Local oscillator power requirement and saturation effects in NbN HEB mixers.

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Abstract The local oscillator power required for NbN hot-electron bolometric mixers (P_{LO}) was investigated with respect to mixer size, critical temperature and ambient temperature. P_{LO} can be decreased by a factor of 10 as the mixer size decreases from $4\times0.4\ \mu m^2$ to $0.6\times0.13\ \mu m^2$. For the smallest volume mixer the optimal local oscillator power was found to be 15 nW. We found that for such mixer no signal compression was observed up to an input signal of 2 nW which corresponds to an equivalent input load of 20,000 K. For a constant mixer volume, reduction of T_c can decrease optimal local oscillator power at least by a factor of 2 without a deterioration of the receiver noise temperature. Bath temperature was found to have minor effect on the receiver characteristics

Introduction.

Hot-electron bolometric (HEB) mixers are the most sensitive heterodyne receivers at frequencies above 1 THz. Their all-planar technology allows fulfillment of HEB mixers in both waveguide and quasioptical variants. HEB mixers do not need any RF or IF matching circuits. That is very important, since at terahertz frequencies only normal metal can be used for such circuits and it would cause big input losses.

HEB mixers work at a condition when superconducting gap is suppressed by the radiation of the local oscillator (LO) and effective electron temperature is equal or close to T_c. Under such circumstances the mixer resistance is very sensitive to the oscillation of the electron temperature caused by the beating of LO and RF waves. It has been shown that

that phenomenon is frequency independent in a wide frequency range, from MM up to near IR [1]. Relaxation of the electron temperature can occur via either electron-phonon interaction (phonon cooling, dominates in thin dirty superconducting films) or heat out-diffusion (diffusion cooling, dominates in short bridges of clean superconducting films).

In this paper we consider phonon-cooled HEB mixers based on NbN film. DSB receiver noise temperature for such mixers is from 650 K to 1100 K in the band from 1.6 THz to 2.5 THz[2]. Receiver noise temperature from 3000 to 8000 K was measured up to 5 THz [3]. Stable and reliable operation of NbN HEB mixers has been proved by a set of radio telescope sessions [4]. A gain bandwidth of 4 GHz is achieved at the most sensitive bias point (while noise bandwidth is up to 8 GHz), but can be extended up to 9 GHz with larger bias voltages [2, 5].

Unfortunately, technology of tunable solid state local oscillators (LO) for the terahertz range does not develop so fast. Output power from such sources decreases rapidly with frequency (Fig.1). That is an obstacle for applications in satellite-based receivers and in large arrays. It brings up the task to develop mixers, which require as low local oscillator power as possible.

It has been reported that P_{LO} required for NbN mixers scales with the mixer volume and mixers with P_{LO} of 100 nW can be made [6, 7, 8, 9]. For this mixers 1 dB compression point was found to be from 15 dB to 25 dB below LO power level.

In this paper we investigate the question: which mixers or operation parameters have the strongest effect on the optimal value of the LO power. We fabricated a mixer which requires LO power not more that 15 nW and showed that no saturation occurs up to a load temperature of 20000 K. The investigation was performed at frequency 650 GHz.

Device fabrication and experimental Set-up.

HEB mixers were fabricated from 3.5 nm superconducting NbN film. NbN films were deposited on 350 μm thick single crystal MgO and silicon substrates by reactive dc magnetron spattering. Details about NbN film deposition and device fabrication can be found in [10, 11]. The NbN microbridge was placed in the center of planar spiral antenna made of 200 nm gold film. NbN bridge size was from 4x0.4 μm^2 to 0.6x0.13 μm^2. Device geometry was controlled by a scanning electron microscope.

Experimental set-up is presented in Fig.2. Two backward wave oscillators (650 GHz) were used as LO and RF sources. Variable quasioptical attenuators allowed smooth tuning of both LO and RF power. 12 μm Mylar film served as a beam splitter. Cryostat vacuum window was made of 1.2 mm polyethylene. 250 μm thick Zitex G108 was mounted on the 4.2 K shield as a IR filter. In the frequency band of 3 THz (estimated for the spiral antenna used in the experiment) background radiation at 300 K is of the order of nanowatts. So, it can not be neglected in comparison with LO power for the smallest mixers. In order to cut-off the background radiation a thin layer of Ecosorb was attached to 4.2 K shield just behind IR filter. Its attenuation was at least 17 dB. Mixer chip was mounted on a 12mm elliptical silicon lens without antireflection coating. The intermediate frequency (IF) chain consisted of bias-T, isolator, HEMT low noise amplifier, room temperature amplifier and band-pass filter. IF band was 30 MHz centered at 1.5 GHz. IF signal was measured by a microwave power meter.

