NbN Hot Electron Waveguide Mixer for 100 GHz Operation

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NbN is a promising superconducting material used to develope hot-electron superconducting mixers with an IF bandwidth over 1 GHz. In the 100 GHz frequency range, the following parameters were obtained for NbN films 50 Å thick: the noise temperature of the receiver (DSB) $\sim$ 1000 K; the conversion losses $\sim$ 10 dB; the IF bandwidth $\sim$ 1 GHz; the local oscillator power $\sim$ 1 μW. An increase of NbN film thickness up to 80-100 Å and increase of working temperature up to 7-8 K, and a better mixer matching may allow to broader the IF band up to 3 GHz, to reduce the conversion losses down to 3-5 dB and the noise temperature down to 200-300 K.

In the submillimeter waverange hot electron mixers can have high conversion coefficient and low noise temperature. The main limitation in using this kind of mixers is restricted IF band. For example, for the mixers based on n-InSb cooled to 4,2 K, the IF band is about 1 MHz [1]. A mixer based on superconductive thin Nb film in the resistive state gives an IF band less than 500 MHz [2]. The width of the IF band is restricted by the electron-phonon relaxation time τ_{eph}. To improve heat removal from the working area, mixing elements based on thin superconductive films are manufactured in the form of narrow strips. A possible way of extending the IF band is to reduce the strip length to the value of $L \leq \sqrt{D\tau_{eph}}$ [3]. In this case the IF band can be determined by the time of hot carriers escape from the strip.

An alternative way to extend the band is using superconductors with small τ_{eph}. In [4], τ_{eph} was studied in thin NbN films at various temperatures of the electrons Θ. The measurements were taken in a state close to equilibrium. τ_{eph} was determined from film resistance relaxation time in the resistive state. The resistivity was created by an external magnetic field $H \simeq H_{c2}$. The chosen levels of bias current and microwave radiation power applied to the strip were so small that Θ was practically equal to the working temperature T of the thermostat . Fig. 1 shows how τ_{eph} depends on T for two samples with different mean free paths of electrons. At a temperature of 10 K, which approximately corresponds to the superconductive transition temperature in very thin NbN films $\tau_{eph} \simeq 15$ ps. This value of τ_{eph} must secure an IF band of 10 GHz. If the superconducting strip acts in the resistive state as an electromagnetic radiation mixer, then the state of its electron subsystem is far from equilibrium. In this case the magnetic field is absent and the resistivity is created by transport current and local oscillator power which cannot be considered as small. Nonetheless, the electron-electron interaction grows in films with a small electron mean free path, which leads to the fact that electron distribution function become a Fermi function so that the state of electrons may be described by the electron temperature $\Theta > T$.

The parameters of 100 GHz range mixers based on thin NbN films were studied using an experimental setup whose block scheme is shown in Fig 2. The samples to be studied were placed in a microwave mixer block, which was located in a helium cryostat at a working temperature of 4.2 K. Microwave radiation was applied to the mixer block along a circular waveguide with conical transition. Losses which occurred between the cryostat input and the input to the mixer block did not depend on frequency in the 80-120 GHz and amounted to 2 dB. Local oscillator and signal radiation were merged into a single channel using a directional coupler. A backward wave tube generator was used as the source of signal, while a Gunn generator served as local oscillator. Radiation power, which had been previously measured using a thermistor, was varied by calibrated attenuators. To measure the noise temperature of the mixer, a noise generator (discharge tube) with calibrated noise temperature was switched instead of the BWO generator. The voltage source created a bias current flowing through a sample. The frequency and the amplitude of the converted signal were measured by a spectrum analyzer after a 50 dB amplification. The installation allowed to measure IV-curves of samples, conversion coefficient and its IF dependence, as well as the noise temperature of the mixers.

The studied structures, used as mixers, were manufactured from thin NbN films 50 Å thick, which had been produced by reactive magnetron sputtering of an Nb target in an argon/nitrogen mixture onto a polished substrate made of crystalline quartz. The configuration of strips and the design of the mixer block are shown in Fig. 3. Contact pads and a microstrip filter were sputtered onto the same substrate. The element thus produced was mounted in the middle of the waveguide. One contact pad was grounded in the mixer block, while an IF signal was taken from the mixer through the filter over a coaxial cable. A direct bias current was applied over the same cable. To match the mixer with the radiation, a mobile backshort was placed into the mixer block.

