HEB Quasi–optical Heterodyne Receiver for THz Frequencies

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Abstract

The performance of NbN based HEB mixers has been investigated at THz frequencies in a receiver with quasi–optical coupling. The best performance is achieved with devices made from NbN films deposited on crystalline MgO substrates, with film thickness $d = 3.5\,\text{nm}$ and a critical temperature $T_c = 9 - 10\,\text{K}$. Double–side band receiver noise temperatures are 530 K at 0.6 THz, 650 K at 1.6 THz and 1100 K at 2.5 THz. The intermediate frequency (IF) bandwidth is 4.5 GHz under operating conditions yielding the lowest noise temperature. Operating the bolometer at high bias voltages can increase the IF bandwidth up to 9 GHz at the expense of a drop in sensitivity by a factor of two.

1 Introduction

Superconducting hot–electron bolometers (HEB) are suitable mixers for heterodyne receivers at frequencies at and above 1 THz. Their high sensitivity and comparitively low local oscillator (LO) power requirement make them superior to other mixers like SIS junctions or Schottky diodes.

Two concepts of HEB, employing different cooling mechanisms, are under development. The diffusion cooled type, suggested by Prober [1], is a *short* bridge of niobium and cooling takes place by diffusion of hot electrons out of the ends of the bridge. In the phonon cooled type, a microbridge made from *ultrathin* niobium nitride films, electrons are predominantly cooled by inelastic scattering with phonons in the film and subsequent heat transfer into the substrate [2]. Both HEB types have been integrated into receivers with quasi–optical or wave guide coupling and have shown low noise figures at THz frequencies along with an intermediate frequency (IF) bandwidth of up to 9 GHz [3–5].

The technology for NbN based HEB mixers has been continously improved during the last years. At a level of comparitively low noise temperatures, $T_{\text{rec,DSB}} = 650\,\text{K}$ at 1.6 THz and 1100 K at 2.5 THz, less than 20 times the quantum noise $hf/2k_B$, the question arises what are the limiting factors in receiver performance. In particular, what are the contributions from coupling loss and mixer conversion loss. There are methods to measure the sum of both [6], but more detailed investigations face the difficulty that different loss contributions in the submillimeter circuit (antenna, bolometer) can not easily be studied separately. For

the performance of the HEB mixer itself, predictions based on existing models can not explain experimental results in all cases, which makes it at this stage difficult to give exact design rules in order to further optimize the receiver.
This paper gives an overview of recent results obtained with quasi–optically coupled NbN based HEB mixers, possible improvements in receiver technology are discussed.

2 Measurement Set–up

Figure 1 shows the set–up used for receiver noise temperature measurements. Local oscillator sources are a BWO for 0.6 THz or a far infrared laser for 1.6 and 2.5 THz. The signal from hot/cold black body loads is combined with the LO by means of a beam splitter, a 12 μm thin Mylar foil, and injected into the cryostate through a polyethylene window. A 0.25 mm thick Zitex filter on the 4 K shield blocks IR radiation from entering the mixer. The mixer chip is clamped onto the flat side of an elliptical lens and mounted into a copper block. Lenses with a $\lambda/4$ antireflex coating made from Parylene are used for measurements at 1.6 THz and 2.5 THz. The read out line for the IF signal consists of a bias–T, a low noise amplifier (LNA) with center frequency 1.5 GHz, a room temperature amplifier, a bandpass filter and a power meter.

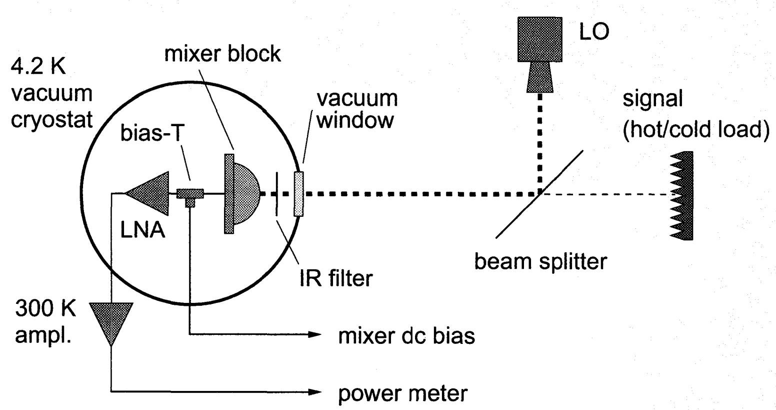

Figure 1: Schematics of the measurement set–up. The radiation coupling optics consists of "hot" (beam splitter, vacuum window) and "cold" (IR filter, lens + antenna) parts.

