NbN HOT ELECTRON BOLOMETRIC MIXERS AT FREQUENCIES BETWEEN 0.7 AND 3.1 THz

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Abstract

The performance of NbN based phonon-cooled Hot Electron Bolometric (HEB) quasioptical mixers is investigated in the 0.7-3.1 THz frequency range. The devices are made from a 3.5-4 nm thick NbN film on high resistivity Si and integrated with a planar spiral antenna on the same substrate. The length of the bolometer microbridge is 0.1-0.2 µm, the width is 1-2 µm. The best results of the DSB receiver noise temperature measured at 1.5 GHz intermediate frequency are: 800 K at 0.7 THz, 1100 K at 1.6 THz, 2000 K at 2.5 THz and 4200 K at 3.1 THz. The measurements were performed with a far infrared laser as the local oscillator (LO) source. The estimated LO power required is less than 500 nW at the receiver input. First results on the spiral antenna polarization measurements are reported.

Introduction

In the past years, several research groups have been working on the development of low noise broadband receivers for detection of THz radiation. They are needed in particular for atmospheric observation and radio astronomical applications. Only Schottky diode mixers are used now as receivers at frequencies beyond 1 THz. The prime advantage of this mixer technology is the possibility to operate at room temperature. However, Schottky diodes have rather poor sensitivity which makes it difficult to detect weak signals. In addition, the local oscillator (LO) power requirement for these mixers is very high. Due to the few available powerful laser lines in the THz frequency range, this is a very important issue.

The concept of superconducting HEB mixers has been suggested for receivers at submillimeter wavelengths in [1]. They have already been shown to be competitive with SIS mixers at frequencies around 1 THz [2-4] and represent a very attractive candidate at higher frequencies [5-7]. The development has now reached a stage where they are successfully used for astronomical observations [8]. HEB mixers can in principle operate up to at least 30 THz without degradation in performance. Optical losses, however, increase with frequency. Therefore, careful design and choice of materials for the optical components in the receiver is needed.

An intermediate frequency (IF) bandwidth of several GHz has been achieved for both phonon-cooled [9-11] and diffusion-cooled [12,13] HEB mixers in experiments below 1 THz. Another attractive feature of HEB mixer technology is a very low power required from the LO source. In our experiments the measured power absorbed in the bolometer element is about 100 nW. Taking into account the estimated optical losses of 3-5 dB we end up with less than 500 nW needed from the LO source at the input of the receiver. This is 3-4 orders of magnitude lower than that of Schottky diode mixers.

At the previous Symposium we reported the measurements of NbN HEB mixers in the 0.65-1.1 THz frequency range [2]. Since that time we went up towards higher frequencies and in this paper we present results of heterodyne mixing between 0.7 and 3.1 THz.

Mixer fabrication and design

The devices are made from a 3.5-4 nm NbN film sputtered on a high resistivity, double side polished, silicon substrate. The film is patterned by e-beam lithography to form a 0.1-0.2 μm long and 1-2 μm wide strip across the center gap of an Au spiral antenna. A SEM micrograph of the bolometer integrated with the antenna is shown in Fig. 1. Details of the fabrication process can be found in [14]. The normal state resistance of the bolometer measured at 20 K ambient temperature is 250-450 Ohm depending on the bolometer strip geometry and film thickness. The critical current density at 4.5 K is about 4×10^6 A/cm^2. The antenna is an equiangular spiral with a 90° arm width yielding a self-complementary design. This implies that the antenna impedance is purely real and equal to 75 Ohm for the antenna on a Si substrate. Three different antenna designs have been used: spiral "A", "B" and "C". The spiral structure of all antennas extends 1.5 turns and the spiral expansion rate is 3.2 per turn. The spiral "A" antenna is the largest one with an outer radius of 100 μm and inner radius of about 10 μm. Spirals "B" and "C" are the products of scaling down spiral "A" by a factor of 2 and 4, respectively.

Measurement setup and technique

The setup for heterodyne measurements at frequencies between 0.7 THz and 3.1 THz is shown in Fig. 2. The local oscillator source is a far infrared (FIR) laser which is optically pumped by a CO_2 laser. To prevent back-coupling between the FIR and CO_2 laser cavities the FIR laser cavity uses a ring laser design. The FIR laser power is coupled out via a 3 mm diameter hole coupler. To be able to monitor its output power, part of the FIR laser beam is coupled onto a pyro detector via a wire grid. For measurements at 3.1 THz a different laser system is used. Here, the FIR laser consists of a high-Q FIR cavity that is transversally excited by the CO_2 laser. Outcoupling is done by a movable mirror.