Local oscillator power

The absorbed local oscillator power was measured with an isothermal technique [12]. In brief, that technique is based on the assumption of the equal effect of both P_{LO} and P_{dc} on the mixer dc resistance R_0. So, for a constant resistance line ($I=U/R_0$) $P_{LO} + P_{dc}$ is constant. Therefore, for points 1 and 2 (Fig.7 a) one can write $P_{dc,A}= P_{dc,B}+ P_{LO}$. This technique has been widely used for the estimation of the absorbed LO power for HEB mixers. But we have to note that the error of about 20% shall be assumed for this technique. That value comes from the scattering of P_{LO} data obtained for the same mixer but for different R_0 value. Such accuracy was also confirmed by comparing the relative change of the absorbed P_{LO} (obtained from the isothermal technique) for the mixers with different volume and the change of the attenuation level of the attenuator 1 (Fig.2). Output power of BWO 1 corresponded well to its bias conditions and was the same through all experiments.

In the first part of the investigation DSB receiver noise temperature was measured as a function of the local oscillator power at the bath temperature 4.2 K. Fig.3 (a and b) presents the data for mixers with the same size 4x0.4 μm^2 but different critical current density. As can be seen the optimal value of P_{LO} can be reduced by a factor of 2 just using NbN film with smaller T_c, and therefore smaller j_c. For both mixers minimum of the function $T_r(P_{LO})$ was quite broad and deviations of P_{LO} from the optimum up to 10÷15% did not cause noticeable change of the mixer performance. Fig.3 demonstrate that “underpumping” of the mixer with LO even with an expense of an increase of T_r did not give any significant benefit for P_{LO}. For the sample M12-2 at the optimum bias voltage (around 1 mV) the minimum P_{LO} at which the mixer is still stable for superconducting oscillations is only 30% of the optimum P_{LO}. Sample M10-2 at the optimum bias voltage became unstable if P_{LO} decreased below to 200 nW. For higher bias voltage the stable mixer operation was possible even for smaller P_{LO}. But as it can be seen from Fig.3 it will lead to a degradation of the mixer performance.

The possibility of decreasing of P_{LO} for smaller Tc of NbN film seems to be more interesting perspective. As it can be seen from Fig.3 a decrease of Tc did not lead to the degradation of the receiver sensitivity. At the absolute minimum of T_r both conversion efficiency and output noise temperature was about the same for both mixers (-12 dB and

50 K). We compared obtained data with a uniform heating model [13]. In this model the local oscillator power required to elevate electron temperature to T_c depends on T_c and the mixer volume:

$$P_{LO} = \frac{\gamma}{3.6 \cdot \tau_\Theta \cdot T_c^{1.6}} \cdot V \cdot (T_c^n - T^n - n \cdot T_c^{n-1} \cdot \Delta T_c) \qquad (1)$$

where γ=2.1·10^2 J/(cm^{3}K^2) is Sommerfeld constant, τ_Θ=35 ps is electron cooling time (measured for 3.5 nm NbN films on MgO substrate [5]), V is the mixer volume, T is the bath temperature, ΔT_c is superconducting transition width, n=3.6 is a constant determined for NbN film.

For the mixer size 4×0.4×0.0035 μm^3, and T_c values of 9.5 K and 8 K P_{LO} from (1) are 540 nW and 260 nW respectively. So, the uniform heating model can describe P_{LO} behavior and we will confirm it once more by the next data.

Receiver noise temperature and absorbed local oscillator power was also measured for the mixer M12-2 at different bath temperatures (see Fig.5). We should note that the temperature of the IF chain was kept unchanged, i.e. 4.2 K. During the experiment the mixer critical current was measured at each temperature and then the mixer temperature was estimated from [14] (see also Fig. 4)

$$I_c(T) = I_c(0) \cdot \left[1 - \left[\frac{T}{T_c}\right]^2\right] \cdot \left[1 - \left[\frac{T}{T_c}\right]^4\right]^{0.5} \qquad (2)$$

The validity of (2) we have checked for one of the sample.

