Quasioptical phonon-cooled NbN hot electron bolometer mixers at 0.5-1.1 THz

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Abstract

The noise performance of a receiver incorporating spiral antenna coupled NbN phonon-cooled superconducting hot electron bolometric mixer is measured from 450 GHz to 1200 GHz. The mixer element is thin (thickness ~3.5 nm) NbN 1.5 μm wide and 0.2 μm long film fabricated by lift-off e-beam lithography on high-resistive silicon substrate. The noise of the receiver temperature is 1000 K at 800-900 GHz, 1200 K at 950 GHz, and 1600 K at 1.08 THz. The required (absorbed) local-oscillator power is ~20 nW.

Introduction

Over the last few years, hot electron bolometric (HEB) mixers have become a rapidly developing field of terahertz technology. Two types of HEB mixers are currently developed: so-called phonon-cooled HEB mixers [1-6] and diffusion-cooled HEB mixers [7-11]. Both mixer types have produced impressive results during the last year. For the former, the following values of receiver noise temperature were obtained: 410 K (430 GHz) [2,3], 480 K (636 GHz) [3], 600 K (700-800 GHz), 850 K (910 GHz), and 1200 K (1.1 THz) [4]. The conversion bandwidth was 4 GHz [5], and the noise bandwidth reached 8 GHz [6]. The optimal local oscillator power was of the order of P_{LO}~1 μW. The latter type of HEB mixers showed a noise temperature of 650 K (533 GHz) [8], 1880 K (1267 GHz) [9], 2700 K (2.5 THz) [10], and a noise bandwidth of about 2 GHz [9,10], and a conversion bandwidth of up to 6 GHz was achieved for the shortest bridges at 20-40 GHz frequency, as reported in [11]. The optimal local oscillator power for the diffusion-cooled HEB mixers was 10-100 nW [9-11]. One of the differences between the performances of the two kinds of mixers was the order of magnitude of their local oscillator power. A lower P_{LO} may prove necessary at terahertz frequencies, where the absence of solid-state sources of a considerable power is an important factor contributing to a wider scope of application.

At the same time, the optimal P_{LO} for the phonon-cooled HEB mixers may show a considerable variance, since it is proportional to the volume of the superconducting film. The dimensions of the film are not a critical parameter for this kind of HEB mixers, unlike the diffusion-cooled HEB mixers, where the small length of the superconducting film located between normally conducting contacts determines the size of the mixer bandwidth. Typical P_{LO} values so far obtained for the phonon-cooled HEB mixers are of an order of few microwatts, as determined by the facilities of photolithography: the characteristic film size in plane is 1 μm. A decrease in the optimal P_{LO} value means a shift to electron-beam lithography and to submicron dimensions, although they need not be so small as those required for the diffusion cooled HEB mixers. The results of the present work show that the P_{LO} for a NBN film of $1.5\times0.2\times0.003\mu m^3$ is about 20 nW. It is important that the noise temperature and conversion losses drop with a decrease in size. For one of the spiral antenna coupled HEB mixers presented in this paper, the noise temperature of the receiver is about 1000K at 800-900 GHz, 1200K at 950 GHz, and 1600K at 1.08 THz. A decrease in the superconducting film volume may result in a decrease of the optimal local oscillator power and a notable drop of the noise temperature but may bring about certain negative effects. One of these is a narrowing of the dynamic range. Another effect, which may be not so self-evident, is a possible increase of the direct detection contribution into the response manifested in Y-factor measurements. Indeed, the responsivity of a HEB is inversely proportional to the volume of the film [1], whereas the heterodyne response shows a much weaker growth with the decrease in the volume. As a result, the direct detection response to black body radiation from hot and cold loads may become comparable with the heterodyne response. In this paper, we have made an attempt at an assessment of this contribution.

Devices and fabrication

To manufacture spiral antenna coupled HEB mixers, a layer of thin (30-35 A) NbN film was deposited onto a Si high-resistive (with a resistivity of 5 kOhm cm) 350 μm thick substrate using reactive magnetron sputtering. The process of sputtering the NbN film is described in detail in [5].

The central part of the spiral antenna was formed using lift-off electron lithography based on metallization of 800 A thick Cr-Au layer. The dimensions of the gap that opened the active NbN film in the antenna were 0,2-0,4 μm by 1,0-2,0 μm. To remove the NbN layer from the chip field, a repeated lift-off electron lithography with alignment was used, in the course of which the whole central spiral was covered by an Al mask, which duplicated the topology of the Cr-Au spiral antenna, but overlapped the gap. The NbN which was not protected by the Al mask was then removed using ion milling in an Ar atmosphere, and after that Al was chemically removed in a selective etchant, not affecting Au and NbN.

