LOW-NOISE NbN PHONON-COOLED HOT-ELECTRON BOLOMETER MIXERS AT 810 GHz

C. Rösch [*], T. Lehnert, C. Schwoerer,
M. Schicke, K. H. Gundlach, K. F. Schuster

Institut de Radio Astronomie Millimétrique
300 rue de la Piscine, Domaine Universitaire de Grenoble
38406 St. Martin d'Hères, France

Frank Schäfer
Max-Planck-Institut für Radioastronomie
53121 Bonn, Germany

Abstract

NbN phonon-cooled superconducting hot-electron bolometric mixers with quasi-optical coupling were fabricated in a self-aligned process by means of e-beam-lithography. The mixer element consists of a 5 nm thick NbN film sputtered on a fused quartz substrate. Noise performance was investigated in the frequency range of 798 to 813 GHz for intermediate frequencies from 1.0 to 1.75 GHz. Uncorrected double sideband receiver noise temperatures of about 900 K were measured at an intermediate frequency of 1000 MHz with a 50 MHz bandpass filter.

The gain bandwidth was determined by superposing two local oscillator signals and measuring the height of the discrete line at the intermediate frequency output. A 3dB-roll-off-frequency of some 1.3 GHz was obtained.

1. Introduction

Superconductor-insulator-superconductor (SIS) mixers have nearly replaced Schottky-diode mixers in millimeter and submillimeter astronomical studies. Presently, the first choice for low-noise receivers up to nearly 1.2 THz are Nb SIS junctions with Al embedding circuits [1, 2, 3]. The frequency limit $f_l = \frac{4\Delta}{h}$ is set by the energy gap of niobium $\Delta(Nb) \simeq 1.4$ meV. The higher energy gap of NbN $\Delta(NbN) \simeq 2.4$ meV suggests to employ NbN junctions

[*]email: roesch@iram.fr

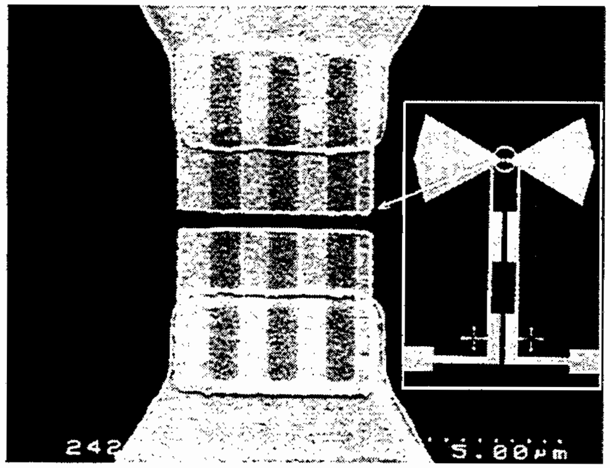

Figure 1: Microbridges integrated in the center of an dipole-antenna

with Al embedding circuits for frequencies up to 2 THz. So far, the relatively large leakage current and the high specific capacity conflicts with the desired low-noise performance [4, 5].

While superconducting hot-electron bolometers (HEB) can compete with SIS-mixers at 1 THz they are supposed to be superior at higher frequencies. Since the mixing mechanism in a HEB utilizes the temperature dependence of the resistance near the transition temperature T_c, this device is not limited by the energy gap of the superconductor as SIS mixers, and is therefore expected to have a good performance up to several terahertz [6]. Schottky mixers which also work in the THz region are noisier and require orders of magnitude more local oscillator (LO) power.

Two types of bolometers are known, differing in their cooling mechanism. While the cooling mechanism in Nb bolometers [7, 8, 9] is based on the fast out-diffusion of hot electrons and requires extremely short bridges, NbN bolometers [10, 11, 12, 13] are mainly cooled by electron-phonon interaction. Very thin NbN films ensure that the phonons immediately escape into the substrate.

2. Device Fabrication

We fabricated the second type of hot-electron bolometers using thin NbN films. Our devices consist of three parallel lines integrated in the center of a dipole antenna. (See fig. 1)

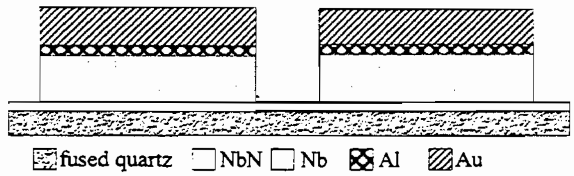

Figure 2: Sectional view of the microbolometer

The thin films for the devices were sputtered on a fused quartz substrate beginning with a blank NbN deposition of 5 nm. Optimized sputter parameters are described elsewhere [14].