Solid line represents Eq.1 that is in a reasonable agreement with experimental points. So, equation (1) was found to describe well the general tendencies of the optimal local oscillator power with respect to the superconducting critical temperature and the bath temperature.

From Fig.3 and 5 an important conclusion can be made. Reduction of T_c from 9.5 K to 8 K leads to a decrease of j_c by 50%. It is followed by a reduction of P_{LO} by a factor of 2 but the mixer sensitivity is not affected. On contrary, a suppression of j_c down to the same value by means of higher bath temperature does not lead to a noticeable benefit with P_{LO}. Although, in this case T_r is not changed much too. Further suppression of j_c finally lead to the drop of P_{LO} but that is followed by a significant increase of the noise temperature.

As a next step we present the data of the optimal LO power for mixer with different volumes (Fig 6). NbN film thickness is 3.5 nm for all mixers and the mixer volume is represented by the product of the mixer length L by the mixer width W taken in micrometers. Therefore, two mixers considered just before, are positioned at L·W=1.6. The smallest mixer had the size 0.6×0.13 μm^2 and the local oscillator power 15 nW. The general tendency is a decrease of the LO power as the mixer volume decreases. The scattering of the data is connected with the same effect which we have discussed in Fig.3 (a,b), i.e. different critical temperatures and therefore critical current density values. For the same mixer volume the heating of the electrons from the bath temperature up to T_c, where HEB mixers have the best sensitivity, consumes more local oscillator power. As a measure of the required local oscillator power we propose to introduce a “volume coefficient” which equals to the $L \cdot W \cdot j_c$, where L and W are taken in micrometers and j_c is taken in 10^6 A/cm^2. This coefficient can be calculated from a mixer dc parameters and then an expected local oscillator power in the optimum point can be estimated. As it can be seen from Fig. 6 b P_{LO} is a monotonous function of the volume coefficient.

Saturation effects in NbN HEB mixers.

As it can be seen from the previous chapter the requirement for LO power for NbN HEB mixers can be substantially decreased with small volume devices. But then, as it has been shown [7], the dynamic range of the mixers reduces too. In this chapter we present investigation of the saturation effects for different volume mixers.

Table 1. Parameters of the mixers used for saturation measurements. L and W are the mixers length and width, P_{LO} is the optimal local oscillator power absorbed in the mixer (obtained from the isothermal technique), T_{load} is a equivalent load temperature corresponded to 3 dB compression point.

Sample	***L×W, μm²***	***P_{LO}, nW***	***3 dB compression, nW***	***T_{load}, K***
M10-4, 1	2×0.3	70	2	20,000
2			4	40,000
L10-2-2	0.6×0.13	15	2	20,000
			4	40,000
		14.5	5	55,000

For this purpose we choused two mixers M10-4 and L10_2_2 (see also Tab.1). IV-curves of these mixers under LO radiation are presented in Fig.7a and 8a. Dependence of the IF signal vs. RF signal was measured in several points for each mixer. Obtained data are presented in Fig.7b and 8b. Solid line shows the linear regime of the mixer. For mixer M10_4 deviation from the linearity occurs at the input signals –57 dBm (2 nW) and –54 dBm (4 nW) for bias point 1 and 2 correspondingly, i.e. 15÷12 dB below absorbed LO power (70 nW). Taking into account the mixer gain bandwidth B=4 GHz one can calculate the effective load temperature of the receiver at the 3 dB compression point:

$T_{load} = \frac{P_{in}}{2 \cdot k \cdot B}$, where k is the Boltzmann constant. Calculated load temperatures are presented in the top x-axis. Saturation signal corresponds to a load temperature around 20,000 K and 40,000 K for point 1 and 2 correspondingly. The difference in the compression points for bias points 1 and 2 can be easy understood if we plot IF signal swing on the IV plane. The arrows mark amplitudes of the voltage oscillations on the mixer along 50 Ohm load line. If the mixer conversion efficiency changes within IF swing, mixer deviates from the linearity. So, saturation occurs at smaller signals for those mixers, which have stronger bias dependence of the conversion efficiency and operate at smaller bias voltages.

