Phonon cooled ultra thin NbN hot electron bolometer mixers at 620 GHz

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ABSTRACT

We have measured the noise performance and gain bandwidth of 35 Å thin NbN hot-electron mixers integrated with spiral antennas on silicon substrate lenses at 620 GHz. A double-sideband receiver noise temperature less than 1300 K has been obtained with a 3 dB bandwidth of ≈5 GHz. The gain bandwidth is 3.2 GHz. A lower noise temperature of 1100 K has been achieved with an improved set-up. The mixer output noise dominated by thermal fluctuations is about 50-60 K, and the SSB receiver and intrinsic conversion gain is about -18 and -12 dB, respectively. Without mismatch losses and excluding the loss from the beamsplitter, we expect to achieve a receiver noise temperature of less than 700 K.

INTRODUCTION

The superconducting hot-electron bolometer (HEB) mixer has proved to be a strong competitor to mixers based on traditional superconducting tunnelling devices or Schottky diodes for frequencies above 1 THz. The mixing mechanism in a HEB depends on the non-linearity of electron heating and the temperature dependent resistance near T_c [1]. The HEB is consequently not limited by parasitic reactances or by the superconducting energy gap as SIS devices, and is therefore expected to have a good performance up to tens of THz. Schottky mixers which also work in the terahertz region are noisier and require orders of magnitude more LO power.

A disadvantage of bolometric mixers is a very narrow IF bandwidth mainly determined by the electron energy relaxation time. The semiconductor InSb and first Nb HEB had a bandwidth of about 1 MHz and 100 MHz, respectively [2, 3]. In both types the electron energy relaxed through interaction with phonons. A larger bandwidth has been obtained in devices of NbN which have shorter electron-phonon relaxation time. Another limitation to the relaxation time is the phonon escape time from film to substrate, determined both by the thermal resistance in the film substrate interface and the film thickness. Thus for ultra thin 35 Å NbN devices an IF bandwidth larger than 3 GHz has been measured at 4.2 K [4], enough for most practical applications.

Another approach for increasing the IF bandwidth is to make the device very short. If the device length $L<\sqrt{12D\tau_{e-ph}}$ (D is the diffusion constant and $\tau_{e\text{-}ph}$ is the inelastic electron phonon interaction time), the out-diffusion of hot electrons into the normal leads dominates over electron-phonon interaction as the main cooling mechanism [5-10].

An important property of the HEB is that the output noise should be dominated by thermal fluctuation noise which has the same frequency dependence as the IF signal [1, 11-13]. Thus the receiver noise bandwidth will be larger than the gain bandwidth. Here we present measurements of DSB receiver noise bandwidth and gain bandwidth for an ultra thin phonon cooled NbN HEB mixer operating in a 620 GHz quasi optical receiver.

MEASUREMENT SET-UP

The measurements were performed with HEB devices made from ≈35 Å thick NbN films with $T_c \approx 10$ K sputtered on silicon substrates by reactive magnetron sputtering in an argon-nitrogen gas mixture [4]. The film is patterned to form a 1 µm long and 13 µm wide bolometer strip across the centre gap of a Ti-Au spiral antenna, which has a frequency range from 300 to 1250 GHz with an impedance of 75 Ω. The substrate on which the device and antenna are integrated, is glued to an anti-reflection coated extended hyper hemispherical silicon lens with a diameter of 12.5 mm.

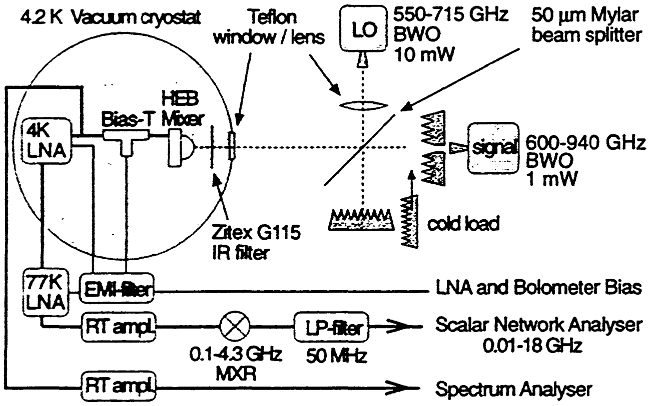

Fig. 1 Measurement set-up

Table 1. RF losses

element	loss [dB]
50µm beam-splitter	0.8
1 mm Teflon window	0.4
Zitex G115 IR filter	0.1
silicon lens	1.8
RF mismatch loss antenna-bolometer	< 2.4
total RF loss	< 5.5

The mixer is mounted in a LHe-cooled vacuum cryostat equipped with a 1 mm thick Teflon window and a 380 μm Zitex G115 IR radiation filter. We use two backward wave oscillators (BWO) as signal and local oscillator (LO) sources with a common frequency range 600- 715 GHz, Fig. 1 for IF bandwidth measurements. The radiation from the LO is focused by a Teflon lens and combined with the signal by a 50 μm thick Mylar beam-splitter. The optical losses are estimated to be about 3 dB, Table 1.

