN,in} = hfB \tag{16}$$

for each sideband.

Notice that the quantum noise contribution according to Eq. (16) is hfB and not $(hfB)/2$. The reason is that the bolometer resistance(s) contribute with $(hfB)/2$ and the source another $(hfB)/2$.

We conclude that in this model the bolometer itself contributes to the receiver RF-noise with

$$P_{CW}(T_c) \approx P_{Planck}(T_c) + (hfB)/2 \approx (hfB)/2 \tag{17}$$

in one sideband. In (17) we have introduced the physical temperature of the bolometer, which is close to T_c, the critical temperature of the superconductor. At THz frequencies and T_c=10K $P_{Planck}(T_c)$ can be neglected.

It is reasonable to assume that there is no correlation of the noise in the two sidebands what so ever. Hence the noise to be downconverted from RF to IF originates from the two sidebands and thus is twice the noise we have considered so far. In this **matched case** the total QN at the bolometer input is $2hfB$. This noise is to be added to the noise of the mixer, i. e. at the input of the bolometer we have,

$$T_{Syst}^{SSB} \approx \frac{2hf}{k} + L_{conv.loss}^{SSB} \cdot \left(T_{mixer}^{out} + T_{IF} \right) \tag{18}$$

where $L_{conv\,loss}^{SSB}$ is the internal SSB conversion loss of the bolometer, i. e. the loss counted from the bolometer input terminals to the IF output. T_{mxer}^{out} *(mixer)* represents the noise output power from the mixer, which is due to Johnson noise and thermal fluctuation noise, and originates in the bolometer itself. Further, T_{IF} is the noise temperature of the IF amplifier.

Since half of $2hf/k$ comes from the bolometer itself and the other half from the source, we have

$$T_{Rec}^{SSB} = \frac{hf}{k} + L_{conv.loss}^{SSB} \cdot \left(T_{mixer}^{out} + T_{IF} \right) \tag{19}$$

The DSB noise temperature becomes half of the SSB noise temperature.

Adding the influence of the optics attenuation, which is assumed the same for both sidebands, and referring the noise temperature to the input of the optics, we get

$$T_{Rec}^{DSB} = L_{optics} \cdot \frac{1}{2} \left(\frac{hf}{k} + L_{conv.loss}^{SSB} \cdot \left(T_{mixer}^{out} + T_{IF} \right) \right) + \left(L_{optics} - 1 \right) \cdot \left(T_{optics}^{Planck} + \frac{hf}{2k} \right) \tag{20}$$

Since each sideband produces the same amount of noise power, the double sideband noise temperature becomes half the single sideband noise temperature. The SSB noise temperature is again twice the DSB noise temperature. Adding the two quantum noise terms, we can write (20) as

$$T_{Rec}^{DSB} = \left(L_{optics} - 1\right) \cdot \left(T_{optics}^{Planck}\right) + \left(L_{optics} - \frac{1}{2}\right) \cdot \left(\frac{hf}{k}\right) + L_{optics} \cdot \frac{1}{2} \left(L_{conv.loss}^{SSB} \cdot \left(T_{mixer}^{out} + T_{IF}\right)\right) \quad (21)$$

6. Comparison with experimental noise measurements

In a typical system, some optical losses are at roughly room temperature ("L_{optics}^{300K}"), and some at 4 K ("L_{optics}^{4K}"). Then we find,

$$\begin{aligned} T_{Rec}^{DSB} &= \left(L_{optics}^{300K} - 1\right) T_{Planck}^{300K} + \left(L_{optics}^{300K} L_{optics}^{4K} - \frac{1}{2}\right)\frac{hf}{k} + \left(T_{mixer}^{out} + T_{IF}\right)\frac{L_{conv.loss}^{SSB}}{2} \cdot L_{optics}^{300K} L_{optics}^{4K} = \\ &= T_{optics}^{300K} + T_{QN} + T_{Rec.mixer} \end{aligned} \quad (22)$$

T_{Planck}^{300K} is the "Planck Temperature" of the optics. At low frequencies, this is simply the physical temperature (300 K or 295 K), but at THz frequencies we use the Planck formula to find the actual "Planck noise power" and equate that to $kT_{Planck}^{300K}B$. We can neglect the Planck Temperature for components at 4K.