More pronounced bias dependence of the saturation point one can observe for a very small mixer. Data for the mixer L10_2_2 are presented in Fig.8 a and b. Absorbed LO power was only 14.5÷17.5 nW. The saturating power was measured at three bias points. As one can see, the saturation for both mixers occurs at the same input signal. It confirms our suggestion that the saturation is caused by IF signal but not by overheating with RF signal. Equivalent load temperatures corresponding to 3 dB compression points were also calculated (Fig.8b). So, even with smallest volume NbN mixers no deviations from the linear regime was observed up to 20,000 K of the load temperature. That allows a practical operation of even smaller mixers. In this case LO power can be of a few nW.

Conclusion.

From the presented data we can conclude, that by decreasing the mixer volume the required LO power can be decreased substantially. For the mixer with size 0.6×0.13 μm^2 the LO power is only 15 nW. Regardless of the mixer volume, the input signal at which 3 dB compression occurs is of the order of 2-5 nW. That corresponds to an input load temperature of 20,000 K. We conclude that fabrication of even smaller mixers requiring LO power of the order of a few nW can be reasonable.

Critical temperature has a big impact on the required LO power. As T_c changes from 9.5 K to 8 K, P_{LO} decreases from 480 nW to 230 nW for 4x0.4 μm^2 mixer. Bath temperature plays a minor role for both P_{LO} and T_r. Only at T=0.75 T_c P_{LO} starts to decrease but it is followed by a growth of T_r.

In order to estimate P_{LO} at the optimum operating point one has to take into account both mixer volume and critical temperature. A product of the mixer volume and critical current density, measured at 4.2 K, is a good measure of P_{LO}.

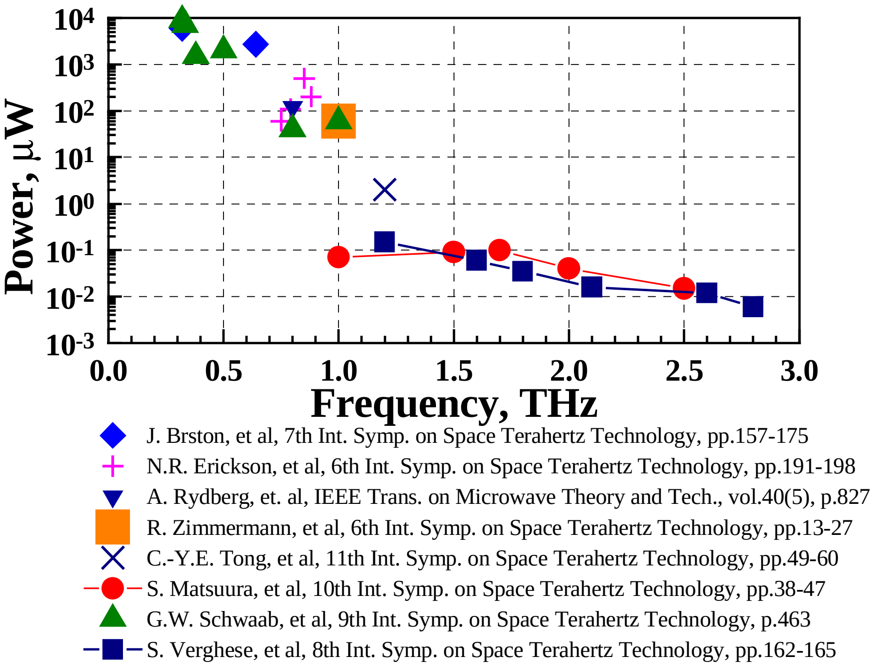

Fig. 1 Output power available from local oscillator sources reported in press.