The absorption/reflection losses in the optics are $\sim$ 2.5 dB at 0.6 THz and increase to $\sim$ 3.5 dB at 2.5 THz (using a lens without anti reflection coating). Data for material absorption losses are taken from [7,8]. The contribution from hot parts in the optics (beam splitter, cryostat window) to the receiver noise temperature $T_{\mathrm{rec,DSB}}$ has been measured to be $\sim$ 60 K at 0.6 THz. The IF chain contributes with 25 – 75 K, calculated from the equivalent noise temperature of the LNA, $T_{\mathrm{IF}}(1.5\,\mathrm{GHz}) \simeq 5\,\mathrm{K}$, and a total conversion loss of $L_{\mathrm{tot}} = 10 - 15\,\mathrm{dB}$.

3 HEB Device

The mixing element is a thin film strip of superconducting NbN on a dielectric substrate. The strip is integrated into an on–chip logspiral antenna with the antenna terminals serving as rf input and IF output port at the same time. The in–plane geometry width/length is chosen such that it yields a normal resistance R_n of the film strip close to the antenna impedance Z_A. Fig. 3 shows an SEM micrograph of one of the mixer chips.

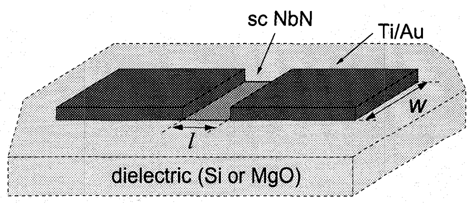

Figure 2: Schematics of the bolometer. The NbN strip with, is contacted by normal metal pads made of 5 nm Ti + 70 nm Au. The width w and length ℓ are of the order μm.

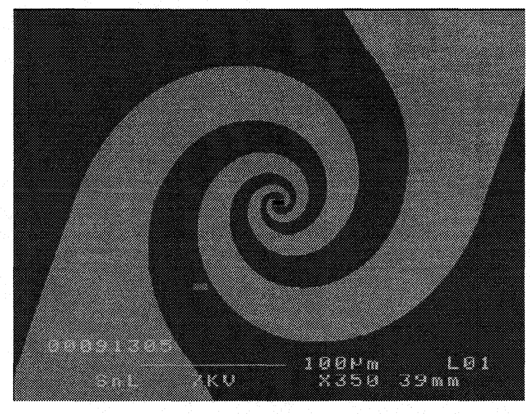

Figure 3: SEM micrograph of the antenna integrated HEB mixer.

3.1 Fabrication

The fabrication makes use of standard thin film and lithographic techniques and has been described earlier [9, 10]. Here, one aspect is looked at in more detail since it is likely to be critical for the device performance. It concerns the quality of the contact between the NbN film strip and the antenna terminals. This contact is established through pads of Ti/Au defined by e–beam lithography in a lift–off technique. The metallization process, using thermal evaporation without in–situ cleaning, requires a thin layer of Ti to achieve good adhesion. There are several reasons why the interface between the Ti/Au pads and NbN film is not ideal:[1]

- Formation of an oxide layer on the NbN film: (a) While being exposed to atmosphere (for some samples as long as months or years), (b) during resist ashing in oxygen plasma (prior to metallisation).
- The highly reactive Titanium will form compounds with contaminants on the sample surface and in the vacuum: (1) a layer of hydro carbones naturally exists on surfaces exposed to atmosphere, (2) remaining gases in the evaporation chamber, mainly oxygen, are gettered by Ti [11].

