OPTIMUM RECEIVER NOISE TEMPERATURE FOR NbN HEB MIXERS ACCORDING TO THE STANDARD MODEL

K. Sigfrid Yngvesson[1] and Erik L. Kollberg[2]

[1]Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003

[2]Department of Microelectronics, Chalmers University of Technology, S-41296 Gothenburg, Sweden

INTRODUCTION

This paper addresses the problem of how to find the optimum noise performance of NbN HEB mixers, based on the original model for such devices, the "standard model". The standard model was developed in the work of Arams et al.[1], and also by the group of Gershenzon et al in Russia [2]. The main assumption inherent in this model is that the device is treated as a uniform bolometer with a heat capacity, C_e, and thermal conductance to the heat sink, G_{th}. The bolometer has a resistance which depends on the electron temperature, θ, and equal amounts of DC and RF (LO) power produce identical changes in the electron temperature. The entire device is taken to be at the same electron temperature. More recent uses of this model include that by Yang et al. [3,4] for 2DEG HEBs, and by Ekström et al. [5,6]. The latter two references analyzed measurements taken at about 20 GHz on a phonon-cooled HEB (PHEB) with Nb, and obtained detailed quantitative agreement of the measured and the calculated conversion loss, as the bias voltage was varied. A popular method for "calibrating" the LO power absorbed by the device is also based on the assumption of equal heating effects due to DC or RF power [6]. Recently, analysis of NbN HEBs exposed to RF power at THz frequencies has shown that this model leads to inaccurate results, in terms of being able to predict the absorbed LO power correctly, see Merkel et al., 1998 [7]. This puts into question the validity of the standard model for calculating other quantities, such as conversion loss, output noise temperature, and receiver noise temperature. In this paper we show that the main functional dependence of these quantities on the LO power, as measured for several NbN HEBs, is still in quite good agreement with measured data, based on the standard model, if the operating point is fairly close to the experimentally determined optimum point for lowest receiver noise temperature. The theory uses two adjustable parameters to fit measured data for receiver noise temperature, and output noise temperature. We also compare the theoretical prediction for the conversion loss, which can be derived from the measured noise data. For all devices, the optimum noise temperature is measured to occur for about the same value of the optimum bias current, I_0, normalized to the bias current without LO power, I_{00}, a ratio which is about 0.3 to 0.45. This optimum results from the competing dependencies of the conversion loss, as well as the different noise processes, upon the LO power, as we discuss in detail below. The model also enables us to make reasonable estimates of the optimum receiver noise temperature which is achievable with this type of devices of the best quality presently available, and to make approximate comparisons with HEBs which use other materials, such as Nb and Al.

DEFINITION OF THE MODEL

The analysis we will use was presented in detail in [5], and [6], and the main equations will be quoted from these references. We refer to these for detailed derivations.

Conversion gain

The conversion gain may be calculated by using measured parameters obtained from the IV-curves of the device, see Figure 1.

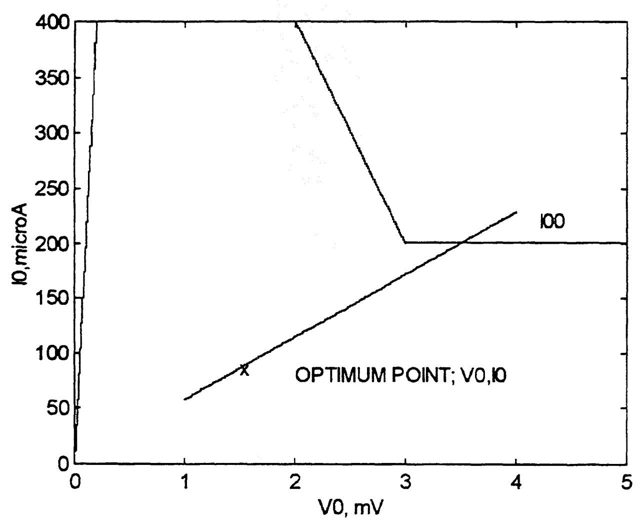

Figure 1. Typical I-V-curve for a NbN HEB device.

The bias currents with and without LO power, respectively, defined along a line of constant resistance, R_0, are I_0 and I_{00}. The quantity C_0 = dR/dP is also assumed to be constant along this line, since it represents a constant electron temperature. The original derivation of the <u>Single Sideband</u> conversion gain of an HEB mixer by Arams et al. [1] yielded the following expression

$$G = 2C_0^2 \frac{P_{LO}P_{DC}}{(R_L + R_0)^2} \frac{R_L}{R_0} \left[1 - C_0 I_0^2 \frac{R_L - R_0}{R_L - R_0} \right]^{-2} \quad (1)$$

where R_L is the IF load resistance. The above equation is equivalent to the one used by Elantiev and Karasik [8, Eq. (17)]. According to the assumptions of the standard model, we can write the local oscillator power P_{LO} as $R_0(I_{00}^2-I_0^2)$, and the DC power dissipated at the bias point, P_{DC}, as $R_0I_0^2$. Inserting these into (1), we obtain

$$G_{dB} = 10\log\left[2C^2x(1-x)\frac{b\sqrt{x}}{\left(b\sqrt{x}+1\right)^2}\left(1-Cx\frac{b\sqrt{x}-1}{b\sqrt{x}+1}\right)^{-2}\right] \tag{2}$$

Here, we have introduced $b= R_LI_{00}/V_0$, where V_0 is the bias voltage with LO power applied. Also, $C_0I_{00}^2 = C$. We let $x=(I_0/I_{00})^2$ represent the variation with the LO power (P_{LO} goes to zero for x=1).

