Fabrication and characterisation of NbN HEB mixers with in situ gold contacts

S. A. Ryabchun*, I. V. Tretyakov, M. I. Finkel, S. N. Maslennikov, N. S. Kaurova, V. A. Seleznev, B. M. Voronov and G. N. Goltsman

Moscow State Pedagogical University, Moscow 119992, Russia

* Contact: sryabchun@rplab.ru, phone +7-495-246 6321

***Abstract*— We present our recent results of the fabrication and testing of NbN hot-electron bolometer mixers with *in situ* gold contacts. An intermediate frequency bandwidth of about 6 GHz has been measured for the mixers made of a 3.5-nm NbN film on a plane Si substrate with *in situ* gold contacts, compared to 3.5 GHz for devices made of the same film with *ex situ* gold contacts. The increase in the intermediate frequency bandwidth is attributed to additional diffusion cooling through the improved contacts, which is further supported by the its dependence on the bridge length: intermediate frequency bandwidths of 3.5 GHz and 6 GHz have been measured for devices with lengths of 0.35 µm and 0.16 µm respectively at a local oscillator frequency of 300 GHz near the superconducting transition. At a local oscillator frequency of 2.5 THz the receiver has offered a DSB noise temperature of 950 K. When compared to the previous result of 1300 K obtained at the same local oscillator frequency for devices fabricated with an *ex situ* route, such a low value of the noise temperature may also be attributed to the improved gold contacts.**

I. INTRODUCTION

Hot-Electron Bolometer (HEB) mixers have long ago established themselves as the primary detectors of choice for heterodyne observations in terahertz radio astronomy. At the same time, the quest for better characteristics – a lower noise temperature and a wider intermediate frequency (IF) bandwidth – has been underway. As far as heterodyne spectroscopy is concerned, a wider IF bandwidth might allow observation of a few relatively narrow lines or mapping a broader line without the necessity to change the local oscillator (LO) frequency, a procedure which is not only inconvenient but may also be practically impossible. In total power receivers the temperature resolution is inversely proportional to the receiver bandwidth and improves as the receiver noise temperature is reduced: $\Delta T = (T_A + T_R)/(B\tau)^{1/2}$, with T_A being the antenna temperature, T_R the receiver noise temperature, B the receiver final detection bandwidth and τ the integration time. Hence, both the increase of the IF bandwidth and the reduction of the noise temperature of a receiver are of great importance to applications.

With respect to the cooling mechanism of electrons HEB mixers are divided into phonon cooled mixers and diffusion cooled mixers, the type of the dominating process depending primarily on the device geometry. For devices with lengths $L > L_{diff} = (D\tau_\Theta)^{1/2}$ (D being the diffusion coefficient and τ_Θ the electron temperature relaxation time) cooling by phonons dominates. In this case the excess energy of the electrons is removed through collisions with the phonons in the film on a time scale of the electron-phonon interaction time τ_{eph} and the subsequent escape of these non-equilibrium phonons into the substrate with the characteristic time τ_{esc}.

There are several models that describe the operation of the phonon cooled HEB mixer, the most known and simplest of these being the uniform heating model (e.g. [1]) and the hot-spot model (e.g. [2], [3]). Only the salient points of the former will be reviewed here, while the latter will not be discussed at all. In the framework of the uniform heating model the HEB mixer is described by a set of two coupled heat balance equations governing the evolution of the electron and phonon subsystems of a superconducting film. These equations are not linear in the electron and phonon temperatures but become such in the limit of a small signal. This means that the deviations of the electron and phonon temperatures caused by absorbed RF power and Joule heating are small compared with their equilibrium values, which is why the uniform heating model works well only when the ambient temperature is close to T_c. In this case one can compute the alternating part of the electron temperature, $\Delta\Theta_{ac}$ ([4]), whence the alternating part of the voltage across the mixer is $\Delta V_{ac} = I_{dc}(\partial R/\partial\Theta)\Delta\Theta_{ac}$, and the output power $P_{IF} \sim |\Delta V_{ac}|^2 \sim |\Delta\Theta_{ac}|^2$:

$$P_{IF}(f) = P(0)\frac{1+(2\pi f\tau_0)^2}{\left(1+(2\pi f\tau_1)^2\right)\left(1+(2\pi f\tau_2)^2\right)} \quad (1)$$

with

$$\tau_0^{-1} = \tau_{esc}^{-1} + \tau_{eph}^{-1}(c_e/c_{ph}),$$
$$\tau_{1,2}^{-1} = \frac{1}{2\tau}\left[1 \pm \sqrt{1-\frac{4\tau^2}{\tau_{esc}\tau_{eph}}}\right], \quad (2)$$
$$\tau^{-1} = \tau_{esc}^{-1} + \tau_{eph}^{-1}(c_e/c_{ph}+1).$$