[1] The "ideal" interface could be obtained with *clean* materials deposited *in–situ*.

In a seperate study, a standard method [12] has been used to measure the specific contact resistance ρ_c between NbN film and Ti/Au pads. The results show that values vary greatly between fabrication batches, with ρ_c falling in the range $10^{-7} - 10^{-6}\,\Omega\,\mathrm{cm}^2$. We attribute this large variation to poorly controlled process parameters as described above. The absolute values for ρ_c are comparable to what is achieved with other ex-situ metallization processes and might not be critical, but in case of small contact areas $\sim \mu\mathrm{m}^2$ a resistance of up to $100\,\Omega$ can occur. The presence of such a contact resistance and consequences for device performance will be discussed in the next section.

3.2 Coupling between antenna and bolometer

Let us discuss the distribution of rf currents close to the NbN bridge: At a frequency higher than $2\Delta/h$ (with Δ the gap energy of the superconductor) the surface impedance of the NbN film equals the normal sheet resistance [13], $R_\square \simeq 500\,\Omega$ and thus much higher than the one of gold. RF currents are therefore concentrated in the gold and will go into the NbN film only within a certain distance from the bridge edge. A first estimate is to assume this length to be of the order of the skin depth in the gold film, $\delta_{\mathrm{Au}} \approx 0.1\,\mu\mathrm{m}$ at 1 THz.

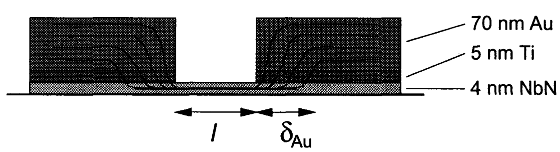

Figure 4: RF current distribution along the length of the NbN bridge.

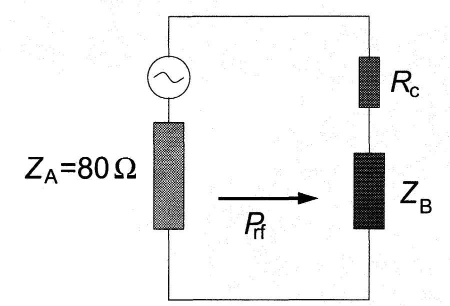

Figure 5: RF ircuit model of the antenna integrated bolometer with contact resistance.

The conclusion from this consideration is that the effective contact area $w \times \delta_{\mathrm{Au}}$ for rf currents is of the order $\sim \mu\mathrm{m}^2$, giving rise to a contact resistance R_c *in series* with the bolometer, see Fig. 5. Hence, coupling of rf–power P_{rf} into the bolometer with impedance Z_{B} is less efficient, additional losses will scale with the ratio R_c/Z_{B}.
Even though no exact values for degradation in coupling efficiency can be taken from this study, the badly controlled interface quality might explain why devices with similar film parameters differ in sensitivity performance. In order to improve reliability and reproducibility of the technology, we suggest to have initially an in–situ deposited gold layer on top of the NbN film. The gold layer is removed after patterning the micro bridge, similar to a process successfully used for fabrication of Nb diffusion cooled mixers [14, 15].

4 Receiver Noise Temperature

Noise temperature measurements have been performed at three different LO frequencies: 0.6 THz, 1.6 THz and 2.5 THz. The IF signal is measured at 1.5 GHz and the standard Y–factor method, with hot (295 K) and cold (77 K) loads in the signal path is used to determine the equivalent input noise temperature of the receiver.[2]
We will first present the data for $T_{\rm rec}$ at $f_{\rm LO} = 0.6$ THz and discuss absolute values of $T_{\rm rec}$ obtained with different mixers. The frequency dependence of the receiver noise temperature is discussed in section 4.2.

4.1 Absolute value

Data of noise temperature measurments have been obtained with mixers where device parameters have been varied within a certain range, see Tab. 1.