Temperature Fluctuation Noise

It has been established for both PHEBs and Diffusion-Cooled HEBs (DHEBs) that the main noise mechanism is that due to fundamental fluctuations in the temperature of the bolometer medium, with an equivalent output noise temperature, T_{FL}. The expressions given by different sources are basically equivalent, but differ in some details, partly because they were compared with experiment in situations which allowed some approximations. For example, Ekström and Karasik [9] give the output noise from the device into a matched load, R_L. A careful re-examination reveals that the R_L-dependence for T_{FL} is the same as for G, a conclusion also consistent with that of Elantiev and Karasik ([8], Eq. (27); we assume that $Z(\infty) = R_0$]. We then find the following expression for the temperature fluctuation output noise, T_{FL}:

$$T_{FL} = \frac{I_0^2R_L(\frac{dR}{d\theta})^2(\Delta T_{FL})^2}{(R_0+R_L)^2\left(1-C_0I_0^2\frac{R_L-R_0}{R_L+R_0}\right)^2} \tag{3}$$

Here, $dR/d\theta$ is the dependence of R on electron temperature at the actual operating point. It can not be obtained by simply using the measured R/T-curve, but can be found by using IV-curves near the desired point taken at different temperatures, as shown in Ekström et al [10]. Here, we regard it as a fitting parameter. Also, $(\Delta T_{FL})^2$ is known from basic thermodynamics to be 4 $k_B\theta^2/G_{th}$ (per unit bandwidth), where $G_{th}= C_e/\tau_\theta$ is the thermal conductance from the device to the heat sink (C_e is the heat capacity of the device, and τ_θ

the energy relaxation time constant). We can simplify (3) by using the fact [5] that $C_0 = (dR/d\theta)(\tau_\theta/C_e)$, introducing x for $(I_0/I_{00})^2$, and defining a numerical constant $N=4\theta^2 (dR/d\theta)$; hence

$$T_{FL} = \frac{Cb^2x^2}{\left(b\sqrt{x}+1\right)^2}\frac{N}{R_L}\left[1-Cx\frac{b\sqrt{x}-1}{b\sqrt{x}+1}\right]^{-2} \quad (4)$$

Note that the two device parameters which determine the strength of the temperature fluctuation noise through N are $\theta \approx T_c$ ($T_{FL} \propto \theta^2$), and $dR/d\theta$.

It was also demonstrated experimentally in [9] that the time-constant which characterizes the frequency-dependence of the temperature fluctuation noise (τ_θ*) is the same as the one for the mixer conversion loss (τ_{mix}). These are given by

$$\tau_\theta^* = \tau_{mix} = \frac{\tau_\theta}{1-C\dfrac{R_0-R_L}{R_0+R_L}} \quad (5)$$

where τ_θ is the energy relaxation time of the medium.

Johnson Noise

The Johnson noise can similarly be written as [6]

$$T_J = \frac{4\theta R_0 R_L}{(R_0+R_L)^2}\frac{(1-Cx)^2}{\left[1+Cx\dfrac{R_0-R_L}{R_0+R_L}\right]^2} = \frac{4\theta b\sqrt{x}}{\left(b\sqrt{x}+1\right)^2}\frac{(1-Cx)^2}{\left(1-Cx\dfrac{b\sqrt{x}-1}{b\sqrt{x}+1}\right)^2} \quad (6)$$

Receiver Noise Temperature

The total (intrinsic) Double Sideband (DSB) receiver noise temperature is now obtained from the usual expression

$$T_{RX,DSB} = L_c/2\ (T_{out} + T_{IF}) \qquad (7)$$

$L_c = 1/G$ is found from (2) above, and (4) plus (6) yield

$$T_{out} = T_{FL} + T_J \qquad (8)$$

For low receiver noise temperature situations, we may also need to take into account a term = $2T_{in}/L_c$ which contributes to T_{out} in (8) (from both sidebands ; T_{in} is usually either 300 K or 77 K).

Elantiev and Karasik [8] derived an expression for the receiver noise temperature , T_m^{TF} , in the idealized special case for which the only noise process included is that due to temperature fluctuations, and the IF amplifier noise is neglected. They found that it is predicted to approach zero as the LO power is increased indefinitely. We can confirm this by calculating the ratio of Equations (5) and (2), by which we recover Eq. (28) in [8].

$$T_m^{TF} = \frac{2\theta^2 G}{P_{LO}} \quad (9)$$

The receiver noise temperature vanishes despite the fact that the conversion loss goes to infinity. We illustrate this for typical values of the parameters in (2) and (5) in Figure 2 which displays the DSB receiver NT:

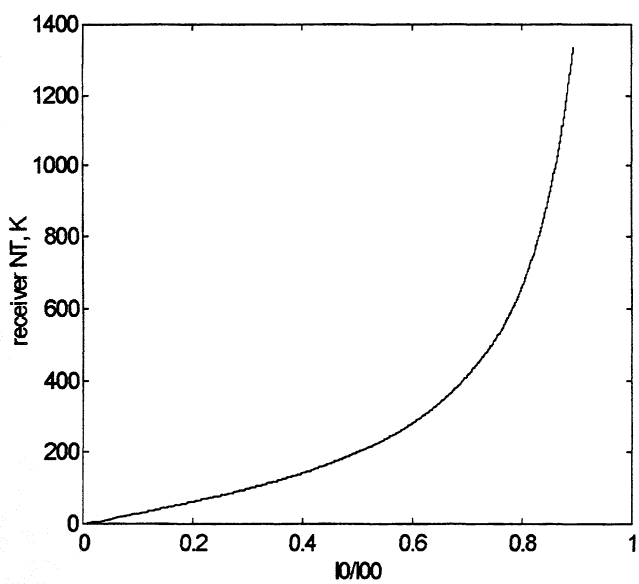

Figure 2. Predicted intrinsic receiver noise temperature for an ideal HEB receiver which has only temperature fluctuation noise.

The parameters used in Figure 2 are typical for NbN PHEBs (C=1, b=4, dR/dθ = 75 ohms/K, T_c = 10 K, R_L = 50 ohms).

In Figure 3 below, we can clearly see the opposite trends of the two contributions to the output noise, T_{FL} and T_J , as the LO power is changed. Figure 4 indicates that the conversion loss has a minimum for a fairly low LO power, i.e. large I_0/I_{00} (about 0.85).

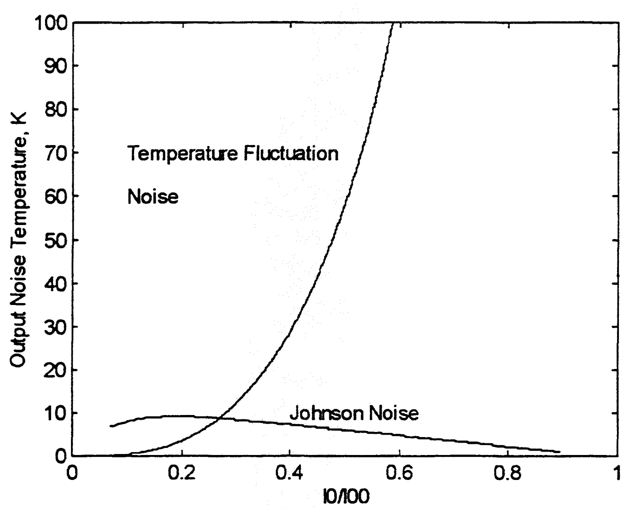

Figure 3. Temperature fluctuation noise and Johnson noise at the output of a typical NbN HEB mixer. Parameters are: C=1, dR/dθ = 55 ohms/K, b=4, T_c =10K

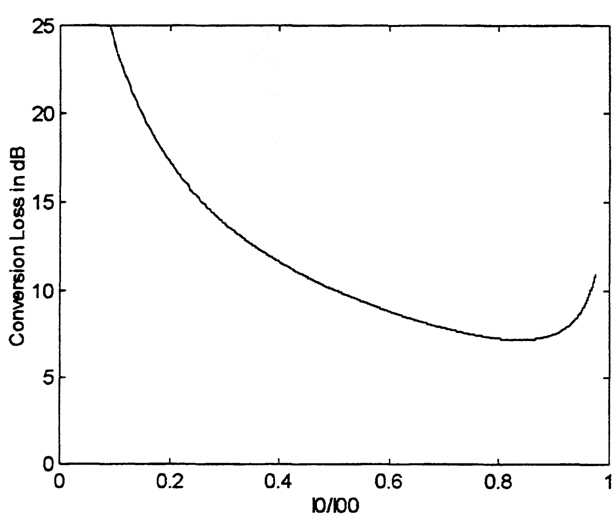

Figure 4. SSB Conversion loss versus normalized current (I_0/I_{00}) for the same HEB mixer as in Figure 3.

Due to the other noise sources in a practical receiver (Johnson noise, IF amplifier noise) beyond the fluctuation noise, increasing the LO power to a very large value will not be the condition for which the receiver noise temperature will be optimized. Conversely, the region of very low LO power, in which the conversion gain has a maximum, will not result in the lowest receiver noise temperature either, since then the temperature fluctuation noise becomes very large. The optimum receiver noise temperature should occur for an LO power in between these extremes. We will explore this question as we compare the predictions from the standard model to experimental data obtained recently on NbN PHEB devices.

COMPARISON WITH EXPERIMENTAL DATA

Many experiments yield data for both T_{out} and $T_{RX,DSB}$ (see [10]). The measured DSB receiver noise temperature is of course the total value, including input losses. One can then also find L_c from (7). This value will be the total SSB conversion loss, from the mixer input (outside the dewar) to the IF amplifier, including all input losses, and mismatch at the RF and the IF. Often, it is possible to either independently measure, or to estimate, the losses outside the mixer itself, and thus one can also find the intrinsic receiver noise temperature, and the intrinsic mixer conversion loss, $L_{c,int}$. These are the quantities calculated in (2) and (7). Experiments can thus obtain data for three quantities:

(i) $T_{R,DSB,int}$;
(ii) T_{out};
(iii) $L_{c,int,SSB}$.

