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Published in:
Applied Physics Letters

DOI:
10.1063/1.1887812

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Citation: Appl. Phys. Lett. **86**, 163503 (2005); doi: 10.1063/1.1887812
View online: https://doi.org/10.1063/1.1887812
View Table of Contents: http://aip.scitation.org/toc/apl/86/16
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS **86**, 163503 (2005)

Direct detection effect in small volume hot electron bolometer mixers

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(Received 18 October 2004; accepted 16 February 2005; published online 14 April 2005)

We measure the direct detection effect in a small volume (0.15 μm $\times$ 1 μm $\times$ 3.5 nm) quasioptical NbN phonon cooled hot electron bolometer mixer at 1.6 THz. We find that the small signal sensitivity of the receiver is underestimated by 35% due to the direct detection effect and that the optimal operating point is shifted to higher bias voltages when using calibration loads of 300 K and 77 K. Using a 200 GHz bandpass filter at 4.2 K the direct detection effect virtually disappears. This has important implications for the calibration procedure of these receivers in real telescope systems. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1887812]

NbN phonon cooled hot electron bolometer (HEB) mixers are currently the most sensitive heterodyne detectors at frequencies above 1.2 THz.[1,2] They combine a good sensitivity (8–15 times the quantum limit), an IF bandwidth of the order of 4–6 GHz,[3–6] and a wide RF bandwidth from 0.7 to 5.2 THz. However, for use in a space based observatory, such as Herschel, it is of vital importance that the local oscillator (LO) power requirement of the mixer is compatible with the low output power of present day THz LO sources.[7] This can be achieved by reducing the mixer volume and critical current density.[5] However, the large RF bandwidth and low LO power requirement of such a mixer result in a direct detection effect, characterized by a change in the bias current of the HEB when changing the RF signal from a black body load at 300 K to one at 77 K.[8–11] As a result the measured sensitivity using a 300 K and 77 K calibration load differs significantly from the small signal sensitivity relevant for astronomical observations. In this article we describe a set of dedicated experiments to characterize the direct detection effect for a small volume quasioptical NbN phonon cooled HEB mixer.

The devices are fabricated on a high purity Si wafer that is covered at MSPU, Moscow with a NbN film with T_c =9.3 K and an expected thickness of 3.5 nm. The fabrication is mostly identical to the process described in Refs. 3 and 12, however, in stead of a spiral antenna we use a twin slot antenna with a center frequency of 1.6 THz and a bandwidth of 0.9 THz. The bolometer length is 0.15 μm, the width 1 μm, the critical current I_c=68 μA at 4.2 K and the normal state resistance is 170 Ω at 11 K. In the experiment we use a quasi-optical coupling scheme in which the HEB mixer chip is glued to the center of an uncoated elliptical Si lens. The lens is placed in a mixerblock thermally anchored to the 4.2 K plate of a liquid Helium cryostat. We use one Zytex G104® at 77 K as infrared filter and 0.9 mm HDPE as vacuum window. The LO power required to reach the optimal pumping level of the mixer, as determined by the isothermal technique, $P_{\mathrm{LO,iso}}$=30 nW. The real LO power need P_{LO}, determined from the output power of a calibrated LO source and the known optics losses, has been estimated to be 2.4 times larger for similar mixers,[13] hence P_{LO}=70 nW.