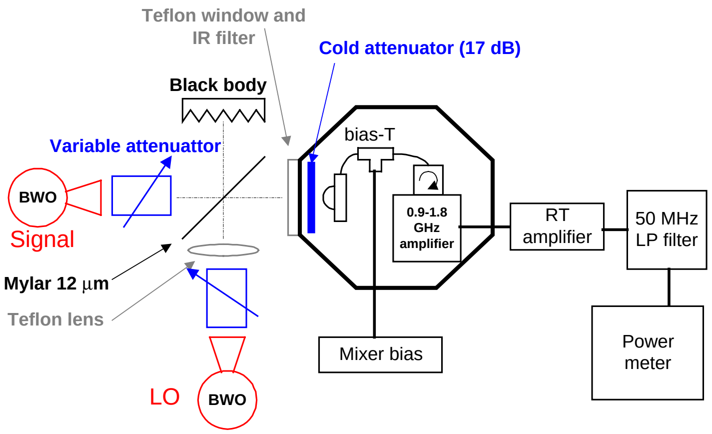

Fig. 2 Experimental set-up used for saturation measurements of HEB mixers. For the receiver noise temperature measurements, the cold attenuator in the cryostat was removed, signal BWO was replaced by 300K/77K black body.

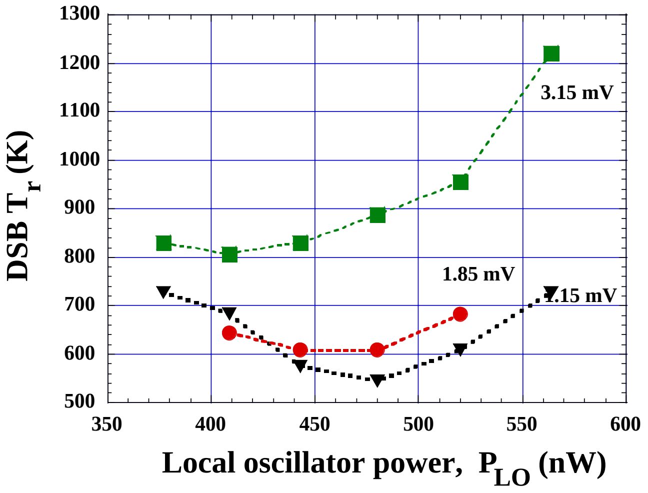

Fig. 3 a DSB receiver noise temperature vs LO power for different bias voltages. Mixer M12-2, width W=4µm, length L=0.4µm. j_c(4.2 K)=2.7·10^6 A/cm^2, T_c=9.5 K.

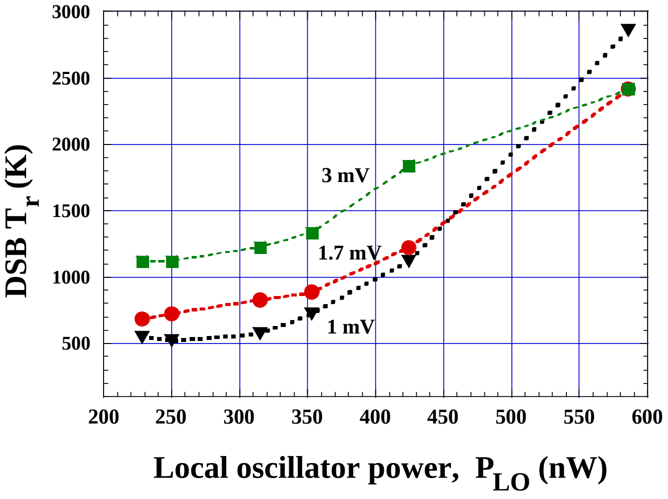

Fig. 3 b DSB receiver noise temperature vs LO power for different bias voltages. Mixer M10-2, width W=4µm, length L=0.4µm. j_c(4.2 K)=1.75·10^6 A/cm^2, T_c=8 K.