The final operations included deposition of a relatively thick (the thickness of the Au layer was 0.5 μm) Ti-Au metallization of the peripheral part of the antenna; direct lithography over this metallization using alignment marks, which provided alignment of the external and the internal spirals; ion milling of Au; chemical etching of Ti; and, finally, partitioning the wafer by scribing it into separate chips. Fig. 1 shows a SEM photo of a completed device.

Experiment and discussion

The substrate on which the device and antenna are integrated, is glued to an extended hyperhemispherical silicon lens with a diameter of 4.2 mm. The mixer is mounted in a liquid He-cooled vacuum cryostat equipped with a 1-mm-thick Teflon window and a 380 μm Zitex G 115 IR radiation filter. We use three backward wave oscillators (BWO) as local oscillator sources with a common frequency range 450÷1250 GHz. The radiation from the LO is focused by a Teflon lens and combined with the signal by a 20-μm-thick Mylar beamsplitter. 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. The receiver sensitivity is measured using the Y-factor method of alternately placing a hot load at 295 K and a cold load at 77 K at the input of the receiver. The receiver noise temperatures T_r reported are not corrected to account for losses. The sensitivity refers to the double-sideband receiver noise temperature.

Fig.2 shows three IV curves: an unpumped one, one pumped by optimal LO power, and another one pumped by optimal LO power reduced by a factor of α=0.8 dB. To calculate the optimal LO power absorbed by NbN film, we use a conventional technique common for the bolometers. Supposing that the resistance of the film in the resistive state only depends on electron temperature, we can draw the isotherm as a straight line that crosses the last two IV-curves in the points 1 and 2 (fig.2) and calculate the absorbed LO power:

$$P_{abs} = \frac{\alpha}{\alpha - 1}(I_2V_2 - I_1V_1) \qquad (1)$$

The precision of this procedure appears to be better if the isothermal line corresponds to a resistance much higher than that observed at the working point of the mixer. In this case, the resistive state is more uniform, which validates the assumption of the crucial role played in the resistance by the electron temperature. This assumption is accurate in a normally conducting state, but in such a case the resistance hardly shows any dependence on the temperature, and the precision of I_1V_1 and I_2V_2 products prove to be utterly insufficient. Calculations by (1) yield an absorbed optimal P_{LO} of 20nW, and for the given working point of the mixer $P_{dc} = I_0V_0 = 15$ nW (fig.2). It should be emphasized that the dependence of the noise temperature of the receiver on P_{LO} and P_{dc} over quite a wide range is very weak. This can be seen from the same figure, which also shows the dependence of T_r on bias voltage. The bias voltage may vary from V_0=0.3 mV to V_0=1.5 mV, while T_r only shows a 20% change. The same figure shows the bias current range where the noise temperature varies within the same limits with the change of P_{LO}. Here, P_{LO} shows a 4dB change, i.e., it changes from 15 nW to 32 nW.

It is interesting to make a theoretical estimation of the required local oscillator power. The simplest way to do this is to ignore the heating of the lattice and to perform the calculations for a pure hot electron bolometer [1, 12]. In this case, for NbN

$$P_{dc}+P_{LO}=AV(\theta^{3.6}-T^{3.6}), \qquad (2)$$

where $A=C_e(T)/3.6\tau_{eph}(T)T^{2.6}\approx3\cdot10^4$ W·cm^{-3}K^{-4} for NbN, V is the NBN film volume, θ is the electron temperature. Assuming that T_e=8 K, we will obtain $P_{dc}+P_{LO}$=36nW, while experimentally assessed values of $P_{dc}+P_{LO}$ may vary from 25 to 55 nW without any significant increase of T_r.

Fig. 3 shows the dependence of the noise temperature of the receiver on the frequency for a HEB mixer studied at T=4.5K. In the 800-900 GHz range, T_r does not vary and is equal to 1000 K, but at frequencies F<750 GHz and F>950 GHz it shows a smooth growth. The atmospheric absorption makes a considerable contribution to the measured T_r(F) dependence at high frequencies. A rather significant line of water absorption can be observed around the 1.18 THz mark and a much smaller line can be seen near the 730 GHz mark.

There are a great variety of factors that contribute to the frequency dependence of the noise temperature, which are still difficult to distinguish. They include the frequency dependence of the NbN film impedance ($h\nu<2\Delta$ for NbN in the used frequency range), and hence its mismatch with the antenna, the frequency dependence of the silicon lens reflection, etc. One of the principle ways to increase the noise performance of NbN HEB mixers made by e-beam lithography is the advancement of manufacturing processes. The purpose of this is to achieve in the final product a high critical current density, high critical temperature, and a small width of the superconducting transition, which has been attained for thin NbN films (and for NbN HEB mixers made by photolithography).

