Intermediate Frequency Bandwidth of a Hot-Electron Mixer: Comparison with Bolometric Models

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Abstract**—The gain bandwidth of a superconducting NbN hot-electron mixer quasioptically coupled to radiation was evaluated in different operation conditions and compared to presently known bolometric mixer models. Heterodyne regime was obtained with a 2.5 THz quantum cascade laser as a local oscillator and alternating thermal loads and also by mixing radiation of the quantum cascade laser and a gas laser. The results rather agree with the hot-spot mixer model than with any of the homogeneous bolometric models.**

Index Terms **— bolometers, gain measurements, superconducting devices, thin film devices.**

I. INTRODUCTION

SHORTLY after the introduction of superconducting thin-film hot-electron bolometric mixers [1,2] their usable intermediate frequency (IF) band has been recognized as one of the most important parameters. In terahertz heterodyne applications, this is the lack of tunable radiation sources that enhances the importance of the gain bandwidth of hot-electron bolometric mixers. Since the factors limiting the bandwidth are the thermal coupling of the film to a substrate and diffusion of electrons and phonons in the film (for details see e.g. the reviews [3]), great efforts were made in order to decrease the thickness and the lateral size of the mixers as well as to find an optimal substrate material for a particular superconducting film. During the last decades suitability of many materials for heterodyne detection were evaluated but only NbN and NbTiN superconducting films met the requirements of practical applications [4]. For bolometers made from NbN films, phonons leaving the film through the film-substrate interface dominate the cooling process. Substrates from crystalline MgO [5] have demonstrated the best thermal coupling to NbN films whereas substrates from Si, although providing a slightly weaker coupling, have been shown [6,7] to better compromise with all practical constraints. There is no common opinion on whether the thermal coupling to a substrate [8] or the intrinsic interaction times [9] limit the IF bandwidth of mixers from NbTiN films. However, independently on the substrate used, these mixers exhibit a bandwidth noticeably smaller than mixers from NbN films.

Besides the practical importance of realizing a possibly large IF bandwidth, studying the bandwidth variations with the change of the mixer operation regime allows one to better understand the mixing mechanism. The bolometric models introduced so far are the homogeneous hot-electron models [10, 11, 12] and the hot-spot model [13,14] with the zero phonon escape time. In this paper we compare the IF bandwidth measured at 2.5 THz for the NbN hot-electron mixer with the predictions of these two models and with earlier published data.

II. DEVICE FABRICATION AND MEASUREMENTS

The films were deposited on optically polished R-plane sapphire substrates by DC magnetron sputtering of pure Nb target in Ar+N_2 gas mixture. The substrates were laid on the surface of a heater without any thermo-conducting glue. The temperature of the heater during deposition was kept at 750 °C. The base pressure in the sputtering chamber was approximately $2\cdot10^{-7}$ mbar at room temperature and reached an order of magnitude higher value when the temperature of the heater increased to 750 °C. During deposition the partial pressure of Ar and N_2 was $5\cdot10^{-3}$ mbar and $7\cdot10^{-4}$ mbar, respectively. The nominal deposition time was 14 sec. Using ellipsometry we found for our films a thickness of 5 ± 1 nm that corresponded to a deposition rate of ≈ 0.65 nm sec^{-1}. The superconducting transition temperature T_C taken as the temperature corresponding to the offset of the film resistance was measured for freshly deposited films by means of the standard four-probe method. Depending on the stoichiometric composition, T_C varied between 9.5 K and 11 K whereas the width of the transition was ≈ 0.9 K and remained almost unchanged for all compositions. The surface resistance of our films at the maximum of the temperature dependence of the resistance amounted at $\approx 1000\ \Omega$ per square that was approximately 1.3 times larger than the square resistance measured at room temperature.

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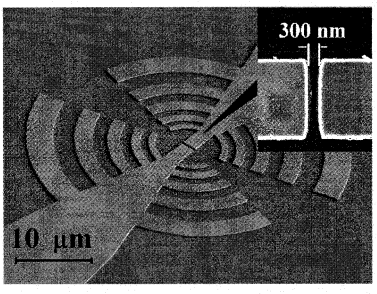

Fig. 1. Picture of the log-periodic antenna and the slit in the center (inset) taken with a scanning electron microscope.