Values for these quantities were obtained from measured data at different points in the IV-diagram, by varying the bias voltage and the LO power, respectively. We have used this procedure for several different NbN devices. We adjusted only the two parameters N and C in order to obtain the best fit between predictions based on the standard model, and the experimental values of the above three variables, measured as a function of LO power. The value of C can be obtained by fitting the conversion loss data, which do not depend on N. This value for C is then inserted in (4) and a fit is obtained to the data for T_{out}. The values of C and N may need to be re-adjusted to obtain a good fit to the data for the intrinsic receiver noise temperature. The noise temperature for the specific IF amplifier used in each experiment was also measured independently, and inserted in the equations. Reasonable fits were possible as the LO power was varied, as shown for one device in Figure 5 though 7. The best fit values of C and N were obtained from similar plots for a total of five devices, measured at frequencies near 650 GHz (devices 1,2,3 and 5) and 1560 GHz (device 4), respectively, as summarized in Table 1. The standard model also predicts well the variation of the output noise temperature with bias voltage at constant LO power, but not the conversion loss and the receiver noise temperature under these conditions, as discussed further below.

TABLE 1. Summary of data derived from a comparison of experimental measurements and calculations based on the standard model.

Dev.#	t,nm	freq. THz	$T_{R,i}$ opt, K	I_0/I_{00} at opt.	$L_{c,i}$ opt dB	T_{out} opt.	C	N times 10^{-4}	$\frac{dR}{d\theta}$ Ω/K	b	V_0 (mV)
1UM	3.5	0.62	190	0.46	8.5	82	1.2	2.6	65	4.45	2.0
2UM	3.5	0.62	240	0.45	10.2	60	1.1	2.2	55	4.45	2.0
3CTH	3.5	0.60	300	0.32	14	30	1.0	3.0	75	3.79	1.4
4UM	4.0	1.56	435	0.37	12.3	42	1.0	4.84	100	2.4	5
5UM	5.0	0.62	500	0.42	15.7	27	0.8	0.86	15	12.5	2.0

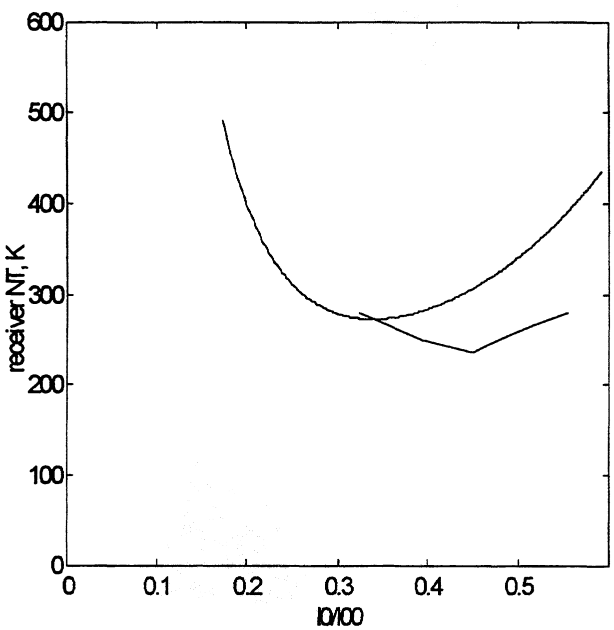

Figure 5: Predicted and measured intrinsic receiver noise temperature versus normalized bias current for device #2 in Table 1. Measurements were done at 620 GHz. In this and the following figures, the smooth curve is the predicted one, if not specifically marked.

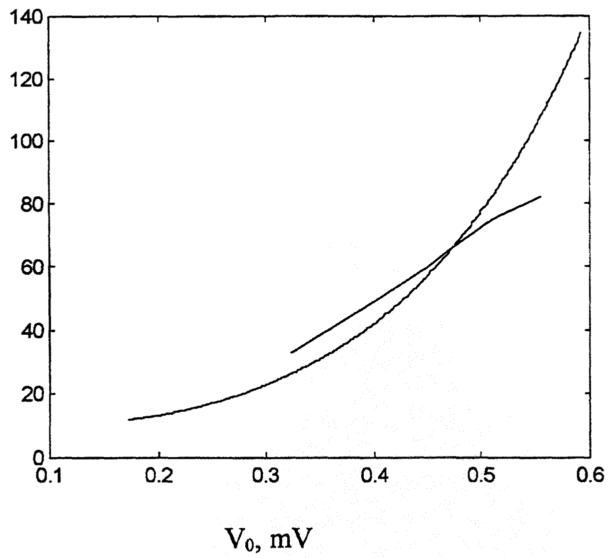

Figure 6: Predicted and measured output noise temperature in K, versus normalized bias current for device #2.