If the length of the mixer is small compared to L_{diff} then cooling by the diffusion of hot electrons out of the bridge into the contact pads is possible and may dominate phonon cooling ([5]). The time constant of a diffusion-cooled HEB mixer is given by ([6])

$$\tau_{diff} = \frac{L^2}{\pi^2 D}. \qquad (3)$$

For diffusion cooling to be feasible it is important to ensure a good interface between the film and the contact pads, otherwise hot electrons will not be able to diffuse out of the film. The model of the diffusion-cooled bolometer gives the following expression for output power ([6]):

$$P_{IF}(f) = P(0)\frac{1}{1+\left(2\pi f \tau_{diff}\right)^2}. \qquad (4)$$

It should be noted that in some cases (1) can be cast into the form of (5) thus allowing the determination of the single time constant of a phonon-cooled mixer (see below).

If one considers the mixer as well as the embedding circuit it will be necessary to introduce the so-called self-heating parameter which describes the effect of the electrothermal feedback between the electron temperature and the DC bias supply and slightly modifies the mixer time constant. This parameter can be shown to depend on the mixer operating point and to be proportional to the derivative of the mixer resistance with respect to the electron temperature ([6]). Our estimates, however, show that this parameter is small in the uniform heating regime, and hence the effect of the electrothermal feedback can be neglected.

As regards RF coupling, up to about 1.5 THz waveguide HEB mixers can be successfully used. However, above this frequency the dimensions of the components become too small, so quasioptical HEB mixers are used. For NbN quasioptical HEB mixers fabricated without special cleaning of the NbN film prior *ex situ* gold deposition a noise temperature of 1300 K at 2.5 THz and 3100 K at 3.8 THz and an IF bandwidth as large as 5.2 GHz in the frequency range 0.85-1 THz have been reported in [7] and [8] respectively. At the same time, it has been reported that significant improvement of the receiver performance can be achieved by additional cleaning of the NbN film before *in situ* gold deposition. Baselmans *et al.* have reported a noise temperature of 950 K at an LO frequency of 2.5 THz and an IF bandwidth of 6 GHz measured with a 600-GHz LO and attributed this result to improved interface between the film and the gold contacts [9]. Waveguide HEB mixers fabricated with the use of the conventional (*ex situ*) technological route have demonstrated noise temperatures of 900-1050 K at 1.035 THz and 1300-1400 K at 1.26 THz and an IF bandwidth of 3.2 GHz at 0.8 GHz ([10]).

II. HEB DEVICES

HEB mixers were fabricated from 3.5-nm NbN films deposited on top of Si substrates by DC reactive magnetron sputtering. The deposition of NbN film was followed by *in situ* deposition of a 15-nm Au layer. The NbN-Au structure was then covered with electronic resist and a window was made in the resist for the subsequent ion milling and chemical etching of the Au layer all the way down to the NbN film. This defined the bolometer length.

The devices had superconducting transition temperatures of about 11.5 K with transition widths of about 1 K. The critical currents were measured to be close to 400 μA and the