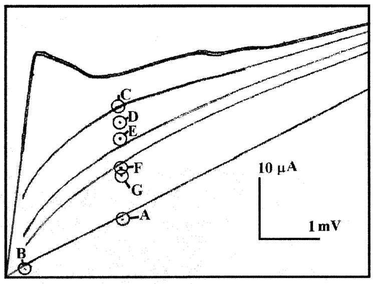

Fig. 2. Set of dc voltage-bias characteristics for few (increasing from top to bottom) levels of the LO power. The upper curve was taken without LO power. IF bandwidth and the noise temperature were measured in the operation conditions shown by encircled points.

The hot-electron bolometers were manufactured by means of electron-beam lithography in the following three-step sequence. First we wrote a set of global and local alignment marks in an electron-beam resist layer from polymethylmethacrilate (PMMA) spun to a thickness of 200 nm on a bare NbN film. Then we deposited a Ti/Au (10/50 nm) bi-layer for the lift-off process. Due to a high material contrast between NbN and Au, such bi-layer formed high quality (sharp and strait) alignment marks which were easy to recognize even under relatively thick resist layers used in the next fabrication steps. Second we opened the window for the antenna in the newly spun 400 nm PMMA and deposited in the opening a 250-nm thick Au layer sandwiched between two 10-nm Ti layers. The length of the bolometer was defined at this stage as the width of the slit between the antenna arms. The third lithography was made in the negative electron-beam resist. In the center of the antenna we formed a rectangle from the resist that defined the width of the bolometer. Finally, using the rectangle and the top titanium layer of the antenna structure as masks, we removed the unprotected part of the NbN film by ion milling. Typically bolometers with a size of 2 x 0.25 μm^2 (width x length) had $T_C \approx 7.8$ K and a resistance of 160 Ω at the room temperature. Fig. 1 shows the antenna and the central slit where the bolometer is located.

Radiation was coupled to the bolometer by an extended hemispherical Si lens. The bolometer with the lens was cooled to 4.5 K in a cryostat with optical access through a polymethylpentene (TPX) window kept at the room temperature and a quartz filter mounted on the 77 K screen. The noise temperature and the conversion efficiency were measured with a conventional radiometric method in that radiation of a local oscillator (LO) at a frequency of 2.5 THz was applied to the bolometer and its response at the intermediate frequency to alternating hot and cold loads was recorded with the lock-in technique. The loads were at an air distance of 50 cm from the cryostat window. We have verified that attenuation of water vapors in the upper and lower sub-bands of our IF band varied in the range smaller than 0.2 dB. Radiation of the load and the local oscillator was combined by a Mylar beam-splitter with a thickness of 6 µm. A chain of broadband cooled low-noise and room temperature amplifiers raised the level of the response signal. In order to maximize the response we eliminated truncation of the bolometer field of view and fully covered it with the loads. The transmission coefficient S_{21} of the IF amplifiers was directly determined as the portion of the "white" noise passing through the chain. The Johnson noise in excess to the intrinsic noise of the first amplifier was produced by the same bolometer driven in the normal state by a sufficiently high LO power. The IF response of the bolometer was then normalized with the S_{21} parameter that gave us the relative conversion efficiency. The use of a very stable quantum cascade laser (QCL) [15] as a local oscillator made it possible to sample the IF band with a resolution of 2 MHz. The mixer was dc voltage-biased to a value corresponding to the smallest measurable noise temperature. The IF dependence of both the mixer noise temperature and the response was then measured at different levels of the LO power, which in tern resulted in different bias currents. Fig. 2 shows dc bias characteristics taken at different LO levels. The point labeled "B" (normal state, no bias) was used to measure the transmission of the IF chain.

We complemented this technique by mixing radiation of the QCL and a gas laser with our bolometer. In this case the IF signal of the bolometer mixer was normalized with the IF signal of an Schottky diode backed by the same amplifier chain (only room temperature amplifiers were used in this experiment). The gas laser was operated at a constant power acting as local oscillator. We scanned the IF band by tuning QCL-frequency with the dc current-bias. A non-stabilized line-width of the QCL less than 1 MHz was sufficient to provide desired accuracy of the gain measurements.

III. DATA AND ANALYSIS

The noise temperature and the normalized conversion efficiency related to the position of the load are shown in Figs. 3 and 4, respectively. Data shown in the pictures were acquired in the conditions labeled with "D" in Fig. 2. Since the mixer noise due to thermal fluctuations decreases along with the mixing product, the noise temperature slowly varies at low intermediate frequencies and exhibits an upturn when the thermal noise drops below the frequency independent Johnson noise. Standing waves in the mixer bias board and also between the board and the first amplifier resulted in the resonance peaks seen in the IF dependence of the noise temperature in Fig 3. As a result of the normalization procedure, which we used to obtain the relative gain, the peaks almost disappeared in the IF dependence of the

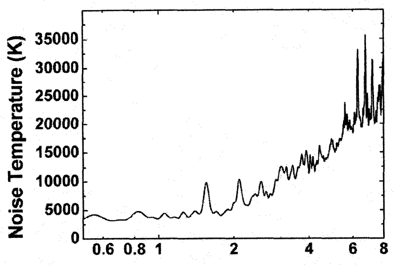

Fig. 3. Noise temperature referred to the position of the load as function of the intermediate frequency.