Table 1: HEB device parameters. The critical temperature $T_{\rm c}$ is measured on the film *prior* to further processing, values of $j_{\rm c}$ are calculated from the critical current of the bolometer at 4 K.

parameter	value
d	$3-5$ nm
$T_{\rm c}$	$9-11.5$ K
w	$0.15-1\,\mu$m
ℓ	$1-4\,\mu$m
$R_{\rm n}$	$50-300\,\Omega$
$j_{\rm c}$	$2-8\cdot10^6$ A/cm^2

Lowest noise temperature, $T_{\rm rec,DSB} = 500-550$ K, is achieved with devices having a *low* critical current density, $j_{\rm c} = 2-3$ A/cm^2 corresponding to a critical temperature $T_{\rm c} = 9-10$ K. Their normal state resistance falls into the range $R_{\rm n} = 80-110\,\Omega$, close to what is expected to give good matching to the antenna impedance $Z_{\rm A} = 80\,\Omega$. A dependence of performance on the bolometer in–plane geometry is not observed.

4.2 Frequency Dependence

Fig. 6 shows results from receiver noise temperature measurements with 3 mixers. The devices have different in–plane geometry and are taken from 3 separated fabrication runs. The first conclusion is that the frequency dependence is similar for all mixers, irrespective of the absolute value. Quantitatively, the increase of the noise temperature is $4-5$ dB when going from 0.6 THz to 2.5 THz.
The degradation in performance is partly explained by about 1 dB higher absorption losses in the optics. It is not clear yet, to which extent other loss mechanisms contribute. While

[2] The *noise temperatures* of hot and cold loads are calculated according to the formulae of Callen & Welton [16].

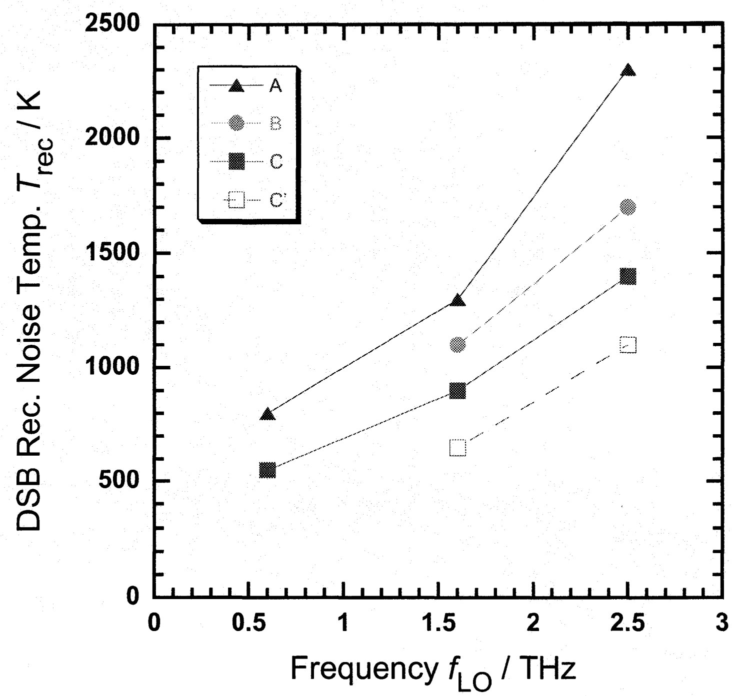

Figure 6: Frequency dependence of the receiver noise temperature for three different HEB mixers. The device in plane dimensions $w \times \ell$ are: $2 \times 0.15\,\mu$m (A), $1 \times 0.15\,\mu$m (B) and $4 \times 0.4\,\mu$m (C). Data (C′) are obtained using Si lenses with a $\lambda/4$ antireflex coating. reducing the coupling loss by about 20 % [4].

the intrinsic conversion loss of the mixer may increase, also other parts of the receiver have frequency dependent characteristics and should be investigated, it concerns:

- Coupling efficiency between free space and the lens antenna.
- Ohmic losses in the antenna.
- Losses between antenna and bolometer due to mismatch.

It has been suggested by Semenov et al. [17], that a non–uniformity in the current distribution across the width of the NbN strip due to the skin effect should be more pronounced at higher frequencies and, as a consequence, lead to increased conversion loss. This problem can be overcome by choosing a device geometry with a small width, comparable to the skin depth in the NbN film, $\delta_{\mathrm{NbN}} \approx 1\,\mu$m at 1 THz. Results from computer simulations using this approach are presented in [18].