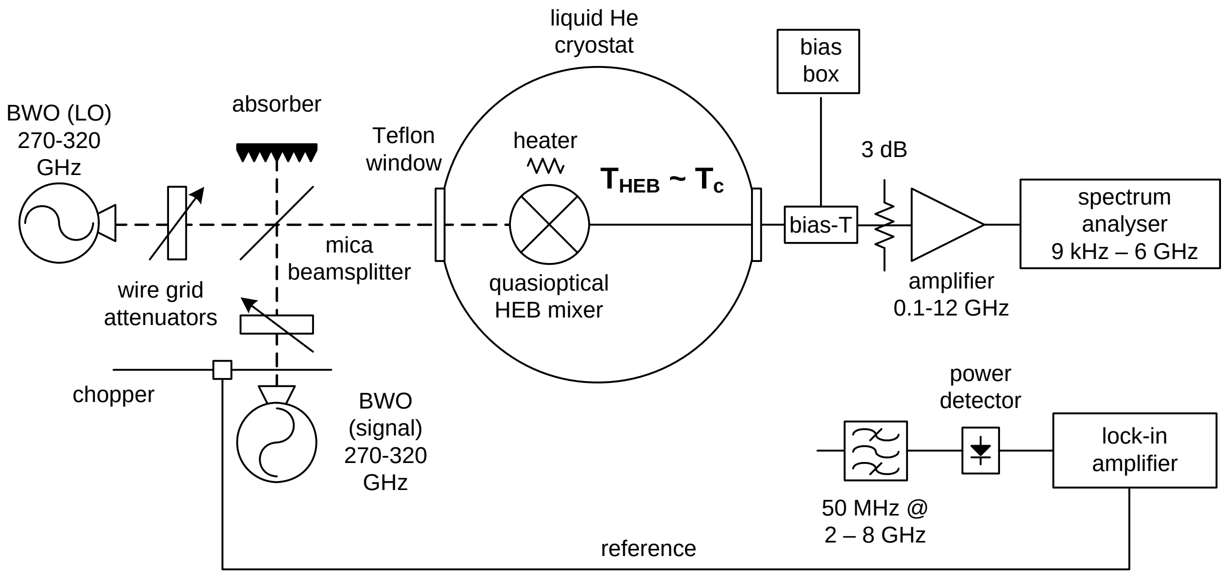

Fig. 1. Schematic of the experimental setup for IF bandwidth measurements

normal state resistances were 60 to 100 Ω.

III. Experimental setup

A. IF bandwidth measurements

The IF bandwidth of our HEB mixers was measured at 300 GHz near T_c. The experimental setup for the IF bandwidth measurements is presented in Fig. 1. The HEB mixer was glued to an extended hemispherical Si lens and installed into a mixer block which was mounted onto the cold plate of a liquid helium cryostat. Two backward wave oscillators (BWO) operating in a frequency range of 270-320 GHz were used as a local oscillator and a signal source, with the frequency of the signal BWO being fixed throughout the experiment. The power levels of both BWO's could be adjusted appropriately with the use of wire grid attenuators. After passing through their respective attenuators the signals were coupled with a mica beam-splitter and delivered into the cryostat. The HEB mixer was IF-coupled to a 1-inch coplanar line with a subsequent transition to a coaxial cable which led the IF signal out of the cryostat to a room-temperature Picosecond Pulse Labs bias-T with a bandwidth of 18 GHz and then to a Miteq amplifier with a pass band of 0.1-12 GHz and a gain of about 36 dB. The insertion loss of the IF chain in dB's, excluding the coplanar line, was found to depend on frequency as $L(f) = -5.6-1.3f$, with the frequency measured in GHz. The frequency range up to 6 GHz was processed with a Rohde&Schwartz spectrum analyser (frequency range 100 kHz-6 GHz). To cover the range beyond 6 GHz we modified the experimental setup by including a chopper in the signal path and replacing the spectrum analyser with a power detector and a lock-in amplifier. A tuneable band-pass filter (BPF) with the centre frequency running from 2 to 8 GHz and a bandwidth of 50 MHz was added to the setup to reduce the noise.

B. Noise temperature measurements

The noise temperature measurements were performed at 2.5 THz. Referring to Fig. 2, the mixer block containing the device was installed into a cryostat with a high density polyethylene window 0.5 mm thick, a Zitex-104 cold infrared filter and a 2-3 THz mesh filter mounted on the cold plate. Radiation from a gas discharge H_2O laser at 2.5 THz was combined with radiation from a blackbody with the use of a Mylar beam-splitter 6 μm thick. The receiver back-end included a wideband bias-T followed by a cryogenic amplifier with a built-in circulator, together forming a unit with a gain of 30 dB and a bandwidth of 1-2 GHz. Outside the cryostat, the IF signal was further amplified by two amplifiers, each with a gain of 30 dB and a bandwidth of 0.01-2 GHz, separated by a 50-MHz BPF with the centre frequency 0.6-1.2 GHz. To suppress standing waves in the IF chain a 6-dB attenuator was placed immediately at the output of the cryostat and two 3-dB attenuators were placed at both ports of the BPF. The output of the second room-temperature amplifier was fed to a power detector followed by a remotely controlled nanovolmeter.