While manufacturing mixers our purpose was to thoroughly study the form of the IV-curves of the mixing element and its radiation induced change. This will help to select an optimal working point and to estimate the extent of input/output matching of the mixer. Fig. 4 shows the IV-curves of the first sample. For all curves, corresponding levels are given of radiation power at which they were derived. At power levels less than -20 dBm, these curves have a hysteretic shape. In this case, if a constant bias is applied to the sample, its resistance is determined by the resistance of the contacts until the current reaches the value of I_c . After that, a sharp growth of sample resistance occurs. A further monotonic growth of sample resistance continuous until normal resistance is achieved. It is impossible to bring the sample into the intermediate state at the "critical" point even for relatively low resistance values of the power supply. This type of instability is connected with the hysteresis of the currents. Under radiation, the I_c current is reduced and, starting from a certain radiation power level, the IV-curves lose this shape. The optimal working point (marked as M) corresponds to local oscillator power of -25 dBm and is located near the resistive/superconductive state breaking point. The IV-curves of sample No 2 are shown in Fig. 5. The samples differ in the quality of the superconductive film. Sample No 2 has a greater normal resistance and smaller working currents and LO radiation power, the current hysteresis is absent. In table 1, parameters of the mixers produced from samples No 1 and 2 are listed. Total conversion losses of the mixer L_{total} are composed of unmatch $L_{mixerblock}$ and dissipation losses $L_{wavequide}$ in microwave input, internal conversion losses of the mixer $L_{internal}$, and unmatch losses in IF output L_{IF}. Total conversion losses of the mixer are directly measured as the ratio of microwave signal and the IF conversion signal. Input and output mismatch losses calculable from the IV-curves, taken under various levels of radiation.

It is to be noted that, in hot electron mixers, radiation has the same heat effect on the electron subsystem the direct electric current flowing in the sample. The sample resistance is determined by the value of Θ alone. Fig 6 clarifies the plan of calculating losses at mixer input $L_{coupling}$. The figure schematically shows the IV-curves for different LO power levels. Straight lines A and B correspond to two different electron temperatures. If one were to advance along the isotherm from low microwave power levels to higher levels, then the reduction of direct current power emitted in the sample should equal the increase of the microwave radiation power absorbed by the sample. Hence, the input mismatch losses can be defined as

$$L_{coupling} = \frac{P_{RFn} - P_{RFn-1}}{P_{DCn} - P_{DCn-1}}, \qquad (1)$$

where P_{RFn} is the radiation power in point n and P_{DCn} is the direct current power in point n.

IF output mismatch losses are calculated from the value of differential resistance at working point R_d:

$$L_{IF} = \frac{4R_dR_L}{(R_d + R_L)^2}, \tag{2}$$

where R_L is the input resistance of the IF amplifier.

In this case, internal conversion losses will be defined as follows:

$$L_{int} = L_{total}/L_{coupling} \cdot L_{IF}. \tag{3}$$

A phenomenological calculation of the conversion coefficient of the hot electron mixer was made by Arams [1]. According to his calculations, the conversion gain is defined as follows:

$$G = 2C\frac{P_{LO}}{P_DC}\frac{R_LR_B}{(R_L + R_B)^2}\left[1 - C\frac{R_L - R_B}{R_L + R_B}\right]^2, \tag{4}$$

$$C = \frac{dR}{dP}I_{DC}^2$$

For mixers based on electron heating effect in thin superconductive films in the resistive state, C is found from [2]:

$$C = \frac{dR}{d\Theta}\frac{\tau_{eph}}{c_eV}I_{DC}^2. \tag{5}$$

IF bandwidth is determined by the time τ, which depends on τ_{eph} and the parameters of circuit:

$$\tau = \frac{\tau_{eph}}{1 - C\frac{R_L - R_B}{R_L + R_B}}. \tag{6}$$

Experimental conversion losses may be compared with those calculated by defining the parameter C. This can be done by measuring the frequency dependence of the conversion gain for different working points. Fig. 7 shows such dependences for sample No 1 at three different working points. According to formula (6), a sharp growth of τ is to be expected when the denominator becomes zero. Fig 7 demonstrates such a growth. The value of $\tau = 110$ ps close to τ_{eph} at 4.2 K for this sample corresponds to the characteristic with the maximum IF band. Therefore, a reduction of τ may only take place as a result of circuit factor effect, accounted for in (6). When the value of C was defined in this way, the conversion gain was calculated whose value corresponded to that measured.