A photograph of the mixer block is shown in Fig. 3. The mixer chip and the 12 mm diameter elliptical lens are mounted from opposite sides on a Si substrate which is clamped on the copper mixer block. The mixer block is placed in a liquid helium vacuum cryostat (Fig. 4) equipped with a high-density polyethylene window. IR radiation is blocked by a

380 μm Zitex G115 filter. The device output is connected through a bias-T to a 1.3-1.7 GHz cooled HEMT amplifier with a noise temperature of ≈5 K. The output of the HEMT amplifier is filtered with a 1.5±0.02 GHz bandpass filter, further amplified and detected with a power meter.

The LO and the signal are combined by a thin dielectric beamsplitter. Earlier we used a Martin Puplett diplexer based on 10 μm thick wire grids but it introduces losses of about 1-2 dB in the signal path. Since the FIR laser is powerful enough it is possible to pump the mixer by reflection from a 6 μm Mylar beamsplitter with almost no transmission losses for the signal. The LO power is adjusted by a rotatable wire grid in the LO path before the beamsplitter.

The receiver noise temperature is measured using the traditional Y-factor technique by alternatively placing a hot/cold (295/77) load in the signal path of the receiver which is normally done without chopping. Using a chopper was necessary only at 3.1 THz because of the poor stability of the laser system at this frequency.

For polarization measurements we used one more rotatable grid in the LO path as shown in Fig. 2. The Mylar beamsplitter is replaced by a metal mirror in order to avoid the polarization modification by reflection from the dielectric film. By changing the orientation of both grids (polarizer and analyzer) and measuring the coupling efficiency one can determine the polarization of the receiver antenna. The radiation coupling to the bolometer is obtained from the pump level of the IV curve which is a measure of the power absorbed in the bolometer. Details of the absorbed power measurement technique can be found elsewhere [3].

Device dc parameters

The results presented here are obtained with 5 devices from two different batches, named "V" and "W". The full information about the devices' geometry, dc parameters and noise temperature data are summarized in Table 1. The device dc parameters (resistance and critical current) scale very well with the geometry of the bolometer element. This fact indicates the spatial uniformity of the film and the reproducibility of the fabrication process. The normal state resistance, however, is about factor of 2-3 higher than that derived from the sheet resistance of the non-patterned film, which is 600-800 Ohm/sq for a 3.5 nm NbN film. A possible reason for this discrepancy is a poor dc contact between the film and antenna arms. The actual length of the bolometer is thus longer and the NbN film covered by Au contact pads also contributes to the device dc resistance. Another indication of this fact is the "multiple tooth" structure of the IV curve for some devices, where several critical currents are observed, see the I_c for devices V24 and V33. The first two critical currents in the IV curve can be thus attributed to the critical currents of the superconducting film under the contact pads and the third one to the critical current of the microbridge in between. We are trying to improve the electrical contact between the NbN film and Au contact pads by using an in-situ cleaning of the film before depositing Au. This could decrease the dc resistance of the bolometer. In addition, it might improve the performance of the mixer because absorption of rf radiation in the film with suppressed superconductivity (under the contact pads) most probably deteriorates the conversion gain.

Noise temperature

The noise temperature data shown in the table is the total DSB receiver noise temperature, not corrected to any losses. It is derived from the measured Y-factor with 77/295 K loads at the input of the receiver. At terahertz frequencies and low temperatures the radiated power temperature of a black body is not equal to its physical temperature. The value of the load noise temperature has been calculated using the Callen & Welton formula which is the Planck formula plus half a photon. The difference between receiver noise temperatures calculated using the "standard" Rayleigh-Jeans and Callen & Welton laws is perceptible at frequencies beyond 2 THz. Details can be found in [15].

All devices measured in this work show very similar performance. The best results of the DSB receiver noise temperature obtained at 4.2 K ambient temperature are: 800 K at 0.7 THz, 1100 K at 1.6 THz, 2200 K at 2.5 THz and 4200 K at 3.1 THz. Lowering the device ambient temperature gives slight improvement of the noise temperature. For instance, 2200 K at 2.5 THz measured for device W24 at 4.2 K drops to 2000 K at 3 K. The reason for the strong rise in the noise temperature to 4200 K at 3.1 THz is not clear yet. We believe that it could be due to increase of optical losses in the mixer (cryostat window, Zitex filter, etc.) and the strong water absorption in the atmosphere at this frequency.