IV. Experimental technique

A. IF bandwidth measurements

Since the gap frequency of NbN is about 900 GHz at helium temperatures, electromagnetic radiation with a frequency of 300 GHz cannot destroy the superconducting state at 4.2 K by breaking Cooper pairs, and hence will not be absorbed uniformly in the superconductor. In this case the heating of the electrons in the material will not be uniform and the model of mixing in phonon cooled hot-electron

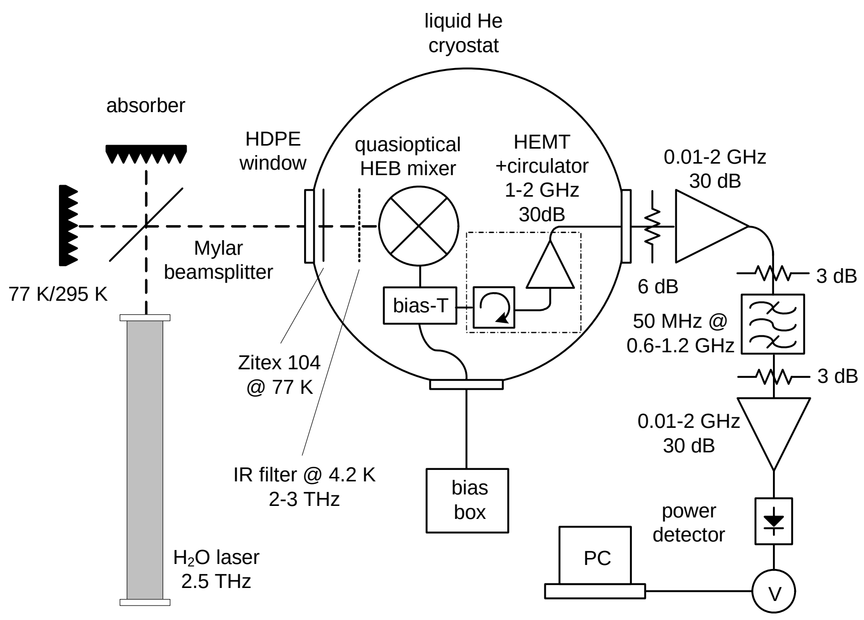

Fig. 2. Schematic of the experimental setup for noise temperature measurements

bolometers outlined in the introduction will not be applicable. To suppress the energy gap enough and thus ensure uniform heating at these frequencies the ambient temperature was raised to about T_c. The $R(T)$ dependence should be measured at as low a bias current as possible to avoid undesirable effects such as pair breaking by the transport current and additional Joule heating. So if one plots a family of IV curves for a device taken at different ambient temperatures, the slope of a curve at the origin, $(\partial V/\partial I)_0$, taken at a certain temperature T will be equal to $R(T)$. Since the critical temperature is usually defined as the temperature for which the device resistance approximately equals half of the resistance at room temperature, $R_n/2$, this means that when $(\partial V/\partial I)_0 = R_n/2$ the mixer temperature is about equal to T_c, the energy gap is sufficiently suppressed, and RF signal may be uniformly absorbed by the bridge. This simple observation allows one to avoid using a thermometer, which introduces certain ambiguities, when setting the operating temperature of an HEB mixer.

Another requirement of the uniform heating model is that the power levels of the signal and the local oscillator should be low. This means that the relative change of the mixer current at some fixed value of the bias voltage should not change appreciably when in addition to heating one applies RF power. Ideally one should have $\delta I_{mixer}/I_{mixer} << 1$ (δI_{mixer} being the change of the mixer current cause by the switching on of the LO drive); in practice, however, this usually leads to the IF signal being too low. We chose $\delta I_{mixer}/I_{mixer} = 0.05$. Now that the operating current-voltage curve had been established we needed to choose the operating point on it. When one computes the impedance of the HEB mixer one gets $Z = R + I(\partial R/\partial I) + I(\partial R/\partial \Theta)(\partial \Theta/\partial I)$, with $R = V/I$ being the device DC resistance and Θ the electron temperature. The first and the second terms are simply the device differential resistance, the second one describing the non-thermal effect of the bias current on the superconducting state (vortices, phase-slip centres). This effect is undesirable if the uniform heating model is to be applied, and to be consistent one would have to ensure the condition $\partial V/\partial I = R$, possibly at the expense of a good signal-to-noise ratio. So, the choice of the operating point is a trade-off between consistency and a good signal-to-noise ratio. Also, as has been outlined in the introduction, the effect of the electrothermal feedback can be neglected, and so one need not worry about the dependence of the mixer time constant on the operating point in the case of uniform heating.