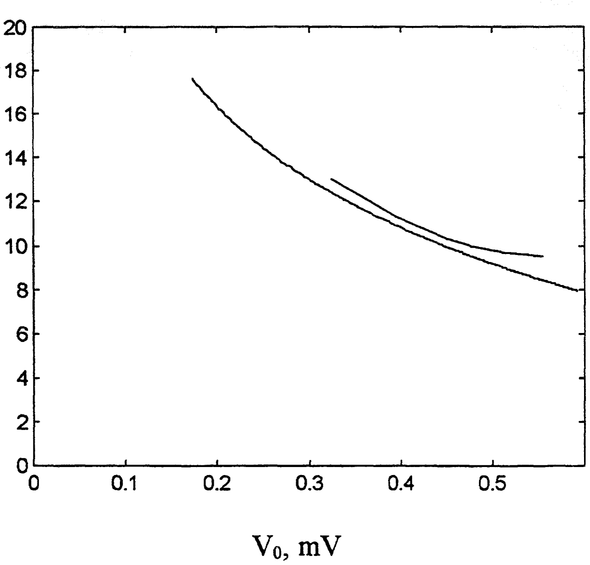

Figure 7: Predicted and measured intrinsic conversion loss (in dB) versus normalized bias current for device #2.

DISCUSSION

The comparison given above between theoretical predictions and experimental data for several devices enables us to draw some general conclusions. Specifically,

1) There is a qualitative agreement between the theoretical and experimental curves of $T_{R,DSB}$, $L_{c,i}$, and T_{out}, as the LO power is varied over the range used in the experiments.
2) The optimum intrinsic $T_{R,DSB}$ is in the range 190 K to 500 K. The thinnest devices consistently yield lower NT.
3) The optimum receiver NT occurs at a very similar I_0/I_{00} value for all devices; the experimental range is 0.32 to 0.46, and this is close to what is predicted from the standard model.
4) The optimum conversion loss is at best 8.5 dB, and more commonly 10-12 dB. The devices with lowest conversion loss typically also have higher output noise temperature. The conversion loss is lower by a sufficiently large factor that $T_{R,DSB}$ is still lower for these devices.
5) The values for $dR/d\theta$ also fall in a fairly narrow range, from 55 to 100 Ω/K, except for the 5 nm device which has $dR/d\theta = 15\ \Omega/K$.

We discuss some of these conclusions further below:

C-value and optimum conversion loss.

We can predict the C-value from the standard model by using the slope of the IV-curve for the no-LO case, i.e. at a current of I_{00}, using the following expression from [5]:

$$\frac{dV}{dI} = R_0 \frac{1 + C_0 I_{00}^2}{1 - C_0 I_{00}^2} \quad (10)$$

For all of our recent NbN devices, the slope at this point of the IV-curve is essentially horizontal, i.e. dV/dI is infinite, and $C = C_0 I_{00}^2 \approx 1.0$. This is seen to agree with the C-value derived from our comparison with the experimental data. For C = 1, the optimum conversion loss is 6 dB, but this is attained for a much larger I_0/I_{00}-value than seen in the experiments ($I_0/I_{00} \approx 0.8$ to 0.9). As mentioned before, the low conversion loss at larger normalized current does not lead to the optimum noise temperature, since the fluctuation noise grows rapidly with increasing I_0/I_{00}. The C-value we derive from fitting the experimental data of receiver noise temperature, etc., is close to 1.0 (the range is 0.8 to 1.2). We can therefore assume an effective value for C of 1.0 when assessing the optimum performance of NbN HEBs (this is quite conservative since we have already measured NbN devices with C as high as 1.2, which have lower noise temperature than we claim for NbN in this section).

To avoid confusion, we should mention that Karasik and Elantiev [8] use a different definition of C ($C=C_0I_0^2$, *where I_0 is the current at the operating point*).

N-value and dR/dθ.

The values for N and dR/dθ also fall within a fairly narrow range. One can estimate dR/dθ based on IV-curves for different temperatures, and this was done for a NbN PHEB in reference [10]. A value similar to what we have found here was obtained, dR/dθ = 63 Ω/K. For Nb DHEB devices, dR/dθ was estimated to be in the range 68-250 Ω/K [11], somewhat lower in operating points which yield optimum conversion gain. However, this reference found that it was not generally possible to predict T_{out} for Nb DHEBs from parameters such as dR/dθ and the standard model [11]. We will compare PHEBs and DHEBs later in this paper.

Discussion of Variation with the Bias Voltage

Measured and modeled data for different bias voltages at constant LO power are given in the following three figures. The bias voltage enters the equations through $b = R_L * I_{00} / V_0$. We used the same values for C and N, resp., which were obtained from the fit in Figures 5 through 7. The values of I_0/I_{00} for each point were found from an experimental IV-curve for constant LO power. This curve included the point at which the optimum receiver noise temperature was measured.

It is clear that the standard model does not predict the variation of receiver noise temperature (Figure 8) or conversion loss (Figure 9) with the bias voltage, although the output noise temperature curve shows a good fit (Figure 10). The predicted conversion loss depends only on C, not on N, and it is thus clear that if one wanted to fit the conversion loss versus V_0 with the standard model expression, then C must also vary with V_0. Specifically, C would need to decrease as V_0 increases. This behavior is actually found in the one-dimensional hot spot model of Merkel et al. [7]. In future work, we plan to incorporate the conclusions from [7] explicitly in our model. This will not be pursued further here, however. Instead, we note that close to the optimum, $C \approx 1$ produces a good fit, and that this point occurs for a bias voltage corresponding to a b-value of roughly 4.