Another important aspect of the measurements deserves special attention. As was noted above, if for a HEB mixer T_r is measured using the Y-factor technique, an additional error may appear due to the contribution of direct detection. When the input of the receiver is switched from hot to cold load, one can observe that the IV-curve shifts a little into the region of higher currents (see Fig.2). At an optimal local oscillator power and bias voltage, the current shift is ~0.3 μA (points 3 and 4 in Fig.2). To assess a possible contribution of direct detection to the measured Y-factor, we have measured, in addition to the output noise power P_{out} for hot and cold loads (after amplification they were 102 μW and 85 μW, respectively), another two values of P_{out} for two different local oscillator powers, one being optimal for conversion gain (P_{out}=102 μW) and another one, reduced by a factor α=0.8 dB (P_{out}=88 μW). These two states of the HEB mixer are marked with points 3 and 5 in IV-curves of Fig.2 In these measurements, bias voltage remained the same, and a hot load was located at the input of the receiver. Since the P_{LO} varies only a little from point 3 to point 5 (the change is 0.8dB), we can approximate the dependence of the output noise power from the bias current in this area by a linear function. This will permit us to estimate the P_{out} value at point 4 in Fig.2 as 100 μW. Thus, when the receiver input is switched from hot to cold load, a small part of the measured Y-factor is due to direct detection. The adjusted value of the noise temperature at a frequency of 880 GHz may be estimated as 1170 K. Note that the obtained correction of the noise temperature of the receiver is only a little higher than the measurement error. At the same time, if the volume of the superconducting film of the HEB mixer is reduced further, or if the frequencies are used at which the heterodyne response drops, the contribution to the direct detection into the measured Y-factor may become considerable. This effect could be seen in Fig.3 in the center of the absorption line located near 1.18 THz frequency point. Assuming complete absorption at this frequency point one can expect that only direct detection contributes to the Y-factor value here. Indeed, this value coincides with the direct detection signal estimated above (Fig.3).

Acknowledgments

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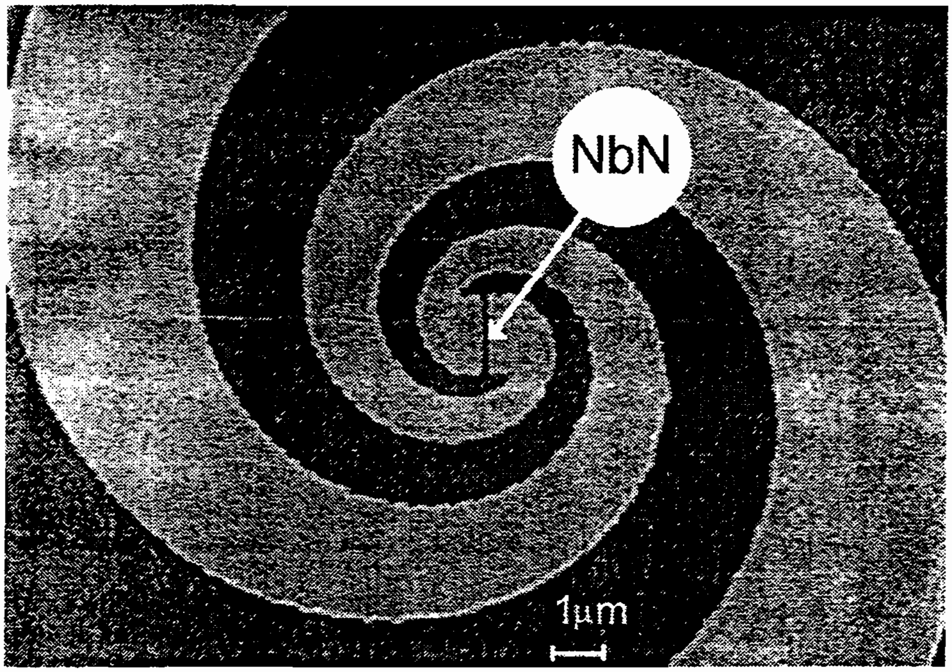

Fig.1. SEM photo of the 0.2 μm by 1.5 μm NbN HEB device integrated into spiral antenna.