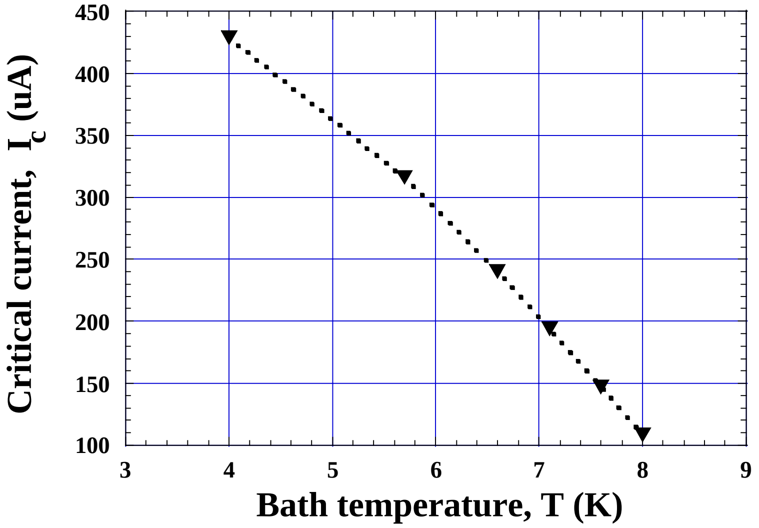

Fig. 4 Critical current vs bath temperature. Sample M12-2, T_c=9.5 K.

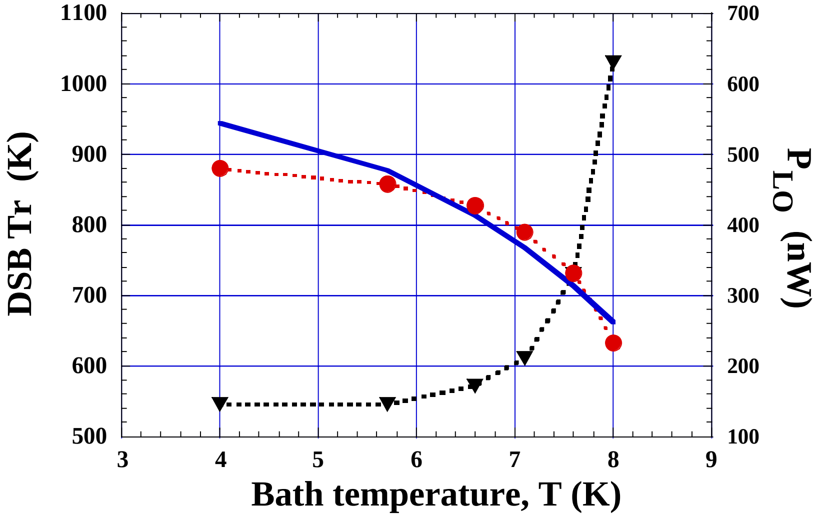

Fig. 5 DSB receiver noise temperature and optimum LO power vs bath temperature. Mixer M12-2, width W=4µm, length L=0.4µm, T_c =9.5 K. Solid line is obtained from Eq.1

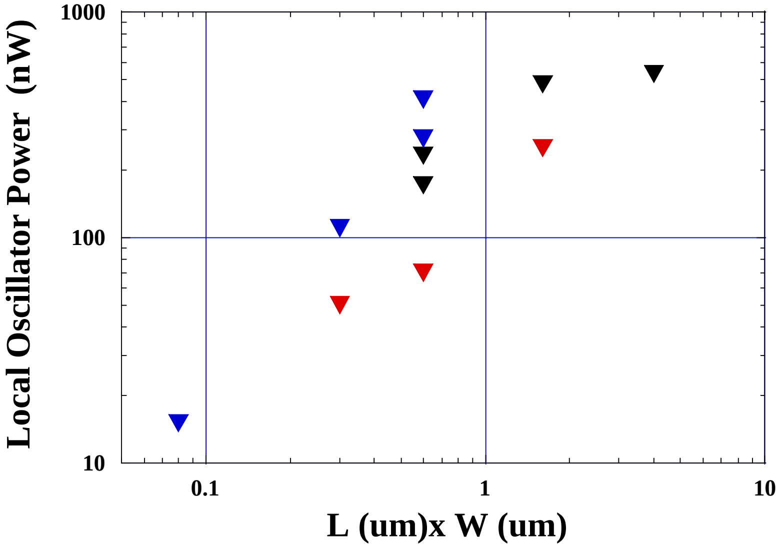

Fig. 6 a) Optimum local oscillator power for different mixer volume. Mixer volume is represented by a product of mixer length L and mixer width W taken in micrometers.