In the first experiment we measure the uncorrected double sideband receiver noise temperature T_N on all possible bias points of the mixer using a measurement of the Y factor $Y=P_{\mathrm{hot}}/P_{\mathrm{cold}}$. $P_{\mathrm{hot/cold}}$ is the output power of the receiver at a hot/cold load evaluated at a single bias point, i.e. at one single value of V and P_{LO}. We use the Callen and Welton definition to calculate T_N from the measured Y factor.[14] Simultaneously we measure $I_{\mathrm{hot/cold}}$, the mixer bias current at a hot/cold load at each bias point. As a hot load we use Eccosorb at 300 K glued to a chopper wheel and as a cold load we use Eccosorb at 77 K. Rotating the chopper wheel enables a switch from a hot load to a cold load, which is done at 12 Hz. We take $I_{\mathrm{hot/cold}}$ and $P_{\mathrm{hot/cold}}$ at each bias point prior to proceeding to the next bias point. As a result we are not sensitive to drifts in the setup with time scales longer than 0.2 s. As a LO source we use a FIR gas laser at 1.627 THz. The LO power is attenuated by means of a rotatable grid. The LO and RF signals are coupled using a 3.5 μm Mylar beamsplitter. The total optics loss in the signal path is estimated to be 4.3 dB, the noise temperature of the optics $T_{N,\mathrm{eff,opt.}}\approx$200 K. Both the grid rotation angle and the position of the hot/cold chopper are computer controlled. The same is true for the bias voltage and the measured mixer bias current. A bias-T separates the DC bias from the IF signal at the output of the chip. The IF signal is directed to the input of a 1–2 GHz isolator and Berkshire HEMT amplifier with 43 dB gain and a noise temperature of 5 K. At room temperature the signal is further amplified and filtered in a 80 MHz bandwidth at 1.4 GHz before it is detected using an Agilent power meter also connected to the computer.

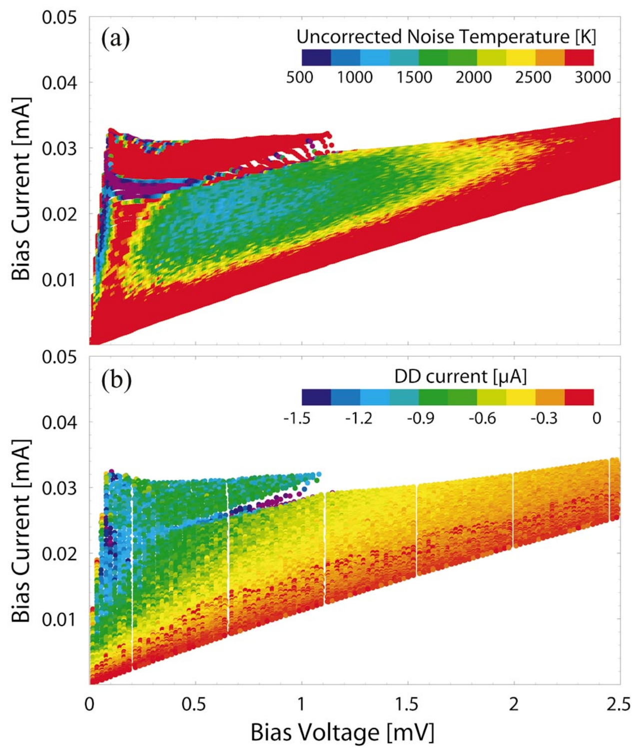

FIG. 1. (Color) (a) T_N uncorrected for any optics losses over the entire IV plane of the mixer, the minimum value is T_N=1400 K. (b) The direct detection current $I_{DD}=I_{hot}-I_{cold}$.

In Fig. 1(a) we present the measured values of T_N. We observe a relatively broad region of optimal response with a maximum sensitivity of T_N=1400 K. The measured direct detection current $I_{DD}=I_{hot}-I_{cold}$ is shown in Fig. 1(b). We observe that I_{DD} is always negative, in agreement with results reported in (Refs. 8, 9, and 11). The magnitude of the direct detection current ranges from virtually 0 μA at high bias voltages, to about −0.6 μA at the optimal bias region to more than −1 μA at very low bias voltages. This indicates that the difference in RF power between the 77 K and 300 K load changes the bias current of the mixer in the same way as an increase in P_{LO}. The RF power absorbed by the mixer from the thermal load within the full RF bandwidth of the receiver, P_{RF}, can be calculated using

$$P_{RF} = k_B \cdot BW \cdot T_{eff,hot/cold} \quad (1)$$

with BW the RF input bandwidth of the receiver, k_B Boltzmann's constant, and $T_{eff,hot/cold}$ the effective temperature of the load in the Callen and Welton limit, given by $T_{eff,cold}$ =152 K and $T_{eff,hot}$=230 K. Hence we obtain P_{RF}=1.9 nW for the cold load and P_{RF}=2.9 nW for the hot load. The difference is 1.3% of the LO power needed to pump the mixer.