In an experiment performed by the Chalmers group at 1.6 THz [11], it was estimated that L_{optics}^{300K} due to a mylar beam splitter and a polyethylene window was 1.1. Losses at 4 K due to a Zitex thermal filter, the silicon lens (with a parylene matching layer), and the antenna were estimated to be 1.33. The total optical loss was thus 1.44. For this mixer the measured T_{Rec}^{DSB} was 800 K . It was also estimated that T_{mixer}^{out} = 54 K, T_{IF} = 6 K, and $L_{Conv.loss}^{SSB}$ = 12.4 dB, by calibrating the IF system through further measurements in which the HEB device was brought to the superconducting state (a standard method). The bolometer was close to being matched to the antenna impedance. Here, $L_{Conv.loss}^{SSB}$ includes all loss effects (SSB) in the HEB from the THz antenna terminals to the IF terminals. We can now estimate all three terms in Eq. (22)

$$T_{Rec}^{DSB} = 40\text{ K} + 70\text{ K} + 690\text{ K} = 800\text{ K} \quad (23)$$

We then see that even at such a moderately high frequency as 1.6 THz, about 14 % of the receiver noise temperature is due to the optical loss at 300 K (T_{optics}^{300K}), plus the quantum noise (T_{QN}). The part of the receiver noise temperature traceable to the QN is about 9 % of the total receiver noise temperature. Note that without this more careful analysis of the QN term, a typical statement would have been "the quantum noise limited noise temperature at 1.6 THz is $hf/2k$ = 38 K, or about 5 % of the total receiver noise temperature".

The fraction of the receiver noise temperature due to QN is expected to become greater as the frequency is increased, as we will show below. In estimating the receiver noise temperature at higher frequencies, we make the following assumptions:

1) The optical losses increase linearly with frequency
2) The intrinsic conversion loss does not depend on the frequency

3) The mixer output noise temperature does not depend on the frequency

Assumption 1) agrees with estimates in [9] and [10]. Assumption 2) is reasonable based on our present knowledge of HEB models, but has not been carefully tested in experiments. It can be tested through direct conversion loss measurements, which we are planning to perform with two laser sources and/or a laser LO and a sideband generator. Assumption 3) has been verified in at least a few experiments [7,11] and appears to be true for typical NbN HEB mixers.

Figure 5 now shows calculations of T_{Rec}^{DSB} for a matched HEB mixer as a function of frequency up to 10 THz, based on an extrapolation of our measured data at 1.6 THz, and using the above three assumptions. The calculated curve is reasonably consistent with other measured data on the same device at 2.52 THz (T_{Rec}^{DSB} = 1,500 K [11]). The top curve is the total receiver noise temperature, the next one down the QN term (term T_{QN} in Eq. (22), and the smallest term the noise due to optical losses at room temperature (term T_{optics}^{300K} in Eq. (22)). **Note that the QN term rises much faster with frequency than the room temperature optics loss term, and that it approaches 50 % of the total receiver noise temperature.**

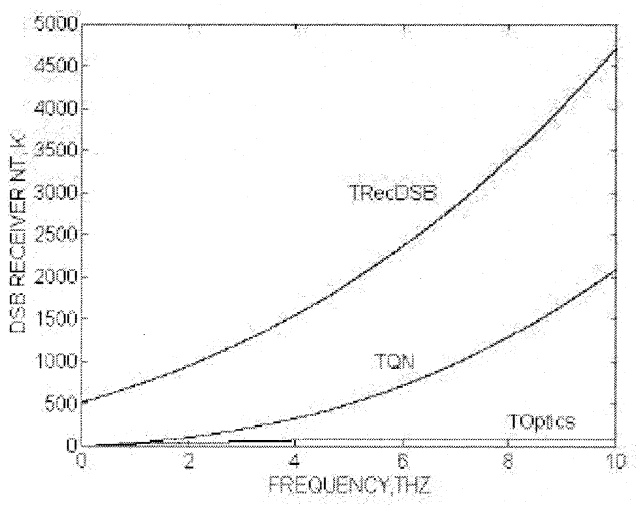

Fig. 5. DSB receiver noise temperature and the contributions from optics and quantum noise.