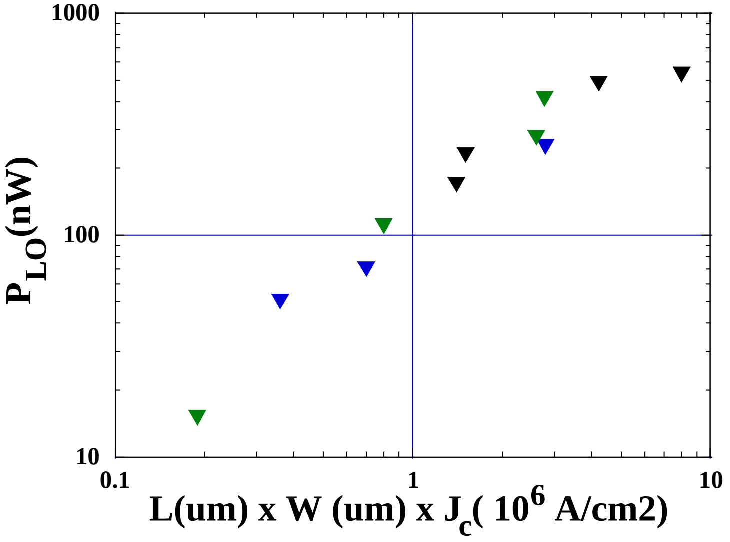

Fig. 6 b) Optimum local oscillator power P_{LO} vs “volume coefficient”, i.e. a product of mixers length L, width W and critical current density J_c. J_c is measured at 4.2 K.

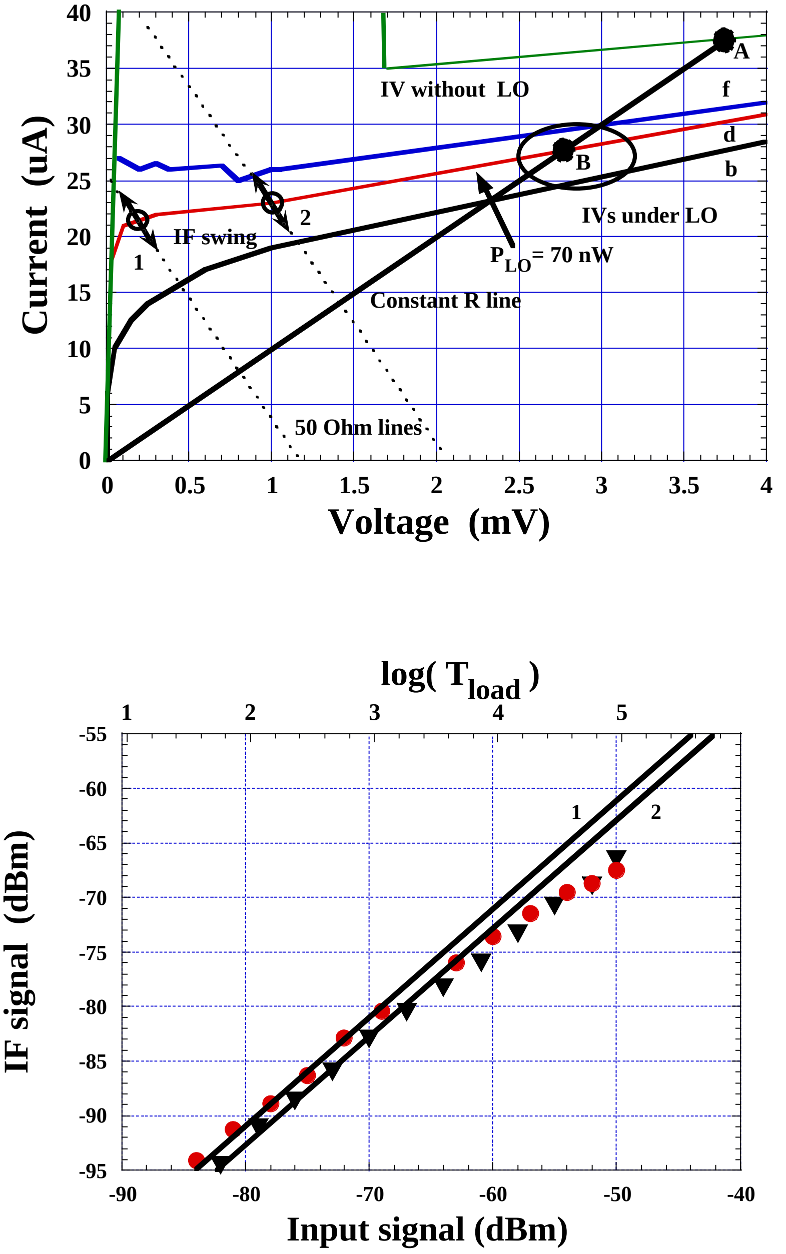

Fig. 7 a) Current-voltage curves of the mixer M10_4. Arrows show the amplitude of the voltage swing corresponding to 3 dB compression point. b) intermediate frequency signal vs. RF input signal for two bias points; bias point 1 (circles), bias point 2 (triangles). 3 dB compression occurs at a load temperature around 20,000 K.