B. *Noise temperature measurements*

All the noise temperature measurements were performed at 4.2 K with the use of the standard Y-factor procedure, with the receiver noise temperature determined as

$$T_R = \frac{T_{hot} - YT_{cold}}{Y - 1}, \qquad (5)$$

where T_{hot} and T_{cold} are the physical temperatures of the blackbody loads equal to 295 K and 77 K respectively, and Y is the ratio of the output power levels P_{hot}/P_{cold} when the mixer input is terminated with T_{hot} or T_{cold}. Although HEB mixers are known to display quite an appreciable direct detection effect (e.g. [11]), the values of the noise temperature presented below were not corrected for this effect. The use of the mesh filter in front of the mixer allowed us to suppress direct detection, and on replacing the cold load (77 K) with the hot one (295 K) we observed a decrease of only 0.04-0.06 % in the mixer current over the measurement area on the IV plane. The corresponding value of $\partial P_{IF}/\partial I$ was positive and varied between 1.4 a.u./μA and 1.6 a.u./μA over the measurement area. Our estimates showed that the correcting for the direct detection effect might improve the receiver noise temperature about 5 %.

V. Experimental results

A. *IF bandwidth measurements*

Fig. 3 shows the results of the IF bandwidth measurements

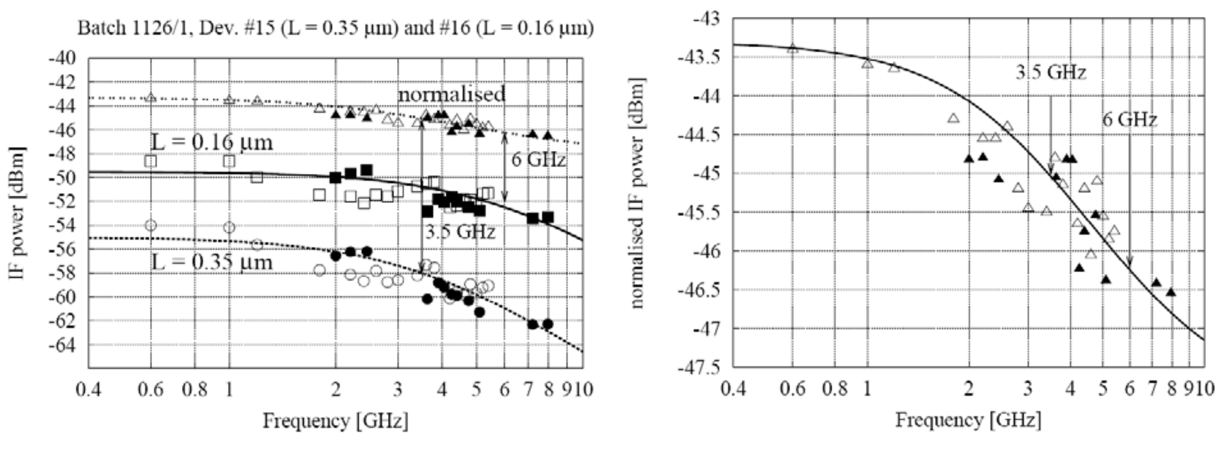

Fig. 3. On the left is shown the IF power versus intermediate frequency for HEB mixers with different bolometer lengths. Also shown is the ratio of the output power levels for the two lengths. The same ratio is shown on the right on a different scale.

TABLE I
PARAMETERS OF THE DEVICES USED IN THE EXPERIMENTS

device	T_c K	ΔT_c K	L µm	w µm	d nm	c_e mJ(cm^{3}K)	c_{ph} mJ(cm^{3}K)	τ_{eph} ps	τ_{ecs} ps	D cm^2/s
1126/1#15	11.5	1.1	0.35	2.4	3.5	1.5	10.5	10	38.5	0.45
1126/1#16	11.3	1.2	0.16							

for two devices with lengths of 0.35 µm and 0.16 µm. Also shown is the ratio of two conversion efficiencies. Computing this ratio allows eliminating ambiguities in the IF chain calibration procedure. This can be seen as follows. The output of a receiver is the product of the mixer output and the gain of the IF chain, which means that if two mixers are taken we can write