The degradation of the sensitivity of the devices V33 and W47 at 0.7 THz is because this frequency is well below the lower cutoff frequency of antenna "C", see next chapter for details.

Antenna polarization

As mentioned before we have used three antenna designs, spiral "A", "B", and "C". Spiral "A" has inner and outer radii of 10 and 100 μm, respectively. The spirals "B" and "C" are just downscaled versions (factors of 2 and 4) of spiral "A".

The total antenna arm length of spiral "A", calculated from its radii and the expansion rate of 3.2 per turn, is about 300 μm. Setting this equal to a maximum effective wavelength yields a lower cutoff frequency of the antenna of 300 GHz in free space. The cutoff of spiral "B" and "C" is 600 GHz and 1.2 THz. This explains the deterioration of the noise temperature performance of the mixers V33 and W47 (utilizing spiral "C") at 700 GHz.

The higher cutoff frequency of the antenna is defined [16] as the frequency at which the antenna polarization becomes elliptical with an axial ratio of 2 to 1. This frequency depends on the construction precision of the antenna feed. Since the spiral arms naturally converge to a point, one has to terminate the center in a tapered section, see Fig.1. According to [16] the cutoff frequency occurs when the total length of the tapered section becomes effectively a half-wavelength. This length is roughly 20 μm, 10 μm, and 5 μm for spirals "A", "B", and "C" setting the upper frequency limit to 2.2 THz, 4.4 THz, and 8.8 THz, respectively.

The axial ratio of elliptical polarization increases towards higher frequencies. Notice, however, that since there are no distinctive changes in pattern shape of the antenna at these frequencies [16], the antenna can still work efficiently although the polarization might not be circular.

The antenna polarization measurements have been performed at 2.5 THz with a device based on spiral "C". The polarization is elliptical with the ellipse axial ratio of about 3 to 1. The last number is within ± 50% error due to the uncertainty of the absorbed power measurement technique. This technique is based on the assumption that the resistance of the bolometer is equally affected by dc and rf power. The limited accuracy of this technique causes an error for determining the coupling efficiency and hence the ellipse axial ratio. The long axis of the ellipse coincides with the direction of the tapered section in the antenna center, Fig. 1.

The obtained result on the antenna polarization does not agree well with that reported in [16]. In that paper the change of polarization from circular to elliptical with 2 to 1 ratio happens at a frequency such that the tapered section is equal to the effective half-wavelength. At higher frequencies the ellipse axial ratio increases further. In our case the length of the tapered portion is only 1/7 of the effective wavelength but the axial ratio is already larger than 2 to 1. One possible reason is that not only the length but also the shape of the tapered section is important. The design of the antenna terminal region used in ref. [16] is quite different from our one and may be more advantageous in terms of the polarization property. Another explanation could be that by some reasons (high resistivity of the Au, impedance mismatch, etc) the field decays faster along the antenna arms making the influence of the antenna center larger. To understand this better, further investigation (testing different antenna designs at different frequencies) is needed.

Acknowledgments

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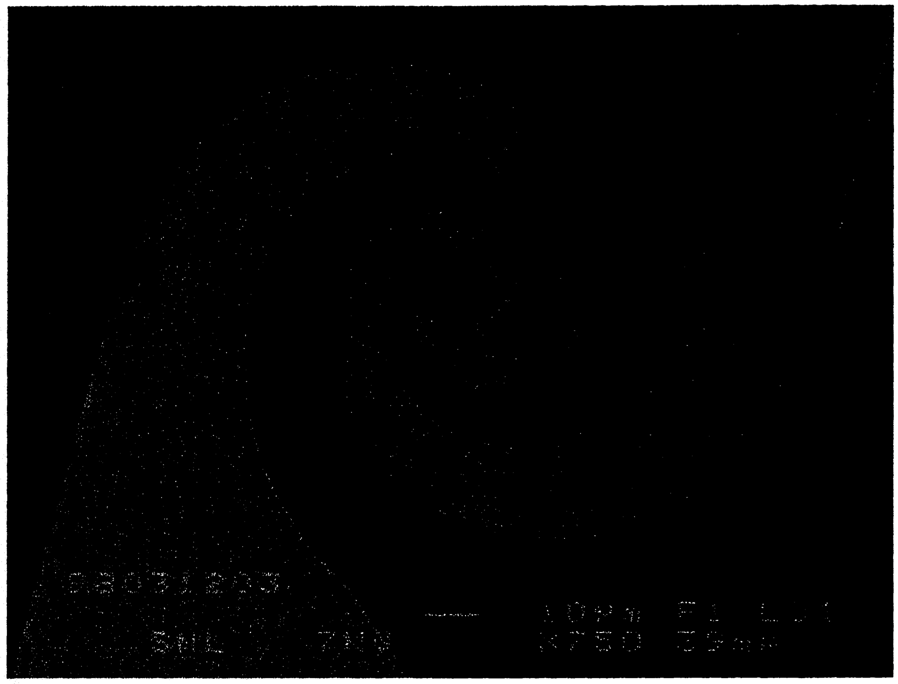