For DC bias and IF signal output the device is attached to a coplanar 50 Ω line soldered to a SMA connector, and connected to a bias-T. Data for the amplifiers used for noise measurements at different IF frequencies are shown in Table 2. Following the last amplifier is a second mixer and a 50 MHz low pass filter at the input of a scalar network analyser. For gain bandwidth measurements the IF signal from the HEB is directly fed to a spectrum analyser, amplified by a 0.01-20 GHz room temperature amplifier.

Table 2

IF freq. [GHz]		0.7	1.5	3.9
LHe LNA	(GHz)	0.68-0.92 1)	1.3-1.8 4)	3.6-4.2 5)
		4 K/17 dB	5 K/33 dB	12 K/33 dB
LN$_2$ LNA	(GHz)	0.1-2.5 2)	–	–
		20 K/40 dB	–	–
RT ampl.		120 K/30 dB 3)	120 K/30 dB 3)	150 K/30 dB 5)
RT ampl.		–	150 K/32 dB 6)	500 K/20 dB 7)

[1] NRAO
[2] Miteq
[3] Miteq
[4] Russian
[5] Russian
[6] Russian AGASTA
[7] Avantek

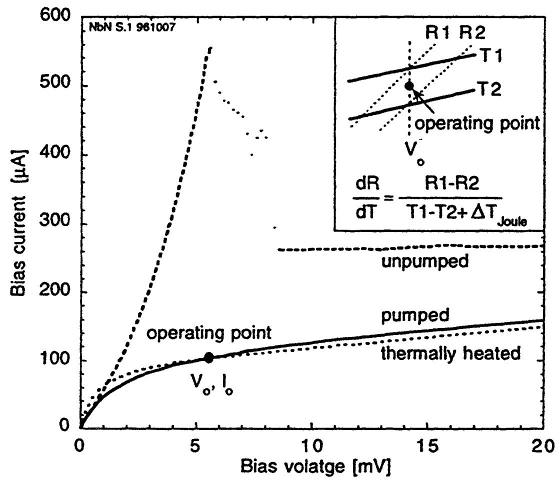

Fig. 2. IV characteristics. Inset shows part of the IV at the operating point, with two curves at different temperatures (T1,T2) and the corresponding resistances (R1,R2) at bias voltage V_0, for calculation of dR/dT.

The optimum bias with respect to minimum receiver noise temperature is found by adjusting the LO-power and the bias voltage at the operating temperature 4.5 K, Fig. 2. The absorbed LO and DC power, are about 2.5 μW and 0.5 μW respectively, and are derived from the IV characteristics assuming that the response to DC and RF power is the same and due to electron heating only.

$$P_{LO} = \frac{V_1 I_1 - V_o I_o}{1-x} \qquad (1)$$

Points 0 and 1 are where the isotherm intersects two IV curves with LO powers P_{LO} and xP_{LO}.

At the optimum bias a change of current or voltage by ±10% does not have any significant influence on the noise performance, Fig. 3.

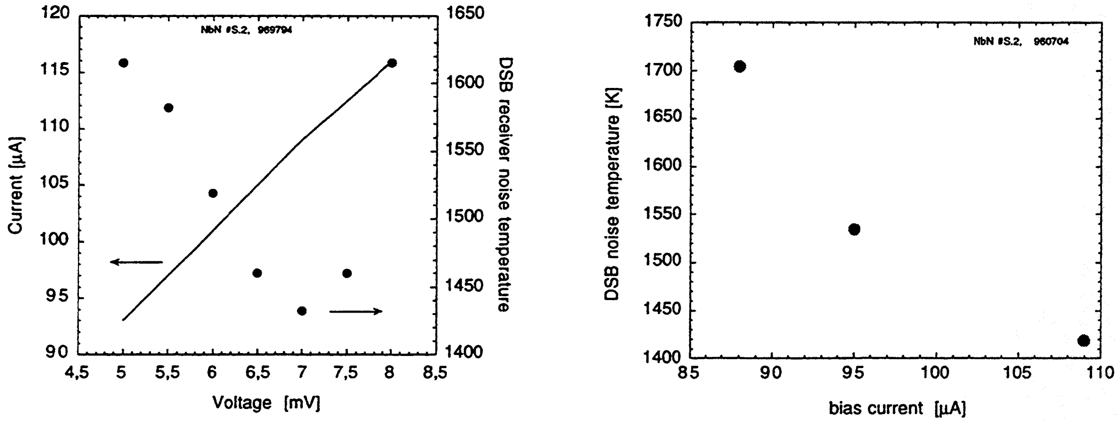

Fig. 3. DSB receiver noise temperature vs a) bias voltage and b) bias current (LO power). No minima is found for an optimum amount of LO power. Further reduction of LO power results in unstable and hysteretic conditions