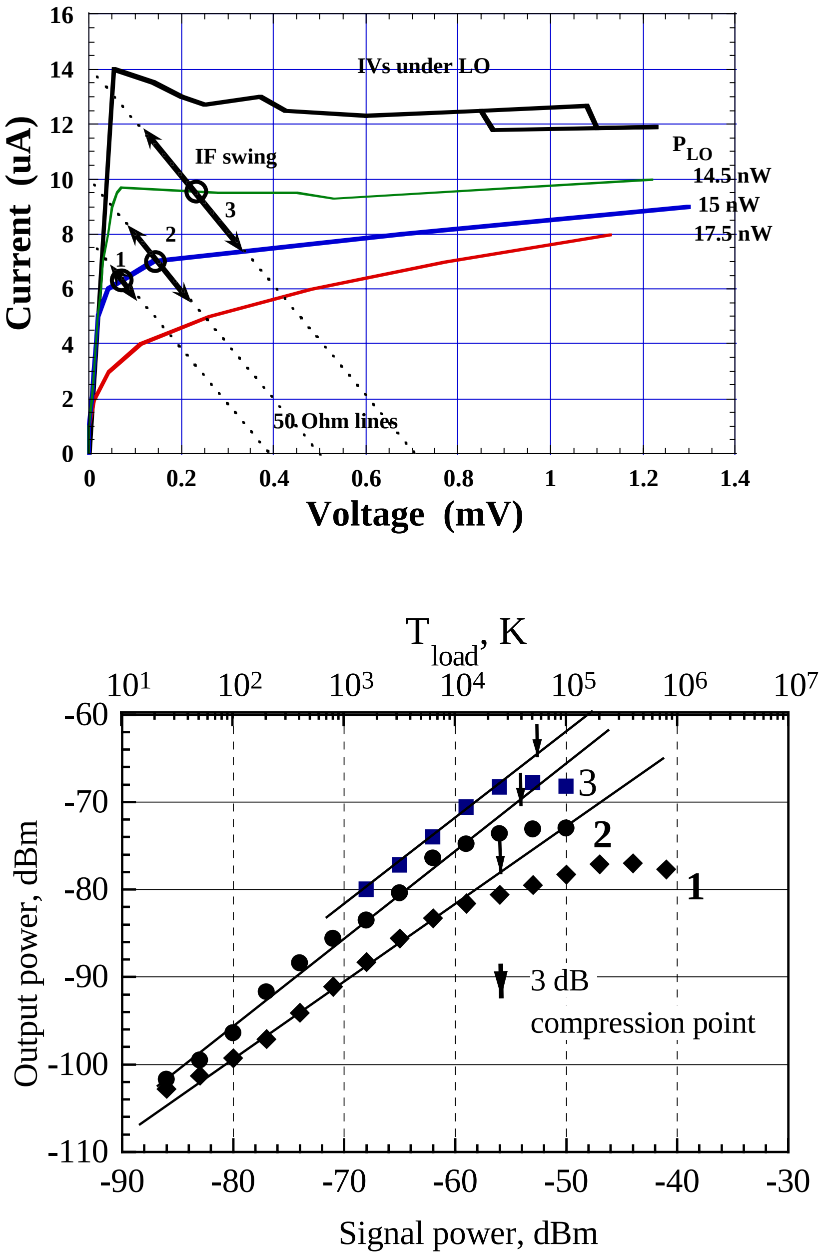

Fig. 8 . a) Current-voltage curves of the mixer L10_2_2. Arrows show the amplitude of the voltage swing corresponding to 3 dB compression point. b) intermediate frequency signal vs. RF input signal for three bias points; 3 dB compression occurs at a load temperature around 20,000 K.

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