Another parameter which changes the value of b in our equations is R_L. Since the b-dependence for receiver noise temperature and conversion loss differs from that of the standard model, we do not at this stage know how to predict how the receiver noise temperature would change if we were to change R_L. We can, however, predict what would happen if we were to change R_L and V_0 by the same factor. In this case, b will be unchanged, and the receiver NT will also not change. There are almost certain to be parameter combinations for which the NT would decrease for a change of R_L from the value of 50 ohms which we assume throughout this paper, however. This offers an intriguing possibility of further lowering the receiver NT of THz HEBs.

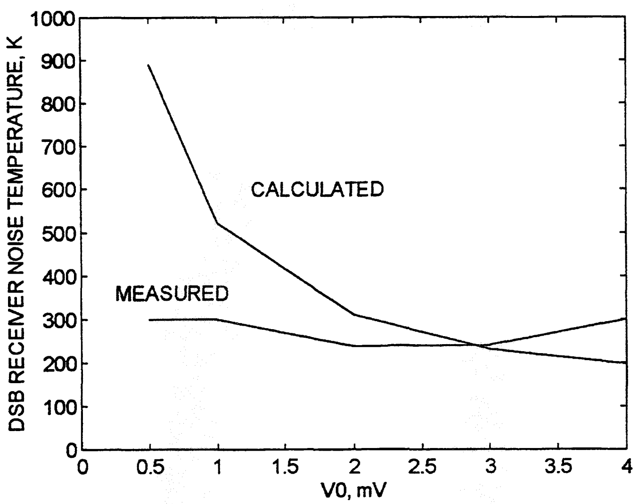

Figure 8: Calculated and measured intrinsic DSB receiver noise temperature versus bias voltage for device #2. The LO power was kept constant for this and the next two plots.

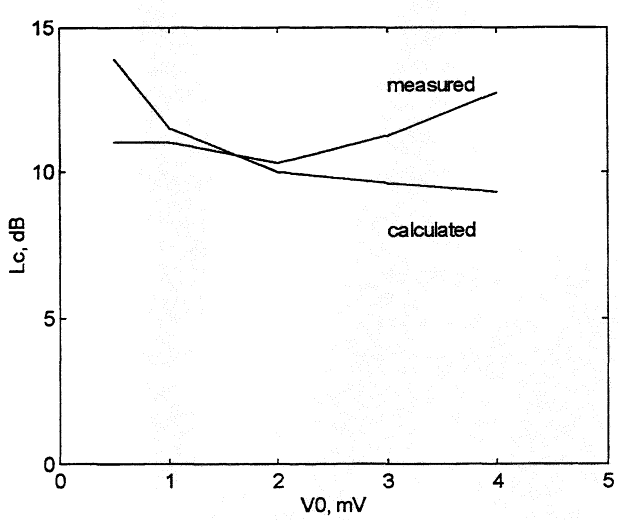

Figure 9: Calculated and measured intrinsic SSB conversion loss versus bias voltage for device #2.

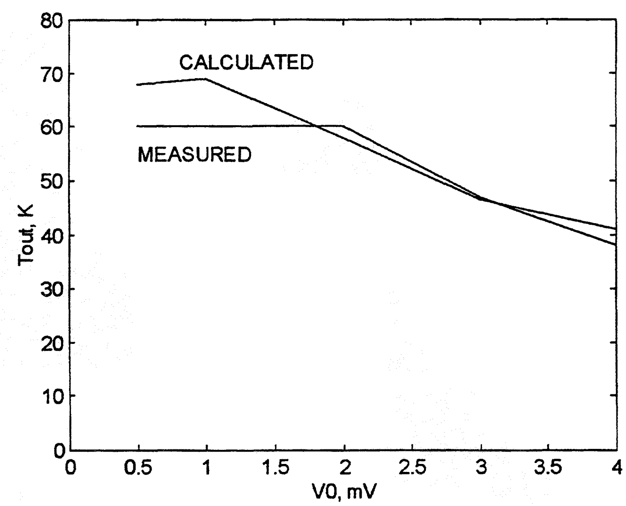

Figure 10: Calculated and measured output noise temperature (K) versus bias voltage (mV) for device #2.

Prediction of Optimum Receiver Noise Temperature for Devices with Different Critical Temperatures.