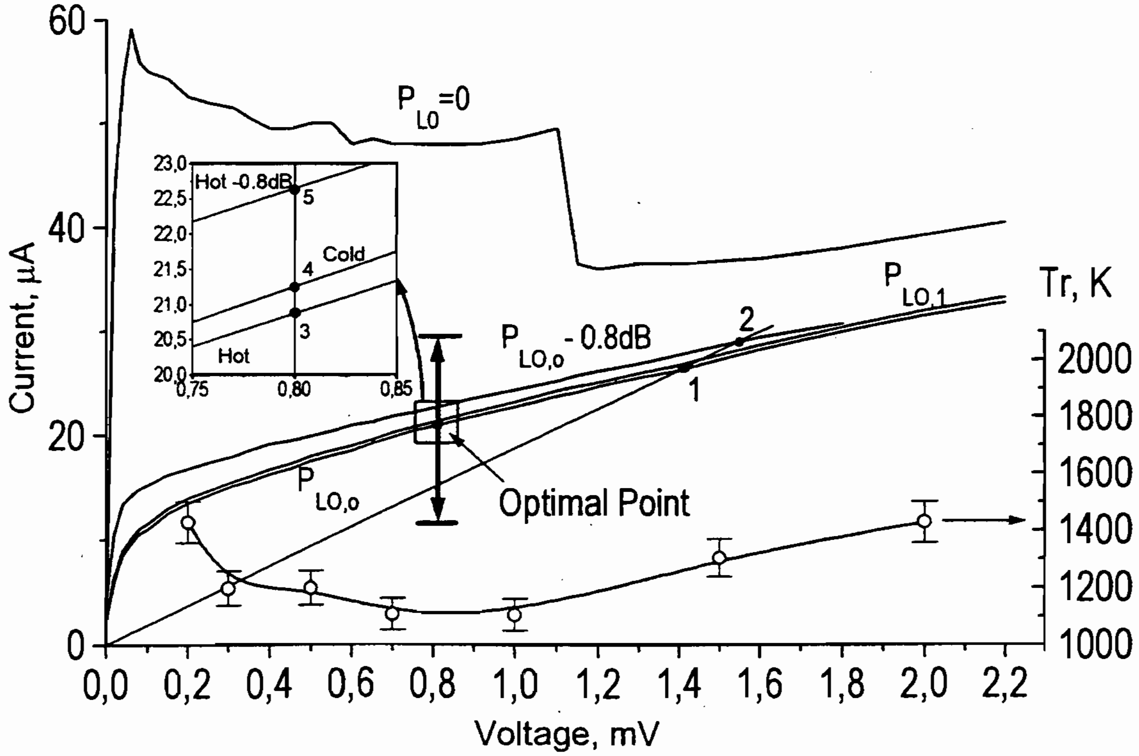

Fig.2. Unpumped and pumped IV-curves at 880 GHz and the receiver noise temperature versus bias voltage.

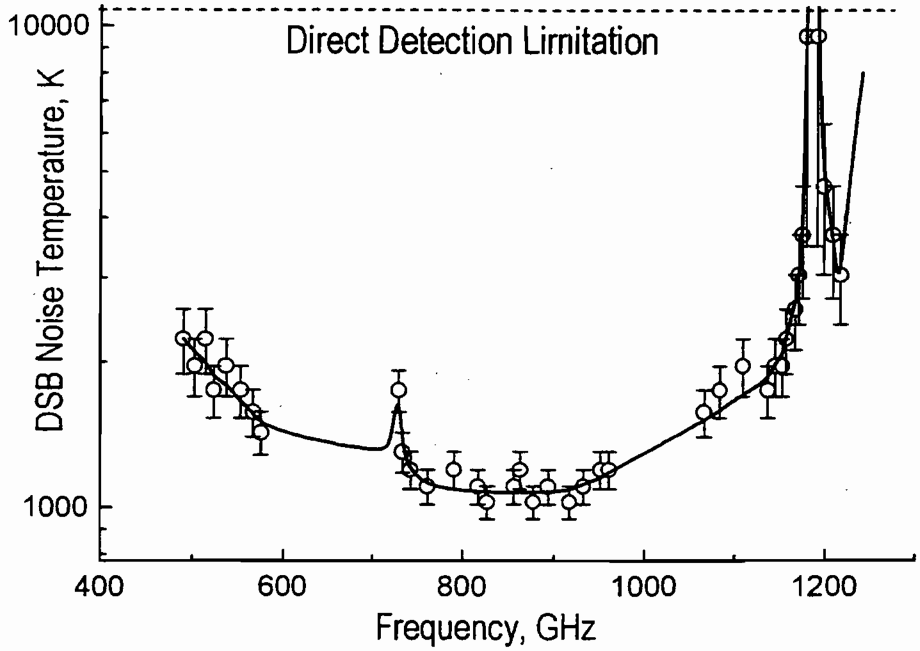

Fig.3. Noise temperature for the NbN HEB mixer receiver within frequency range 450-1200 GHz.