Subsequently, the antenna and the rf-filters, consisting of 100 nm Nb, 8 nm Al and 50 nm Au are patterned by means of optical lithography. The length of the microbridges is defined by two rectangular pads at the center of the antenna, using e-beam lithography. For these pads either 100 nm Au or 100 nm Nb is used indicating no major difference when operated at 810 GHz. Also by means of e-beam lithography three parallel Al lines, defining the microbridges, are patterned across the Au (Nb) contact pads. Al serves as etch mask and will be removed afterwards. Since the effective length of the microbridge is determined by the distance of the two contact pads only, the length of the Al-lines can be chosen arbitrarily, avoiding alignment problems. After reactive ion etching of the NbN layer with CF_4 the Al can be removed easily in a base.

A sectional view of the device is shown in fig. 2. The distance of the two rectangular pads is about 0.5 μm and was chosen to match the resistance of the antenna, which is as low as 100 Ω. Even shorter bridges are feasible with the used technology providing the possibility to reduce the film thickness without increasing the resistance. The shortest bridges produced so far were 0.2 μm long. The width of the microstrips is about 1 μm each (see fig. 1).

3. Experimental Setup

The double sideband (DSB) receiver noise temperature T_{rec} is determined by the usual Y-factor method.

Therefore the device is glued to a hemispherical lens of crystal quartz and mounted in a LHe-cooled cryostat. A Gunn diode followed by a varistor doubler and tripler is used as local oscillator. This assembly provides an LO power of about 80 μW in the range from 798 to 813 GHz [15], which is superposed with the signal of the load using a 19 μm polyester foil as beam splitter. The intermediate frequency (IF) signal was matched to the 50 Ω input of a cryogenic HEMT amplifier by a quarter-wave line. Furthermore the IF-chain consists of two other amplifiers operating at room temperature and a bandpass filter of 50 MHz bandwidth tunable between 1000 and 1750 MHz.

4. Results

With this setup noise temperatures were measured for a range of bias voltages, LO power levels, IF and LO frequencies. The results for the Y-factor are found between 1.155 and 1.225 corresponding to noise temperatures between 890 and 1330 K.

Extreme care has been taken to ensure that no direct bolometric response to ambient thermal radiation occurred. Therefore current/voltage (I/V) curves were recorded with hot as well as with cold load. No difference between these two curves has been observed indicating that the operating point is not altered when switching between hot and cold load. Using the isothermic method first proposed by Ekström [16] an LO power of some 80 nW was obtained.

Fig. 3 shows a typical result of these measurements. The pumped I/V curve is plotted as well as the IF conversion curves for hot and cold load. The unpumped I/V curve which has the typical hysteretic behaviour is not shown in the figure. The critical current for increasing bias voltage is 230 μA and the drop-back current for decreasing bias voltage is 70 μA.

Best bias points are obtained when the LO power is sufficiently high to suppress the hysteresis. The performance of the device was found to deteriorate by the application of higher or lower LO power. Fig. 4 shows the noise temperature as a function of IF and as a function of the LO frequency.

Heterodyning of similar devices was already shown in [10]. Lehnert et al. have superposed two free running solid state oscillators at similar frequencies. One served as pumping-LO and the other one as signal source. The IF signal was observed by a spectrum analyzer. The same setup is used to get a first notion of what the IF bandwidth might be. Therefore the signal height is measured for different intermediate frequencies. The IF is changed by tuning the pumping-LO. The signal-LO is not touched and the signal power remains

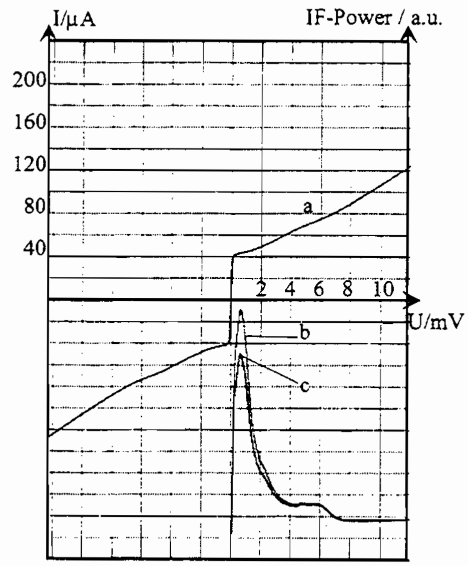

Figure 3: a) pumped I/V curve of the device and conversion curves for b) hot and c) cold load.

constant during the whole measurement. Therefore the dependency of the power level from the frequency does not influence the results. As far as the pumping-LO is concerned, the incident power is kept constant using the I/V curve. After tuning the frequency the output level of this LO is changed until the initial I/V curve is recovered. Whenever the same bias curve is attained the absorbed LO power is assumed to be the same. In Fig. 5 the output signal is shown as a function of the IF. The data points are lying in the range from 500 MHz to 3.3 GHz and reaching a maximum value of about 20 dB above noise. An IF bandwidth of $\omega_{3dB} = 1.3$ GHz can be estimated.