The question naturally arises: Can we distinguish the two main terms T_{QN} and $T_{Rec,mixer}$ through experimental measurements? There is a fundamental difficulty with doing this due to the fact that both terms depend on the optical losses in almost the same way; the minor difference being that a factor of 1/2 is subtracted from the optical losses in the QN case. It would be important to attempt to measure $L_{conv\,loss}^{SSB}$ at different LO frequencies independently, in order to determine the relative size of T_{QN} and $T_{Rec,mixer}$. The RF power from a sideband or laser source *actually absorbed in the bolometer* can be measured by the isothermal method, and together with a measurement of the IF power will yield the conversion loss based on *absorbed power*. There is a difference between the absorbed RF power in the bolometer, and the power delivered to the bolometer terminals, however, as is clear from the earlier discussion and the equivalent circuit we have assumed (see Figure 4). The above measurement therefore does not yield $L^{SSB}_{conv\,loss}$ as used in our receiver noise temperature calculations. Measuring the conversion loss based on absorbed power at different LO frequencies would still allow us to test the important assumption 2) above, if one assumes that R_P/R_A does not vary with frequency. An *absolute* conversion loss measurement requires calibrating the RF power which reaches the bolometer terminals. This test is more difficult to perform accurately, but should also be attempted. It will also yield data on the frequency-dependence of the optical losses.

7. Discussion and Conclusion

We have analyzed the contribution of quantum noise to the system and receiver noise temperatures of THz HEB mixer receivers. The basic model we propose, and the corner stone of our analysis, is that HEB devices appear *uniformly resistive* to the THz radiation, once the radiation frequency is above the superconducting bandgap frequency. It then appears that the Callen-Welton version of the fluctuation dissipation theorem [1] is sufficient to describe the quantum noise aspects of the bolometer. The quantum noise in the bolometer resulting from the input source (the "vacuum fluctuations"), and the bolometer itself, is down-converted to the IF. No further noise sources are assumed on the RF side of the bolometer, or for the actual down-conversion process. These assumptions appear similar to those made by Kerr et al. [3]. Specifically, these authors discuss quantum noise in SIS mixers, with contributions from (1) the input source (R_S in our paper), and (2) the quantized shot noise in the SIS junction, which is down-converted to the IF. No further quantum noise due to the down-conversion process is assumed. Since our present understanding of PHEB models has led to the conclusion that the bolometer has a substantial *passive zone*, as well as an *active, frequency-converting zone*, we have analyzed how noise contributions from these different zones contribute to the total noise. We find that the division of the bolometer into one active and one passive part does not affect the contributions of Planck and quantum noise from the bolometer; rather, it is the total resistance R_B that matters. Of course, the ratio R_A/R_B affects the conversion loss $L^{SSB}_{conv\,loss}$ and therefore the receiver noise contributions related to $T^{out}{}_{mixer}$ and T_{IF} [10]. We have also used the Callen-Welton theorem to analyze the contributions to the receiver noise temperature from the optical components preceding a quasi-optically coupled bolometer. The overall conclusion is that, given the present level of performance of THz HEB receivers, we predict that close to 50 % of the total receiver noise temperature may be traced to quantum noise phenomena, for frequencies in the 5-10 THz range. This represents a larger fraction of the total noise than has previously been claimed.

The first two terms in (22) also have an effect on receiver noise bandwidth measurements, an estimated increase of about 17 % at a frequency of 5 THz, and an increase of 30 % at 10 THz, compared with the lowest THz frequencies.

Quantum noise analyses of receivers have either been carried out for a general "linear amplifier" [2] or for specific types of receivers, such as SIS mixers [3,4,5], maser and laser amplifiers [12], or photo-diode mixers [13,14]. Our analysis is of yet another specific type of receiver, and the question again arises: do the results obtained in this specific case violate limitations derived for linear amplifiers in Caves' extended sense, which also includes mixers. Caves concludes that a linear amplifier amplifies the input $hfB/2$ QN from the source and adds another contribution $hfB/2$ referred to its input, leaving us with a total of hfB as the *system* quantum noise limit. The other papers mentioned above agree with this conclusion regarding the minimum system noise. <u>In the matched bolometer case, we predict $2(hfB)$ as the QN limit.</u> The extra factor of two is due to the fact that both sidebands contribute to the noise independently. We can draw the conclusion that the *general* system quantum noise limit can be interpreted to be *hfB per independent channel.* The specific cases of the (two-channel) SIS mixer and the photo-diode mixer yield the lower limit of $1(hfB)$ due to cancellation of the shot-noise contributions from the two sidebands (i.e. the two channels are *not independent* in this case). We propose that it may be possible to design an HEB mixer with the same lower QN limit of $1(hfB)$ by configuring it as an image rejecting mixer, which allows only one sideband to convert RF to the IF. The analysis of QN in an image-rejection SIS mixer by Kerr et al. [3] also finds a minimum total QN at the input of $1(hfB)$.