Based on the above results, we can make some approximate predictions for the expected optimum receiver noise temperature for different materials, such as NbN, Nb, and Al. The detailed model for diffusion-cooled HEBs is certainly different from that of PHEBs, but it is believed that the standard model is still a sufficiently good guide for this estimate. The standard model was, indeed, used for this purpose by Elantiev and Karasik [8], and by Karasik and McGrath [12]. In performing this estimate, we will choose values of $C = 1.0$, and $dR/d\theta = 55\ \Omega/K$, which are typical for the optimum points of NbN devices. The main difference between the different materials then is the transition temperature, θ, for which we take 10 K for NbN, 5 K for Nb, and 1.5 K for Al. Any real receiver would also be somewhat limited in performance by its IF amplifier, and we assume a value for T_{IF} of 5 K, about the best which is presently achievable. Figure 11 shows our predictions for receiver NT for these materials, assuming the same values for the other model parameters. **The conclusion is that a lower transition temperature in principle helps one achieve a lower receiver NT. However, other factors must also be considered, as becomes clear as we compare these predictions with the best experimental data measured so far.** As expected, the optimum receiver noise temperature occurs for a higher value of I_0/I_{00} (0.46 for Nb and 0.75 for Al) as θ is decreased, since the temperature fluctuation noise is lower. The total output noise temperature at the optimum receiver noise point is 13 K for Nb and 6 K for Al. Our predicted optimum receiver noise temperatures are considerably higher than those obtained by Elantiev and Karasik [8], and later Karasik and McGrath[12]. The latter authors find 50 K for NbN, 12 K for Nb, and 4 K for Al. These estimates utilize approximations which would appear to be equivalent to using a very large C-value (about 6, using our definition), which we believe is unrealistic (see the discussion above). The optimum conversion loss is consequently predicted to be very low (some conversion gain, actually). Conversion gain has been measured in lower frequency HEB mixers [5, 11], and for a NbN PHEB mixer at very low IF (600 kHz) in one case [13]. While HEBs clearly can achieve conversion gain under such special conditions, this has not yet been demonstrated at GHz IF for any THz HEB mixers. Instead, we find a lowest conversion loss of 8.5 dB (see Table 1). In comparing existing measured data for Nb DHEBs with our predictions [11], we note that for the frequencies 533, 1267, and 2540 GHz, the output noise temperature was 41K, 16.6 K, and 10 K, respectively. At the same frequencies, the intrinsic conversion loss was 14 dB, 13 dB, and 18.5 dB. The lowest intrinsic receiver noise temperature was found at 1267 GHz, and would be 210 K, if we assume T_{IF} =5 K. This is comparable to the best NbN results, as are the recent measurements of the total receiver NT at 2.54 THz [14]. The conversion loss at all the above frequencies is higher than for any of the NbN mixers, however, which explains why the measured receiver NT at the present time is roughly comparable for Nb DHEBs and NbN PHEBs. **Thus, low output noise is not sufficient, one also must have low conversion loss, in order to realize the optimum receiver noise temperature performance of which HEB mixers are capable.** Nb DHEBs may also have somewhat higher values of dR/dθ [11], whereas 55 ohms/K was used for the predicted performance in Figure 11. NbN mixers have higher output noise in general, but also considerably lower conversion loss. For NbN we have included two curves in Figure 11: one with C=1, and another one with C=1.2 and dR/dθ = 45 ohms/K which approximately matches the best NbN mixer in Table 1 with $T_{R,DSB}$ of 190 K; note that this performance has already been achieved. The situation for Al is of course completely unpredictable at the moment, until experimental data become available. Specifically, it must be clarified whether low conversion loss is at all possible in Al, for which a different process due to bandgap suppression from the hot electrons (Semenov and Gol'tsman, [15]) may be responsible for the HEB conversion gain, (it appears that no electron equilibrium distribution can become established). Other uncertainties in the Al case are the effective value for dR/dθ, and whether there are any difficulties in operating in the optimum region for this material, which requires lower LO power, based on the standard model (instabilities may become a problem). Finally, we should note that the quantum noise limit for any coherent double sideband mixer is hf/2k = 24 K at 1 THz, and 61 K at 2.54 THz. None of the above HEB mixer technologies can of course produce lower noise temperature than hf/2k, and the intrinsic noise temperatures of NbN mixers are presently less than a factor of ten times this limit. As HEB technology develops further, the difference in receiver NT between different versions will matter less and less, and other factors may assume primary importance.

The standard model versus newer models

We have shown that some features in the measured data for NbN PHEBs can be explained quite well by the standard model, whereas others can not. Specifically, we can not model the dependence of the receiver noise temperature on V_0, and as a consequence also do not know the effect of R_L. HEB receiver designers will require a model which covers all important aspects in order to be able to successfully optimize all aspects of the performance of these already very good receivers, however. The standard model is basically a "zero-dimensional" model which can for example be expected to describe an HEB device exposed to sub-bandgap microwave power. The DC power and the microwave power are then absorbed in equal resistances in any given section of the device, and a single heated region ("hot spot") is obtained. On the other hand, at above bandgap frequencies, THz radiation is absorbed in the entire device, whereas DC heating is likely to still create a hot spot (see Merkel et al.,[7]). A more complicated model is clearly required for the THz case. Progress along these lines will require further work in which HEB theory and "diagnostic" measurements of the type we have used, are coupled in order to validate the new HEB models.