In Fig. 2 we illustrate the effect of a nonzero direct detection current. The two black squares, marked with P_H^A and P_C^B represent the measured values of P_{hot}, I_{hot}, and P_{cold}, I_{cold}, respectively, each obtained at one single operating point, i.e., at one single value of V (V=0.6 mV) and at one single value of P_{LO}. P_{LO} is equal to the optimal LO power. In the same figure we also show $P_{hot}(I)$ and $P_{cold}(I)$. The data was obtained by changing the LO power. To obtain T_N as shown in Fig. 1 we have evaluated the Y factor $Y=P_{hot}/P_{cold}$ $\equiv P_H^A/P_C^B$. It is obvious that the bias current at which P_{hot} is evaluated is lower than the bias current at which P_{cold} is

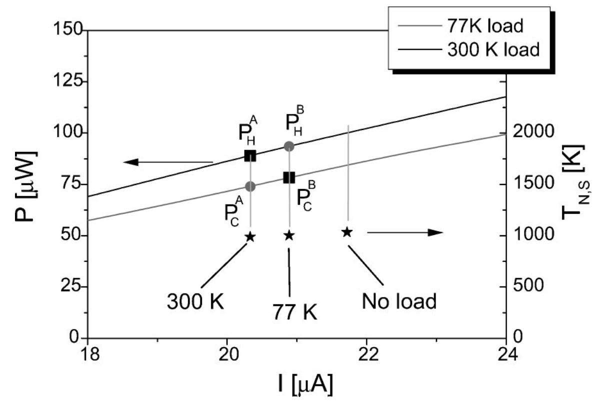

FIG. 2. The effect of a nonzero direct detection current at V=0.6 mV, $I\approx$0.21 mA, where T_N=1400 K. The top line gives the receiver output power at hot load as a function of bias current, the bottom line at cold load. The data is obtained bychanging the LO power at constant bias voltage. The stars give the small signal noise temperature $T_{N,S}$ around three background loads. For an explanation of the symbols we refer to the text.

evaluated. Imagine now that we observe, with the receiver discussed in this paper, an astronomical source which represents itself as a small input power change on top of a background with an identical power input as our 77 K load. A small input power change is in this context defined as a power change that results in a negligible value of I_{DD}. To obtain the receiver noise temperature in this case we need to evaluate the small signal Y factor $Y_S=P_H^B/P_C^B$. This implies that we have to reduce P_{LO} at hot load to make sure that the bias current remains constant, thus compensating for the bias current shift caused by P_{RF} at hot load. The noise temperature in the small signal limit, $T_{N,S}$ obtained in this way, is shown in Fig. 3. We find a minimum value of $T_{N,S}$=900 K, which is 35% lower than the minimum value of T_N =1400 K. We also observe that the location of the minimum in the noise temperature is shifted to lower bias voltages and that the small region with an apparent high sensitivity at V $\approx$0.2 mV and $I\approx$0.24 mA, clearly visible in Fig. 1(a), has disappeared. Evaluating Y_{factor} at a background power level identical to the 300 K load, which can be obtained by evaluating $Y_S'=P_H^B/P_C^B$ gives an identical result. The situation at other background loads can be estimated as follows: Since $I_{DD}(P_{RF})\sim I_{DD}(P_{LO})$ and $I_{DD}(P_{LO})$ is measured to be linear for small changes in P_{LO} we can calculate I_{DD} by linear