Internal conversion losses of the mixers under study amounted to 3-6 dB, while the noise temperature of sample No 2 was 1200 K. As seen from Table 1, noise temperature may be reduced considerably by improving the input/output matching of the mixer and reducing dissipation losses at microwave input. Better matching can be achieved by varying the number of strips in the superconductive mixer.

The 100 GHz radiation frequency is low for NbN, $\hbar\omega < 2\Delta$. The impedance Z of the mixer is much less then its normal resistance. In a higher frequency range, the mixer based on electron heating effect in thin NbN films can be matched better and can have smaller conversion losses. IF bandwidth may be made wider by reducing τ with increasing the working temperature. This method allows to achieve the value of $\Delta f_{IF} =$ 2-3 GHz at $T =$ 7-8 K while preserving the remaining parameters of the mixer.

This work was supported by the Swedish National Board of Industrial and Technical Development and by the Russian Scientific Council on High-T_c Problem (Pr. No. 93169).

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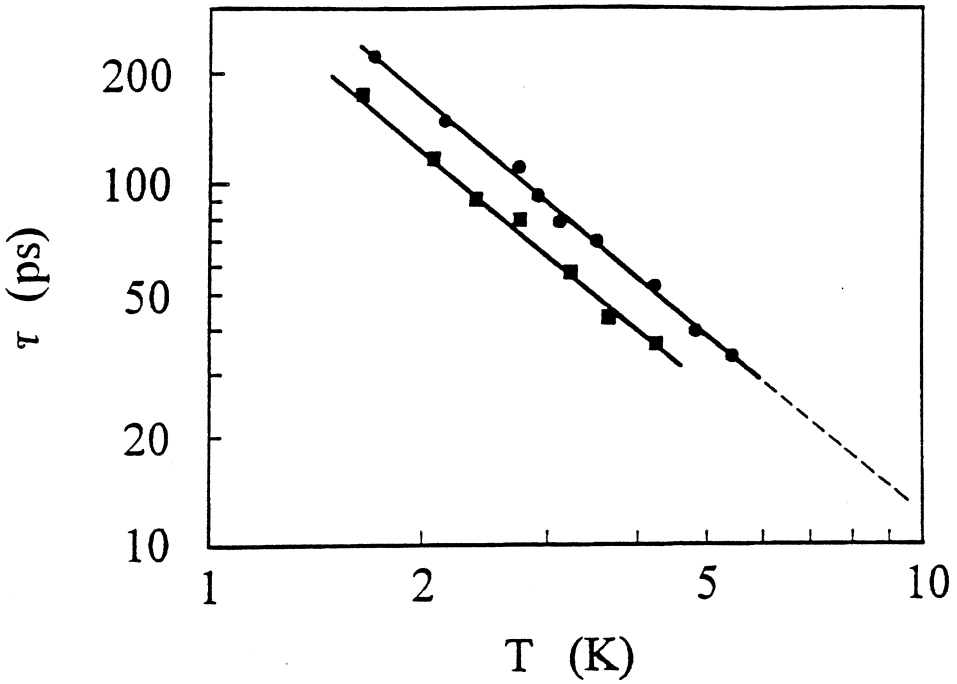

Fig. 1. Temperature dependence of electron-phonon interaction time for two NbN films ($H \simeq H_{c2}$, $\Theta \simeq T$)