RESULTS

The gain bandwidth of the HEB is measured with fixed frequency and power of the signal BWO, while the frequency of the LO BWO is tuned to obtain an IF signal in the frequency range 0-7 GHz. An attenuator is used to keep the LO power at a constant optimum level, as indicated by the bias current. As seen in Fig. 4 the gain bandwidth is slightly larger than 3 GHz.

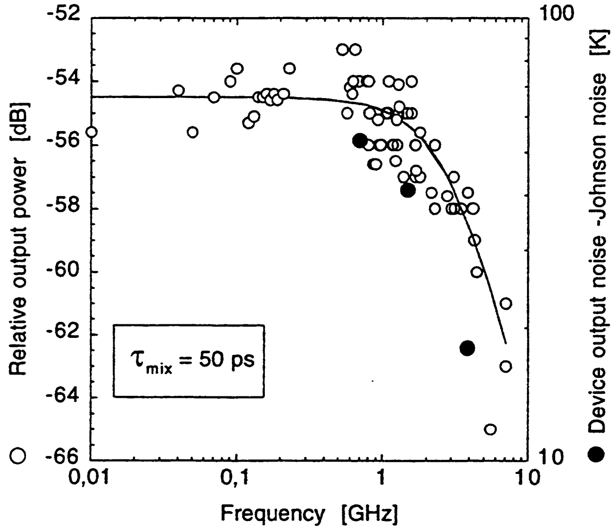

Fig. 4. Relative IF output power and device output noise temperature excluding Johnson noise vs frequency

To measure the device output noise temperature, T_{out}, two noise levels were obtained on a scalar network analyser; one with the device in the operating point, P_r, and a second with the device in the superconducting state, P_s, giving rise only to Johnson noise, T_J, due to the series-resistance in the contacts. An additional noise source is the load of the circulator at the input to the amplifier. The load temperature, T_s=4.5 K, is reflected by the device and is added to the IF amplifier noise temperature, T_{IF}. The ratio of P_r to P_s is then obtained from the equation given below.

$$\frac{P_r}{P_s}=\frac{T_{out}/L_r+T_s(1-1/L_r)+T_{IF}}{T_J/L_s+T_s(1-1/L_s)+T_{IF}} \tag{2}$$

Here L_r and L_s are the mismatch losses in the operating point and superconducting state, respectively. In the latter state $T_J=T_S$. T_{IF} is noise the contribution from the IF-chain, and is obtained with the device in normal state acting as a white noise source and producing only Johnson noise at two temperatures just above T_c . All quantities except T_{out} in Eq. (2) are now known, and we can thus obtain T_{out} at different IF frequencies by measuring P_r/P_S.

The similar frequency dependence of the output noise and IF signal, Fig. 3, as well as the relatively large low frequency value of the output noise, 50-60 K, compared to the Johnson noise, T_J ($\approx$ electron temperature $\theta \approx T_C$), proves that the dominating noise process in the device is due to fluctuations in the equivalent electron temperature. An expression for the fluctuation noise is [11]

$$T_{FL}=\frac{I_o^2}{R_L}\left(\frac{dR}{dT}\right)^2\frac{\theta^2}{c_eV}\tau \tag{3}$$

I_o is the bias current, R_L is the load resistance, $c_e=\gamma\theta$ is the electron specific heat (γ=Sommerfield constant 0.21 mJ $cm^{-3}K^{-2}$). The electron temperature θ in the mixing operating point (V_o,I_o in Fig. 2) is determined by thermally heating the whole device without LO power. In this way the same point (V_o,I_o) is reached at a temperature of the environment of 8.7 K. By adding the excess temperature due to Joule heating $T_{DC}=P_{DC}/G=I_oV_o\tau/c_eV=0.3$ K we obtain θ=9 K. V is the bolometer volume, and the electron energy relaxation time τ=52 ps is obtained from the mixing time constant, τ_{mix} in Fig. 3, according to [3, 14]

$$\tau=\frac{\tau_{mix}}{1-\tau_{mix}\frac{dR}{dT}\frac{I_o^2}{c_eV}\frac{R_o-R_L}{R_o+R_L}} \tag{4}$$

R_o is the DC resistance in the bias point. dR/dT=63 Ω/K is found from the IV-char. according to inset in Fig. 2. This derivation is done at the operating point which is reached by thermal heating without LO power. The change in resistance at constant voltage V_o for a change of physical temperature of 0.05 K is measured, and adding a difference in Joule heating of 0.012 K. The value for the fluctuation noise obtained by Eq. (3) is 31 K. Another contribution to the output noise is from Johnson noise ≈ 9 K. For a pumped device, there is as well a contribution from the 300 K hot load. The SSB conversion loss is ≈18 dB (see below). Thus, the hot load contribution is about 10 K. This gives a total output noise temperature of 50 K, in excellent agreement with the measured value of 50 K at 1.5 GHz IF frequency and 60 K at 700 MHz IF.