5. Conclusion

We succeeded in fabricating the phonon-cooled version of superconducting hot-electron bolometers integrated in a quasi-optical receiver. Since the fabrication process is free of difficult alignment, a high degree of reproducibility can be attained. With these devices DSB receiver noise temperatures and IF bandwidth were determined at an LO frequency of about 800 GHz.

While the IF bandwidth of 1.3 GHz remains relatively small best DSB receiver noise temperatures are as low as 900 K at an IF of 1000 MHz. The

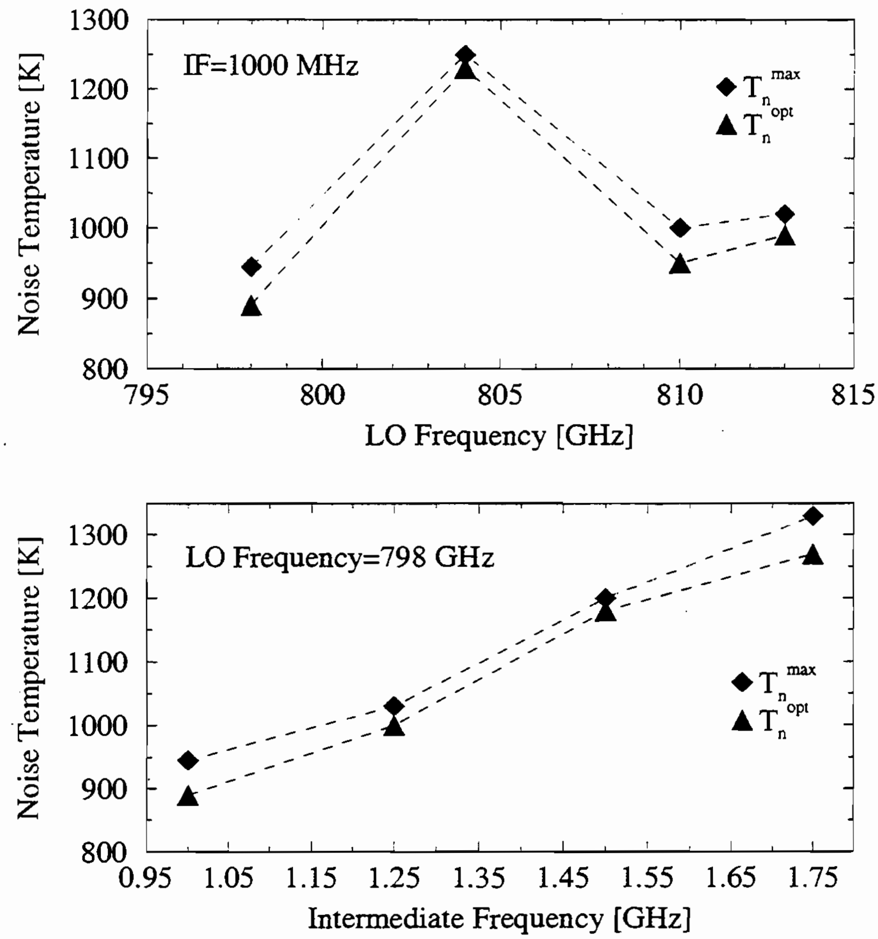

Figure 4: Noise temperatures for a range of LO frequencies (upper part) and different IF (lower part). T_n^{max} is measured at the maximum of the conversion curve while T_n^{opt} is measured at slightly higher voltages.