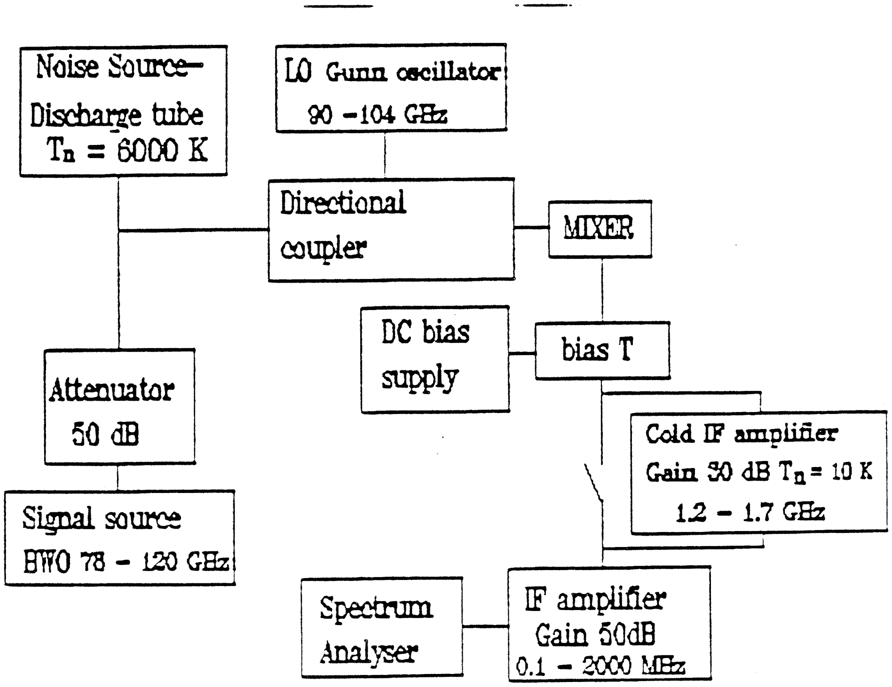

Fig. 2. Experimental setup.