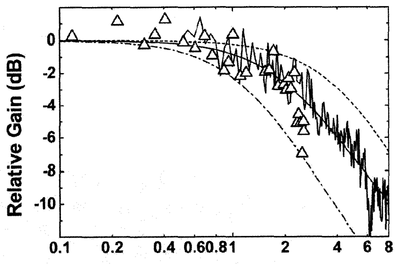

Fig. 4. Relative conversion efficiency of the mixer measured with the hot-cold technique (solid noisy line) and by means of the mixing product of the QCL and the gas laser (open triangles). Smooth lines show the model gain that was computed in the framework of the KE (dotted) NS (solid) and PV (dash-dotted) models with the same set of mixer parameters.

conversion efficiency (Fig. 4). The normalization enormously enhanced the accuracy with which the roll-off frequency of the conversion efficiency was determined. Two methods of gain measurements provide complementary results that coincide fairly well in the frequency range from 0.5 GHz to 2 GHz where the methods overlap. We obtained a 3-dB roll-off frequency F_0 by fitting our experimental IF dependence of the gain with the following relaxation dependence

$$G(F) = \frac{1}{1+\left(F/F_0\right)^2} \quad , \tag{1}$$

where F denotes the intermediate frequency. Thus defined roll-off frequencies are plotted in Fig. 5 as function of the bias current. With the decrease of the LO power (increase of the current) the experimental IF bandwidth decreases from 3.5 GHz to 2.2 GHz. The median value reasonably corresponds to the gain bandwidth of 3.7 GHz measured [16] for somewhat thinner mixer devices on sapphire substrates. Along with the decrease of the bandwidth the noise temperature passes the minimum at the LO power corresponding to $F_0 \approx 2.5$ GHz. We shall emphasize that the minimum value of the noise temperature presented in the Fig. 5 is related to the hot-cold loads. The noise temperature related to the tip of the lens amounts at 1050 K that is close to the best values reported at 2.5 THz.

We compare measured IF dependence of the relative gain with the predictions of the PV [10], KE [11] and NS [12] models (abbreviation is made in all three cases after the names of first two authors). Formally, it is possible to fit experimental data with either model. However each fit would require different fitting parameters. The criterion for applicability of the particular model should be coincidence of the parameters extracted from the fitting procedure with the known material parameters. In the framework of the PV model the IF dependence of the relative gain is

$$G_{PV}(\omega) = \left|\eta(\omega)\right|^2 = \left|\frac{1}{1+j\omega\tau_1}\,\frac{1+j\omega\tau_3}{1+j\omega\tau_2}\right|^2 \quad , \tag{2}$$

where $\omega = 2\pi F$ and the characteristic times τ_1, τ_2 and τ_3 are connected with the electron-phonon interaction time τ_{eph}, phonon escape time τ_{es} and the ratio $R_{eph} = c_e/c_{ph}$ of the electron c_e and phonon c_{ph} specific heat as follows

$$\begin{aligned}
\frac{1}{\tau_1} &= \frac{1}{2}\left(\frac{\tau_{es}+\tau_\theta}{\tau_{eph}\tau_{es}}\right)\left[1+\sqrt{1-\frac{4\tau_{eph}\tau_{es}}{\left(\tau_{es}+\tau_\theta\right)^2}}\right] \\
\frac{1}{\tau_2} &= \frac{1}{2}\left(\frac{\tau_{es}+\tau_\theta}{\tau_{eph}\tau_{es}}\right)\left[1-\sqrt{1-\frac{4\tau_{eph}\tau_{es}}{\left(\tau_{es}+\tau_\theta\right)^2}}\right] \\
\frac{1}{\tau_3} &= \frac{\tau_\theta}{\tau_{eph}\tau_{es}}; \quad \tau_\theta = \tau_{eph} + R_{eph}\tau_{es} \ .
\end{aligned} \tag{3}$$