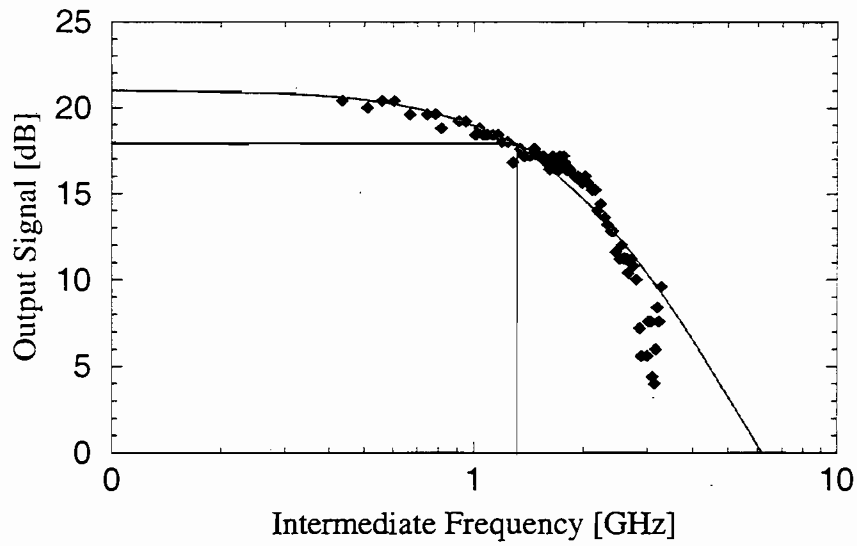

Figure 5: Output signal for different intermediate frequencies. An IF bandwidth of about 1.3 GHz can be estimated.

noise temperature increases to only 1300 K at 1750 MHz. It should be emphasized that the present quasi-optical receiver was initially designed for the 350 GHz frequency band [17]. With a somewhat more sophisticated antenna, an antireflection coated lens and windows optimized for the operating frequency considerably better noise temperatures can probably achieved at 800 GHz.

Crystalline quartz substrates might also be advantageous because of their approximately 10 times higher thermal conductivity and experiments are planned to see whether the use of this substrates results in a higher IF bandwidth. These results demonstrate that NbN hot electron bolometers can compete with well-established SIS-technology at 800 GHz and represent a promising tool for the detection in the THz range.

6. Acknowledgements

The authors like to thank Dr. H. Rothermel for the receiver as well as for his substantial help.

References

[1] M. Bin et al. Low-noise 1 THz niobium superconducting tunnel junction mixer with a normal metal tuning circuit. *Appl. Phys. Lett.*, 68:1714, 1996.

[2] D. Maier et al. Submicron Nb-Al/Al oxide-Nb tunnel junctions sandwiched between Al films. *Physica C*, 268:26 - 40, 1996.

[3] F. Schäfer et al. A quasioptical SIS receiver with normal metal tuning for the 800-900 GHz band. In *8th International Symposium on Space Terahertz Technology*, pages 566 - 569, Cambridge, USA, 1997.

[4] P. Dieleman et al. Performance limitations of NbN SIS junctions with al striplines at 600 - 850 GHz. In *8th International Symposium on Space Terahertz Technology*, pages 291 - 298, Cambridge, USA, 1997.

[5] M. Schicke et al. NbN tunnel junctions with Al tuning circuits and hot-electron transition-edge bolometers for THz mixing. In *ISEC'97*, volume 3, pages 150 - 152, Berlin, Germany, 1997.

[6] D. E. Prober. Superconducting terahertz mixer using a transition-edge microbolometer. *Appl. Phys. Lett.*, 62:2119 - 2121, 1993.

[7] B. S. Karasik et al. Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz. *Appl. Phys. Lett.*, 71(11):1567 - 1569, 1997.

[8] A. Skalare. Large bandwidth and low noise in a diffusion-cooled hot-electron bolometer mixer. *Appl. Phys. Lett.*, 68:1558 - 1560, 1996.

[9] K. Fiegle, D. Diehl, and K. Jacobs. Diffusion-cooled superconducting hot electron bolometer heterodyne mixer between 630 and 820 GHz. *IEEE Trans. Appl. Supercond.*, 7:3552, 1997.

[10] T. Lehnert, H. Rothermel, and K. H. Gundlach. Low-noise heterodyne mixing with NbN microbolometers at 800 GHz. *J. Appl. Phys.*, to be publ. in the 15 March 1998 issue, 1998.

[11] H. Ekström et al. Gain and noise bandwidth of NbN hot-electron bolometric mixers. *Appl. Phys. Lett.*, 70(24):3296 - 3298, 1997.

[12] S. Svechnikov et al. Spiral antenna NbN hot-electron bolometer mixer at submm frequencies. *IEEE Trans. Appl. Supercond.*, 7:3395, 1997.

[13] J. Kawamura et al. Low noise NbN lattice-cooled superconducting hot-electron bolometric mixers at submillimeter wavelengths. *Appl. Phys. Lett.*, 70:1619 – 1621, 1997.

[14] B. Plathner et al. A niobiumnitride mixer with niobium tuning circuit. *Appl. Phys. Lett.*, 69:4102 – 4104, 1996.

[15] *Radiometer Physics GmbH, Meckenheim, Germany.*

[16] H. Ekström et al. Investigation of a superconducting hot electron mixer. *Proc. 5th Int. Symp. on Space Terahertz Technology*, pages 169 – 175, 1994.

[17] H. Rothermel, M. Voss, and K.-H. Gundlach. In *SPIE Proceeding Series*, volume 2211, page 396, 1994.