$$P_R^{(1)}(f) = P_M^{(1)}(f) G_{IF}(f), \quad (6a)$$

$$P_R^{(2)}(f) = P_M^{(2)}(f) G_{IF}(f), \quad (6b)$$

whence the ratio of the outputs

$$R(f) = \frac{P_M^{(1)}(f)}{P_M^{(2)}(f)}. \quad (6c)$$

After the IF chain was thus calibrated out, the dependencies of the IF power versus frequency could be fitted with

$$P_{IF}(f) = P(0)\frac{1}{1+\left(f/f_{3dB}\right)^2} \quad (7)$$

with f_{3dB} = 3.5 GHz and f_{3dB} = 6 GHz for the long and short bridges respectively.

The parameters of the devices used in the experiments are given in Table I. Substitution from Table I into (1) shows that

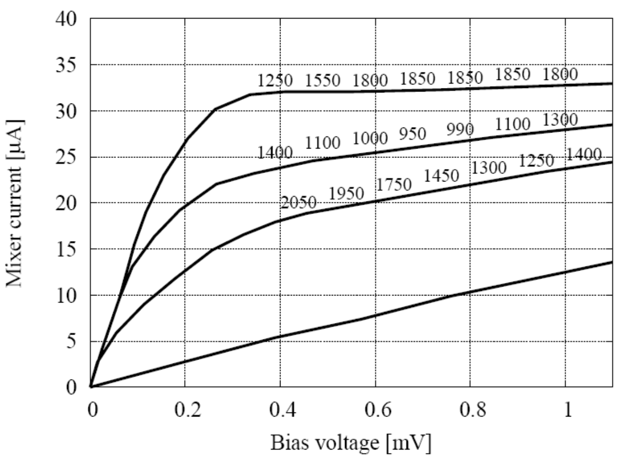

Fig. 4. A family of the IV curves for an HEB mixer taken at different levels of the LO drive at 2.5 THz. The LO power increases from the top curve to the bottom one. Also shown is the receiver noise temperature at various operating points.

the 3-dB roll-off for phonon cooling in the experiments is governed mostly by the escape time of non-equilibrium phonons, τ_{esc}. Hence, the mixer time constant is

$$\tau_m = \left(\tau_{esc}^{-1} + \tau_{diff}^{-1}\right)^{-1}, \quad (8)$$

which yields roll-off frequencies of 4.6 GHz and 6.7 GHz for the long and short bridges respectively. The experimental results, in conjunction with this estimate, show the contribution of diffusion cooling to energy relaxation in our HEB mixers.

B. Noise temperature measurements

Fig. 4 shows a family of the IV curves of an HEB mixer taken at different levels of the LO drive at 2.5 THz. The LO power increases from the top curve to the bottom one. Also shown is the noise temperature of the HEB receiver as a function of the operating point. As can be seen from the plot, there is quite a broad low noise area in the IV plane, with the lowest receiver noise temperature of 950 K. As has been mentioned above, this result was not corrected for the direct detection effect. Also, atmospheric absorption at 2.5 THz was not allowed for. Finally, we did not use an antireflection coating. We expect that taking account of the direct detection effect, atmospheric absorption and reflection losses may improve the receiver noise temperature by about 30%, in which case a noise temperature of about 600 K may be achieved.

CONCLUSIONS

We have demonstrated that the use of *in situ* gold yields an improvement of HEB mixer performance in terms of its noise temperature and IF bandwidth. Specifically, a noise temperature of 950 K was measured at an LO frequency of 2.5 GHz. Minimising the direct detection effect by installing a narrower IR filter should lower the receiver noise temperature. Further improvement might come from the use of an antireflection coating of the Si lens. Finally, allowing for atmospheric losses, or eliminating them by means of a "dry box" ought to lower the noise temperature even more. Taking care of the unwanted effects may thus improve the receiver noise temperature by about 30%. An IF bandwidth as wide as 6 GHz was measured at an LO frequency of 300 GHz near the critical temperature. This value is almost twice as large as that obtained for HEB mixers with *ex situ* gold contacts. The dependence of the IF bandwidth on the length of the bridge unambiguously demonstrates the contribution of diffusion cooling to the energy relaxation process in the HEB mixers fabricated with the use of *in situ* gold, and opens the possibility of further increase of the IF bandwidth by making even shorter bridges.

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