It is possible that some further QN source has been overlooked in the model used in this paper. A system noise less than $1(hfB)$ seems to result when analyzing an *unmatched* bolometer in an image reject mixer in the same way as suggested in this paper. This (potential) disagreement with the accepted general limit for linear amplifiers (and mixers) of 1(hfB) due to Caves mainly represents a theoretical point unless the performance of HEB mixers in terms of intrinsic mixer noise improves very substantially, however. We may also note that all other receivers analyzed in terms of QN so far have been *matched to the input source.* If the down-conversion process is also required to produce hfB/2 of QN, then the above (potential) disagreement with Caves disappears. If an additional noise contribution due to the down-conversion process exists, our results *underestimate* the total QN. This may therefore be a hypothesis which can be tested experimentally more easily, since it increases the coefficient in front of the QN term. Further investigation will be necessary in order to prove or disprove this and other assumptions we have made in our analysis.

8. Acknowledgements

We would like to acknowledge Jonas Zmuidzinas and Anthony Kerr for fruitful discussions during the symposium. One of us (SY) would like to acknowledge support from NASA contract NAS1-01058 with the NASA Langley Research Center for this work.

9. References

[1] H. B. Callen and T. A. Welton, “Irreversibility and Generalized Noise”, Phys. Rev. vol. **83**, no. 1, pp. 34-40, July 1951.

[2] C. M. Caves, “Quantum Limits on Noise in Linear Amplifiers”, Phys. Rev. D, vol. **26**, No. 8, pp. 1817-1839, October 1982.

[3] A.R. Kerr, M. J. Feldman, and S. –K. Pan, “Receiver Noise Temperature, the Quantum Noise Limit, and the Role of the Zero-Point Fluctuations,” in Proc. 8th Int. Nat. Symp. Space Terahertz Technology, March 25-27, 1997, pp. 101-111. Available: URL: http://colobus.aoc.nrao.edu/memos as MMA Memo 161.

[4] A. R. Kerr, “Suggestion for Revised Definition of Noise Quantities, Including Quantum Noise”, IEEE Transactions on Microwave Theory and Techniques, vol. **47**, No. 3, pp. 325-329, March 1999.

[5] J. R. Tucker and M. J. Feldman, Quantum Detection at Millimeter Wavelengths,” Rev. Modern Physics, vol. **57**, no. 4, pp. 1055-1153, Oct. 1985.

[6] A.D. Semenov et al., “Design and Performance of the Lattice Cooled Hot-Electron Terahertz Mixer,” J.Appl.Phys. vol. **88**, p.6758, 2000.

[7] Gerecht et al., "NbN Hot Electron Bolometric Mixers - A New Technology for Low-Noise THz Receivers," IEEE Trans, Microw. Theory Techniques, vol. **47**, pp. 2519-2527, December 1999.

[8] B.S. Karasik and A.I. Elantiev, “Noise Temperature Limit of a Superconducting Hot-Electron Bolometer Mixer,” Appl.Phys.Lett., vol. **68**, pp. 853-855, 1996.

[9] S.Yngvesson and E. Kollberg, “Optimum Receiver Noise Temperature for NbN HEB Mixers According to the Standard Model,” 10th Intern. Symp. Space THz Technol, Charlottesville, VA, March 1999, pp. 566-582.

[10] H.F. Merkel, P. Khosropanah, K.S. Yngvesson, S. Cherednichenko, M. Kroug, A. Adam, and E.L. Kollberg, "An Active Zone Small Signal Model for Hot Electron Bolometric Mixers," 12th Intern. Symp. Space THz Technol, San Diego, CA, Febr. 2001, pp. 67-74.

[11] S. Cherednichenko, et al., “1.6 THz Heterodyne Receiver for the Far Infrared Space Telescope”, accepted for publication in Physica C, 2002.

[12] H.A. Haus, "Noise Figure Definition Valid From RF to Optical Frequencies," IEEE J. Selected Topics in Qu. Electronics, vol. **6,** pp.240-247, 2000.

[13] B.M. Oliver, “Thermal and Quantum Noise,” Proc. IEEE, vol. **53**, pp. 438-454 1965.

[14] M.J. Wengler and D.P. Woody, “Quantum Noise in Heterodyne Detection,” IEEE J. Qu.Electronics, vol. **QE-23**, 613-622,1987.