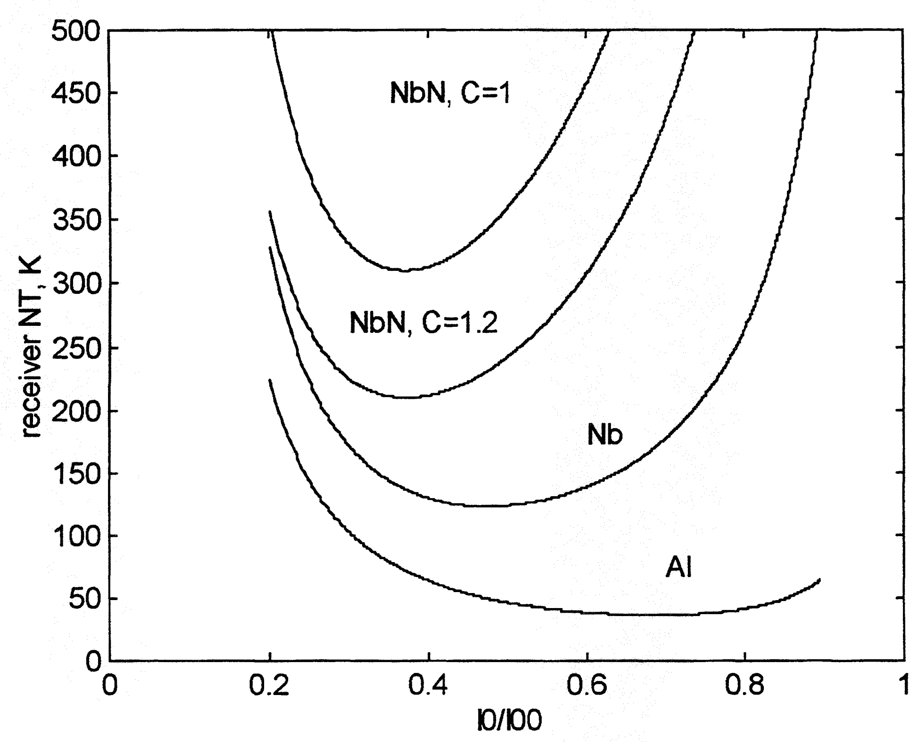

Figure 11. Optimum noise temperature for three different HEB technologies, predicted from the standard model. Parameters assumed are C=1 (additional curve for NbN with C=1.2), b = 4, R_L = 50 ohms, and dR/dθ = 55 ohms/K. T_c is 10 K, 5 K, and 1.5 K, respectively, for NbN, Nb, and Al.

CONCLUSION

Comparison of experimental data for several NbN PHEBs with calculations based on the standard model indicate good agreement with the variation of receiver NT, output noise and conversion loss as a function of LO power. As the bias voltage (V_0) is varied, it appears that the effective self-heating parameter C decreases with increasing voltage. Further investigations of this problem should be able to include the variation with V_0, and result in predictions of the optimum IF load impedance. It would be interesting to extend the measurements to the IF impedance, and compare this with model predictions. Ultimately, HEB designers need a comprehensive model upon which to base the detailed design of matching circuits, which optimize not only the noise temperature, but the IF bandwidth and the flatness of the receiver NT versus IF frequency as well.

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REFERENCES

[1] F. Arams, C. Allen, B. Peyton, and E.Sard, Proc. IEEE, **54**, 308 (1965).
[2] E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, A.I. Elant'ev, B.S. Karasik, A.D. Semenov, Sov.Phys.Superconductivity, **3**, 1582 (1990).
[3] J.-X. Yang, F. Agahi, D. Dai, C. Musante, W. Grammer, K.M. Lau, and K.S. Yngvesson, IEEE Trans. Microw.Theory Techniques, **MTT-41**, 581 (1993).
[4] J.-X. Yang, Ph.D. thesis, University of Massachusetts at Amherst, Dept. of Electrical and Computer Engineering, Sept. 1992.
[5] H. Ekström, Ph.D. thesis, Chalmers University of Technology, Dept. of Microelectronics (1995).
[6] H. Ekström, B. Karasik, E. Kollberg and S. Yngvesson, "Conversion Gain and Noise of Niobium Hot-Electron Mixers," IEEE Trans.Microw.Theory Techniques, **MTT-43**, 938 (1995).
[7] H.F. Merkel, E.L. Kollberg, and K.S. Yngvesson, Proc. Ninth Intern.Symp.Space THz Technology, p. 81 (1998). Also see paper by Merkel et al. in this conference proceedings.
[8] B.S. Karasik, and A.I. Elantiev, Proc. Sixth Intern.Symp.Space THz Technology, p. 229 (1995).

[9] H. Ekström, and B.S. Karasik, Appl.Phys.Lett, **66**, 3212-3214 (1995).
[10] H. Ekström, E. Kollberg, P. Yagoubov, G.Gol'tsman, E. Gershenzon, and S. Yngvesson, Proc. Eighth Intern.Symp.Space THz Technology, p. 29 (1997).
[11] P.J. Burke, Ph.D. thesis, Yale University, Dec. 1997.
[12] B.S. Karasik, and W.R. McGrath, Proc. Ninth Intern.Symp.Space THz Technology, p. 73 (1998).
[13] E. Gerecht, C.F. Musante, H. Jian, K.S. Yngvesson, J. Dickinson, J. Waldman, G.N. Gol'tsman, P.A. Yagoubov, B.M. Voronov, and E.M. Gershenzon, Proc. Ninth Intern.Symp.Space THz Technology, p. 105 (1998).
[14] R. Wyss, B. Karasik, W.R. McGrath, B. Bumble, and H. LeDuc, "Noise and Bandwidth Measurements ...", this conference proceedings.
[15] A. Semenov and G. Gol'tsman, paper submitted to JAP, 1998.