However, it should be pointed out that there is an error in the calculated value of about ±20 K. The factor α by which the mixer noise bandwidth will be larger than the gain bandwidth, due to the dominating fluctuation noise is given by [1, 12].

$$\alpha=\sqrt{\frac{T_{out}(0)}{T_J}}=\sqrt{\frac{T_{FL}(0)+T_{load}+T_J}{T_J}} \tag{5}$$

where $T_{out}(0)$ is the output noise in the low frequency limit. Since we have different noise contributions from the IF chain in the different bands, Table 2, the noise contribution from the IF is excluded in Eq. (5) so as to enable us to compare it with the measured receiver noise bandwidth. We also want to judge the performance of the HEB independently of our particular IF chain. With $T_J \approx 9$ K and $T_{out}(0) \approx$ 50-60 K we should have a mixer noise bandwidth about 2.3-2.5 times larger than the gain bandwidth, i.e. ≈ 7.5-8 GHz. The DSB receiver noise temperature, T_{DSB}, was determined from the Y-factor with a hot/cold load (300/80K) at a signal frequency of 620 GHz and at IF frequencies of 700 MHz, 1.5 and 3.9 GHz. The response was obtained within a 40 MHz band at each IF frequency. The best DSB receiver noise temperature is 1280 K with a 50 µm beam splitter and ≈1100 K with a 12 µm beamsplitter. Fig. 5 shows the measured noise temperatures at the different IF frequencies including an error of ≈±50 K. The frequency dependence gives a 3 dB receiver noise bandwidth of roughly 5 GHz. Subtracting the noise contribution from the IF chain (which includes an error of ≈ ±25%), shows that the HEB device has a 3 dB mixer noise bandwidth of about 8 GHz, 2.5 times larger than the gain bandwidth, in agreement with the value derived from Eq. (5).

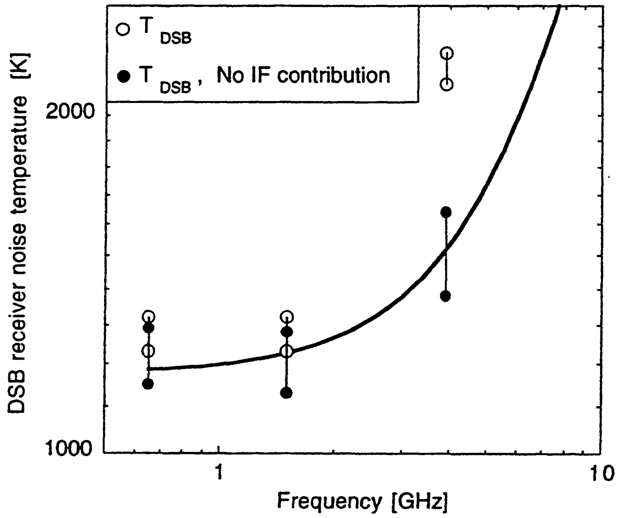

Fig. 5. DSB receiver noise temperature vs IF frequency with and without contributions from the IF chain.

The RF (350 Ω) and IF (120 Ω) impedance mismatch loss is about 2 and 1 dB, respectively. With no mismatch losses, which can be obtained with shorter devices, and excluding beamsplitter loss, it is possible to achieve a DSB receiver noise temperature of about 700 K with devices of this type of NbN film.

An estimation of the single-sideband receiver conversion gain from the output and receiver noise measurements is obtained by

$$G_{SSB} = \frac{T_{out} \cdot L_{IF} + T_{IF}}{2 \cdot T_{DSB}} \tag{6}$$

and gives ≈-18 dB gain. Excluding the RF and IF mismatch and the loss in optics (≈3 dB) we have an intrinsic conversion gain of ≈ -12 dB.

In summary, we have measured the mixer gain and receiver noise bandwidth of ultra thin NbN HEB at 620 GHz to 3.2 and ≈5 GHz, respectively. Excluding the noise contribution from the IF chain, the mixer noise bandwidth is ≈8 GHz. For an optimised receiver with the same device, a receiver noise temperature of 700 K DSB is possible to obtain.

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