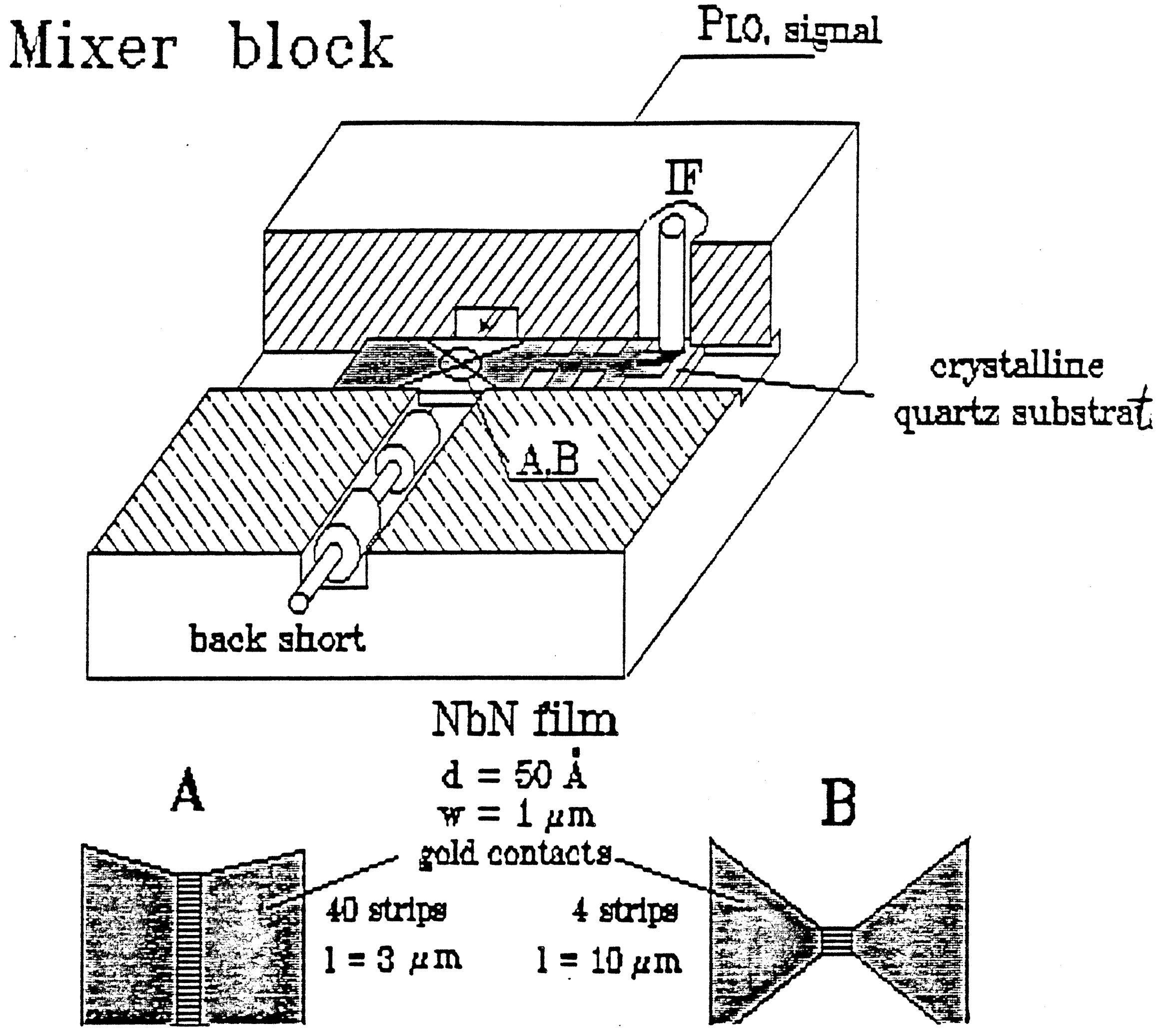

Fig. 3. Design of the mixer block and configuration of mixer chips.

Table I

No	L_{total}	$L_{coupling}$	L_{mixer}	T_N	P_{LO}	Δf_{IF}
		$L_{waveguide} + L_{mixerblock}$	$L_{int} + L_{IF}$			
1	10dB	7dB = 2dB + 5dB	3dB = 3dB + 0dB	–	-28 dBm	0.6 GHz
2	14dB	6dB = 2dB + 4dB	8dB = 6dB + 2dB	1200 K	-45 dBm	1.4 GHz

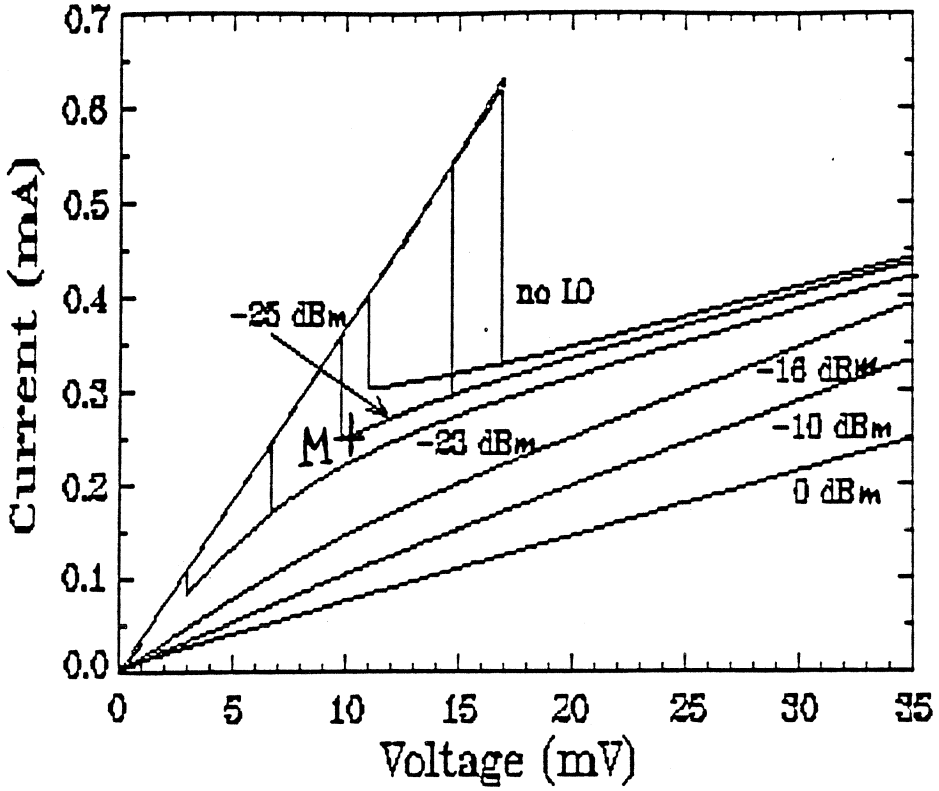

Fig. 4. IV-curves under LO power for sample No. 1.