Fig.1. SEM micrograph of the spiral antenna integrated HEB mixer. The antenna design is spiral "B".

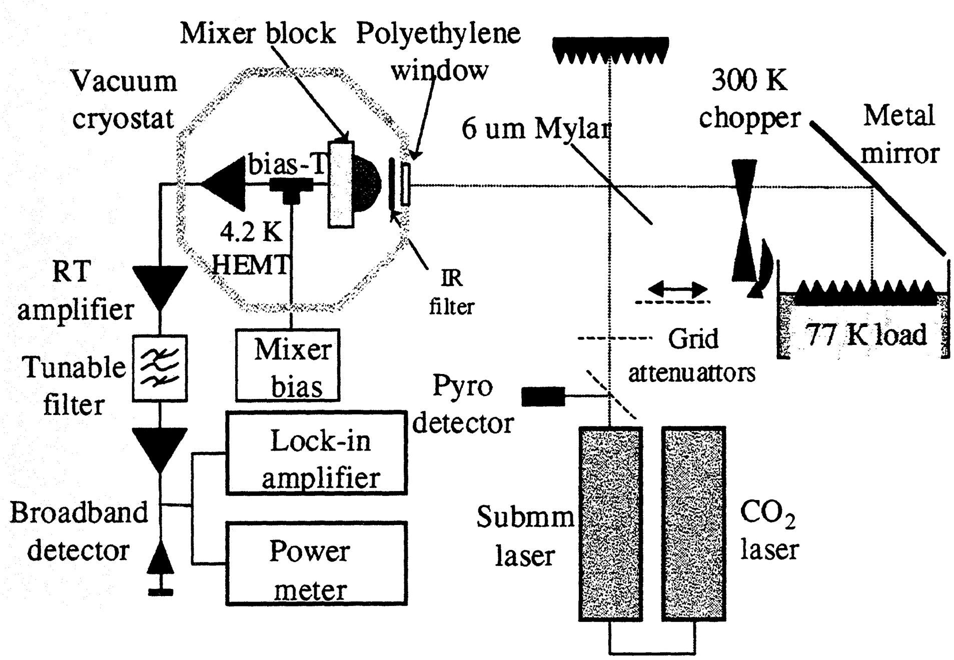

Fig.2. Setup for noise temperature measurements.