5 IF Bandwidth

The maximum speed of a hot electron mixer is set by the electron temperature relaxation time τ_θ which is a function of the film parameters [9]. However, due to electro thermal feedback from the IF circuit with load impedance R_L, the effective bolometer time constant $\tau_\theta^\star$ differs from τ_θ depending on bias conditions. In the frame of a uniform heating model, the IF band width reads [19]

$$f_{3\,\mathrm{dB}} = \frac{1}{2\pi\,\tau_\theta^\star} = \frac{1}{2\pi\,\tau_\theta}(1-C)\,, \quad \text{with } C = C_0 I_0^2\,\frac{R_L - R_0}{R_L + R_0}\,, \tag{1}$$

$R_0 = U_0/I_0$ is the dc resistance in the operating point and $C_0 = dR/dP_{\mathrm{dc}}|_{R=R_0}$ the dc responsivity. Hence, by choosing operating conditions with $R_0 > R_L$, the value of the self–heating parameter C becomes negative and one can in principle obtain a large band width $f_{3\,\mathrm{dB}}$.

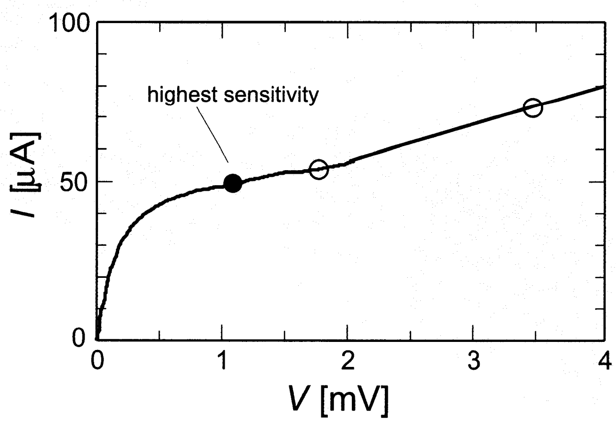

Figure 7: IV curve with the bias points for bandwidth and noise temperature measurements indicated.

The bias dependence of mixer performance has been investigated with an HEB device made from a 5 nm thin film. IF bandwidth as well as receiver noise temperature has been measured in three different bias points as indicated in Fig. 7.

Table 2: Data of IF band width and receiver noise temperature. The self heating parameter C is calculated according to Equ. 1, with $R_L = 50\,\Omega$ (input impedance of the IF amplifier) and C_0 obtained from the IV curve in the actual bias point.

$R_0\,/\,\Omega$	C	$f_{3\,\mathrm{dB}}\,/\,\mathrm{GHz}$	T_{rec} at 0.6 THz	T_{rec} at 1.6 THz
24	0.23	2.7	600 K	650 K
34	0.1	3.5	600 K	700 K
51	0	9	1200 K	1400 K

The change in bandwidth from $f_{3\,\mathrm{dB}} = 2.7$ GHz to 3.5 GHz is due to the reduced heating parameter C in the second bias point. The increase to $f_{3\,\mathrm{dB}} = 9$ GHz at the highest voltage, can not be explained by the effect of electro thermal feed back alone, since $C = 0$ in this bias point. Within the same bias range, the noise temperature increases by a factor of two, showing that a wide IF bandwidth and still good sensitivity can be achieved with this type of mixer.

6 Conclusions

Sensitivity and IF bandwidth of phonon–cooled HEB mixers based on NbN, integrated into a quasi–optical receiver, have been measured at THz frequencies. The lowest DSB receiver noise temperatures are 530 K at 0.6 THz, 650 K at 1.6 THz and 1100 K at 2.5 THz. For optimization of the receiver it will be necessary to have a more accurate characterisation of the optics and the rf–embedding circuit of the mixer. This will allow a break down of receiver input losses and may allow conclusions about degradation in sensitivty performance at higher frequencies. In addition the fabrication process needs to be developed for better control of the contact resistance at the mixer rf input.

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