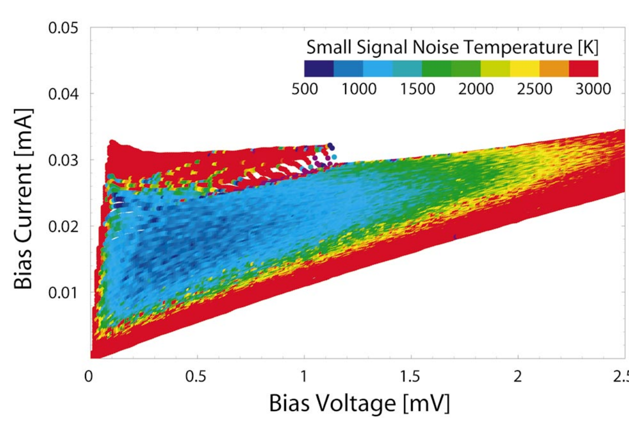

FIG. 3. (Color) The double sideband receiver noise temperature in the small signal limit, $T_{N,S}$, around a background corresponding to the 77 K load. The minimum value is $T_{N,S}$=900 K. A background corresponding to the 300 K load gives an identical result.

extrapolation from the two measured values at 300 K and 77 K for any load. We show as an example in Fig. 2 the value of I_{DD} in the limit of zero background and zero optics losses. In this case the effective input power is given by half a noise quantum, corresponding to 35 K at an LO frequency of 1.6 THz.[14] We find that $T_{N,S} \approx 980$ K for all three background loads. This is indicated by the stars in Fig. 2.

The physical process responsible for the direct detection effect can be explained as follows. For any receiver we know that noise temperature is a combination of the conversion gain η and the output noise of the mixer T_{out}. However, both quantities are, for a HEB, a strong function of the mixer bias current, i.e., $\eta = \eta(I)$ and $T_{\mathrm{out}} = T_{\mathrm{out}}(I)$. So the expression for the Y factor can be written as

$$Y = \frac{P_{\mathrm{hot}}}{P_{\mathrm{cold}}} \equiv \frac{2\eta(I_{\mathrm{hot}})T_{\mathrm{hot}} + T_{\mathrm{out}}(I_{\mathrm{hot}})}{2\eta(I_{\mathrm{cold}})T_{\mathrm{cold}} + T_{\mathrm{out}}(I_{\mathrm{cold}})}, \qquad (2)$$

with $\eta(I)$ the single sideband receiver gain and $T_{\mathrm{hot/cold}}$ the temperature of the hot/cold load. In the small signal limit, where $I_{DD}=0$ we use the same equation with $I_{\mathrm{hot}} = I_{\mathrm{cold}} = I$. To illustrate the usefulness of this approach we calculate η and the current dependence of $T_{\mathrm{out}}(I)$ at the same bias point as discussed in Fig. 2 ($V=0.6$ mV, $I \approx 0.21$ mV) using the uniform electron heating model.[1,15] The implementation of this procedure gives a uncorrected noise temperature $T_N = 1400$ K where the small signal noise temperature $T_{N,S} = 980$ K is used as input parameter to calculate the magnitude of T_{out}. This agrees well the experimental results.

To confirm these results we have repeated the experiment with a metal mesh RF bandpass filter mounted in front of the mixer at the 4.2 K stage of the cryostat.[16] The effective bandwidth of the filter we use is 200 GHz, centered around 1.6 THz. Hence the filter reduces the effective input bandwidth of the receiver by a factor of 4.5. As a consequenceP_{RF} is reduced compared with the previous experiment to $P_{\mathrm{RF}} = 0.42$ nW and $P_{\mathrm{RF}} = 0.62$ nW for cold and hot load, respectively. The difference between the two is 0.2 nW, only 0.3% of P_{LO}. A similar effect could have been achieved by using a reduced temperature difference between the hot and cold load. We find a minimum noise temperature of $T_N = 1050$ K, 25% lower than the T_N without the use of the filter, but still higher than $T_{N,S}$ (see Fig. 1). This difference is caused by a small remaining direct detection effect together with the limited in-band transmission of the filter.