The KE and NS models include the heating of the mixer by the bias current and the electro-thermal feedback through the IF load. These are essentially the same phenomena that are responsible for the decrease of the response time of a voltage-biased transition edge sensor [17]. Formally the effect of the feedback is described with the self-heating factor C. It can be extracted from the dc bias characteristics as $C = (R_d-R)/(R_d+R)$ where R_d and R are the differential and dc resistance of the bolometer in the operation conditions. In both models the relative gain of the mixer connected to an IF load with the real resistance R_0 can be presented as

$$G(\omega) = \frac{\left|C\left(R-R_0\right)+\left(R+R_0\right)\right|^2}{\left|C\left(R-R_0\right)+\left(R+R_0\right)\varphi(\omega)\right|^2} \tag{4}$$

with either $\varphi(\omega) = \eta(\omega)^{-1}$ in the NS or $\varphi(\omega) = 1+j\,\omega\,\tau_\theta$ in the KE model. The KE model relies on an approximation of the PV model at $\tau_{eph} >> R_{eph}\tau_{es}$ that fairly good describes e.g. Nb bolometers. In the NS model the effective temperature of phonons T_{ph} is supposed to differ from the effective electron temperature T_e and has to be calculated via steady-state energy balance equations. The difference between T_{ph} and T_e influences the interaction times and the specific heat ratio. Fig. 4 shows the relative gain that we have computed in the framework of each model with the same set of parameters. Experimental data ($C = 0.55$) are best fit by the NS model with $\tau_{es} = 38$ ps assuming the following temperature dependences of the parameters: τ_{eph} [ps] $= 474\,T^{-1.6}$, $c_{ph} = 9.8\,T^3$ and $c_e = 280\,T$ (c_{ph} and c_e are in J cm^{-3} K^{-1}; temperature in Kelvins). We computed $T_{ph} = 6.9$ K using $T_e = 7.5$ K that was the value found from the superconducting resistive transition $R(T)$ for the actual dc resistance of the bolometer. The best-fit parameters coincide with the parameters concluded from the pulse measurements [18] if one assumes τ_{es}[ps] $= 8\,d$ [nm] where

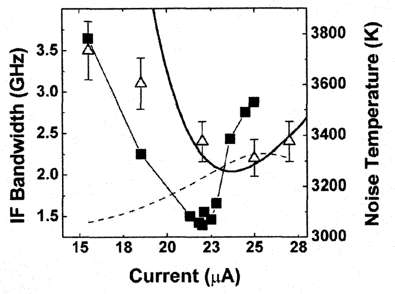

Fig. 5. IF bandwidth (open symbols) and the noise temperature (closed symbols) measured at different levels of the LO power are shown as function of the corresponding bias current. The broken solid line is to guide the eyes. Smooth lines show the IF bandwidth computed with the hot-spot model (solid line) and with the NS model (dashed line).

d is the bolometer thickness. Fitting the experimental gain with the KE model would require a noticeably larger $\tau_{es} \approx 130$ ps.

Defining the model bandwidth as the 3-dB roll-off frequency of the model gain and using the experimental values of C and T_e, we computed the bandwidth for each LO power. The bandwidth obtained with the NS model (dashed line in Fig. 5) is obviously inconsistent with the experimental data. Similar disagreement was found for other two uniform bolometric models.

The hot-spot (HS) approach, which was used [14] to analytically evaluate the IF bandwidth, invoked the velocity of the boundary between the normal spot and superconducting portion of an infinitely long bolometer. The velocity was found by solving time dependent diffusion equations for hot-electrons. Phonons with their actual temperature can also be included at the expense of analytical transparency [19]. For the limited range of bias currents the HS-model gain is

$$G_{HS}(\omega) \propto \left| 1 + \omega^2 \tau_\theta^2 \left(\sqrt{\frac{J^2 \rho_n \tau_\theta}{c_e (T_C - T)}} - 1 \right)^2 + j\omega\tau_\theta \right|^{-2}, \quad (5)$$

where J is the density of the bias current an ρ_n the normal-state resistivity. The current dependence of the IF bandwidth computed with Eq. 5 is shown in Fig. 5 with the solid line. The HS model follows the trend in the experimental data. However, the approximation of a free normal domain is still too schematic. It does not take into account the effect of the contacts that restricts the movement of the domain walls and thus decreases the bandwidth. This is most likely the reason for the disagreement between the model and the experiment at small currents when the size of the normal domain approaches the length of the bolometer.

In conclusion, we have shown that, contrary to homogeneous bolometric models, the hot-spot model of the hot-electron mixer describes both the intermediate frequency dependence of the mixer gain and the variation of the bandwidth with the applied local oscillator power.

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