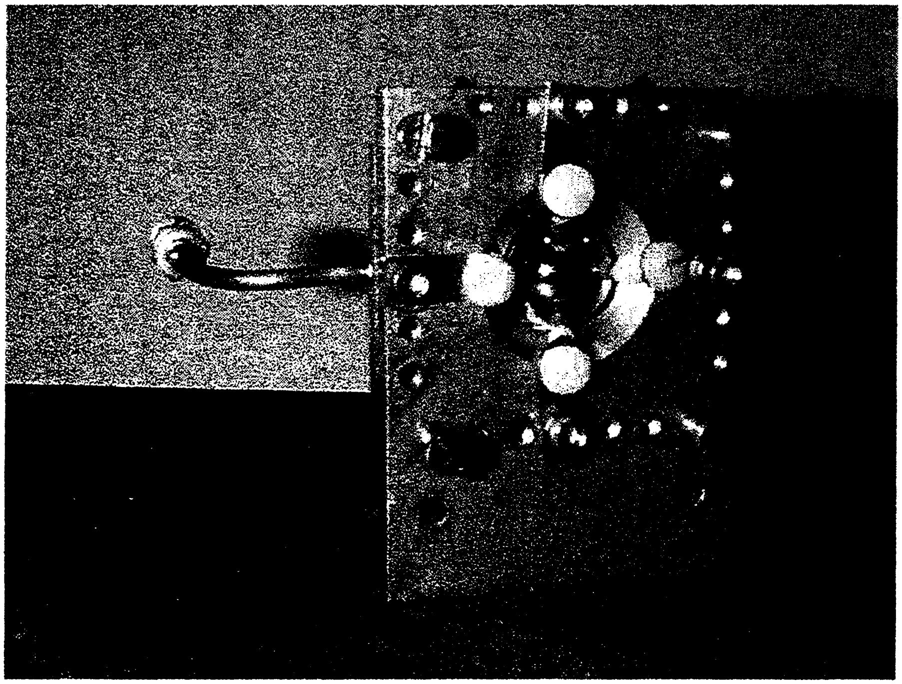

Fig.3. Photograph of the mixer block. The 12 mm diameter Si lens is clamped with springs and four plastic screws against the Si substrate.

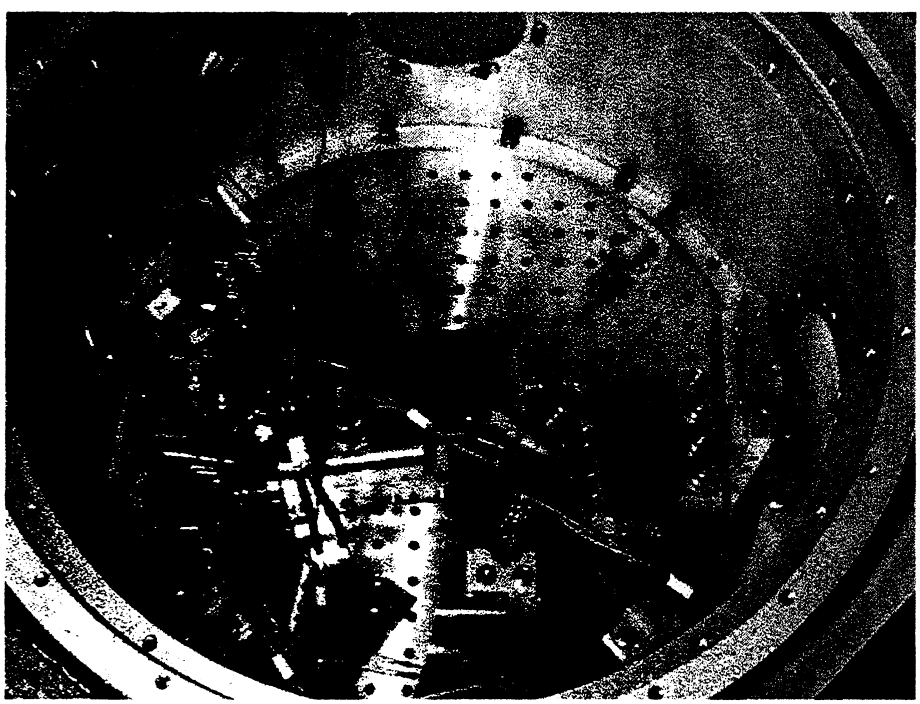

Fig.4. The interior of the LHe vacuum cryostat. The HEMT amplifier is in the center of the cold plate.

Device number	**V14**	**V24**	**V43**	**V24**	**V47**
R_{300K}, Ohm	160	160	230	100	190
R_{20K}, Ohm	350	320	410	230	430
Antenna design	A	B	C	B	C
Bolometer length, µm	0.2	0.15	0.15	≤0.1	≤0.1
width, µm	2	2	1	2	1
I_c, µA (at 4.2 K)	290	180,215,285	110,120,130	280	145
Bias current, µA	45	45	30	60	30
voltage, mV	1.2	0.8	1.2	1.1	1.0
Absorbed LO power, nW	100	100	50	nm	nm
DSB NT, K					
0.7 THz	800	800	1750	1100	1900
1.4 THz	1500	1100	1500	1300	1700
1.6 THz	1300	1100	1300	1300	1700
2.5 THz	2300	2100	2300	2300	2200(2000*)
3.1 THz	nm	nm	nm	4200	4200

nm = not measured
*measured at 3 K ambient temperature

Table 1. Device parameters and results of noise temperature measurements.