We conclude that the direct detection effect significantly changes the response of small volume, quasioptical HEB mixers when measured using the standard Y factor method with a 77 K cold load and a 300 K hot load. Using a combined measurement of the receiver output power and bias current at hot load and cold load we can predict the small signal response of the mixer, relevant for astronomical observations. We have discussed a device with 0.15×1 μm surface area, an input bandwidth of about 0.9 THz and a LO power requirement of 70 nW. The effective input power difference between hot and cold load is 1 nW for this receiver. We observe that the minimum noise temperature obtained using the Y factor at one single bias point, i.e., at one value of the bias voltage and LO power, is 35% higher than the small signal noise temperature around a background signal with a radiated power corresponding to either the 77 K or 300 K load. These results have been verified experimentally using a cold rf bandpass filter in the signal path of the receiver. By this we reduce the effective bandwidth and thus the effective input power difference between hot and cold load with a factor of 4.5–0.2 nW. As a result the direct detection effect virtually disappears, as well as the difference between the conventional noise temperature and small signal noise temperature.

The authors wish to thank J. Kooi, P. de Korte, and H. Hoevers for stimulating interest and support and W. J. Vreeling and Z. Yang for lab support.

[1] E. M. Gershenzon, G. N. Goltsman, I. G. Gogidze, A. I. Eliantev, B. S. Karasik, and A. D. Semenov, Sov. Phys. Semicond. **3**, 1582 (1990).
[2] D. E. Prober, Appl. Phys. Lett. **62**, 2119 (1993).
[3] J. J. A. Baselmans, J. M. Hajenius, R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Gol'tsman, Appl. Phys. Lett. **84**, 1958 (2004).
[4] A. D. Semenov, H.-W. Hübers, J. Schubert, G. N. Gol'tsman, A. I. Elantiev, B. M. Voronov, and E. M. Gershenzon, J. Appl. Phys. **88**, 6758 (2000).
[5] S. Cherednichenko, P. Khosropanah, E. Kollberg, M. Kroug, and H. Merkel, Physica C **372–376**, 407 (2002).
[6] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol'tsman, S. Svechnikov, and E. Gershenzon, Appl. Phys. Lett. **73**, 2814 (1998).
[7] G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, H. Javadi, F. Maiwald, and I. Mehdi, IEEE Trans. Microwave Theory Tech. **52**, 1538 (2004); **52**, 38 (2004).
[8] Yu. B. Vachtomin, S. V. Antipov, S. N. Maslennikov, K. V. Smirnov, S. L. Polyakov, N. S. Kaurova, E. V. Grishina, B. M. Voronov, and G. N. Gol'tsman, In Proceedings of the 15th International Symposium on Space THz Technology, Northampton, MA, 2004.
[9] S. Svechnokov, A. Verevkin, B. Voronov, E. Menschikov, E. Gershenzon, and G. Gol'tsman, in Proceedings of the 9th International Symposium on Space THz Technology, 1999, p. 44.
[10] A. D. Semenov, H.-W. Hübers, H. Richter, M. Birk, M. Krocka, U. Mair, K. Smirnov, G. Gol'tsman, and B. Voronov, in Proceedings of the 13th International Symposium on Space THz Technology, 2002, p. 229.
[11] J. Kawamura, C.-Y. Edward Tong, R. Blundell, D. Cosmo Papa, T. R. Hunter, F. Patt, G. Gol'tsman, and E. Gershenzon, IEEE Trans. Appl. Supercond. **11**, 952 (2001).
[12] M. Hajenius, J. J. A. Baselmans, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Gol'tsman, in Proceedings of the 14th International Symposium on Space THz Technology, Tucson, AZ, April 22–24, 2003.
[13] J. J. A. Baselmans, J. Kooi, A. Baryshev, and S. Cherednichenko (unpublished).
[14] A. R. Kerr, IEEE Trans. Microwave Theory Tech. **47-3**, 325 (1999).
[15] B. S. Karasik and A. I. Elantiev, Appl. Phys. Lett. **68**, 853 (1996); B. S. Karasik and A. I. Elantiev, in Proceedings of the 6th International Symposium on Space THz Technology, Pasadena, CA, 1995.
[16] Obtained from QMC Instruments Ltd., Cardiff University, Cardiff, U.K.