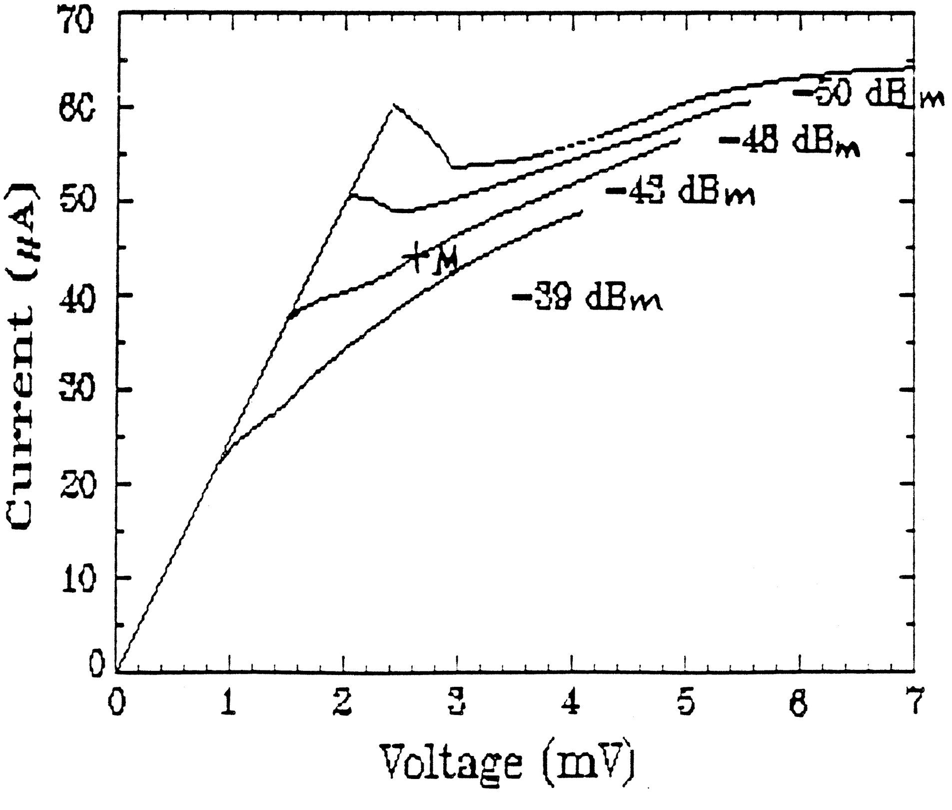

Fig. 5. IV-curves under LO power for sample No. 2.

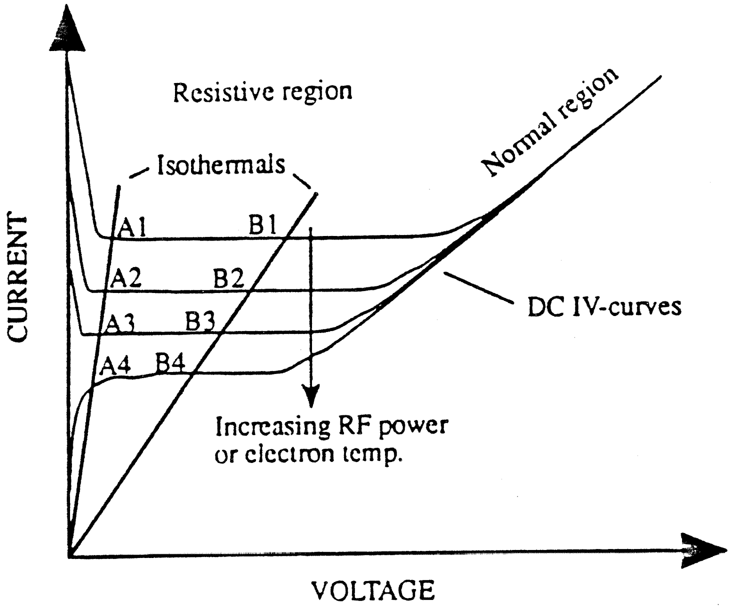

Fig. 6. Schematic IV-curves for different LO power. Straight lines A and B correspond to two different electron temperatures.

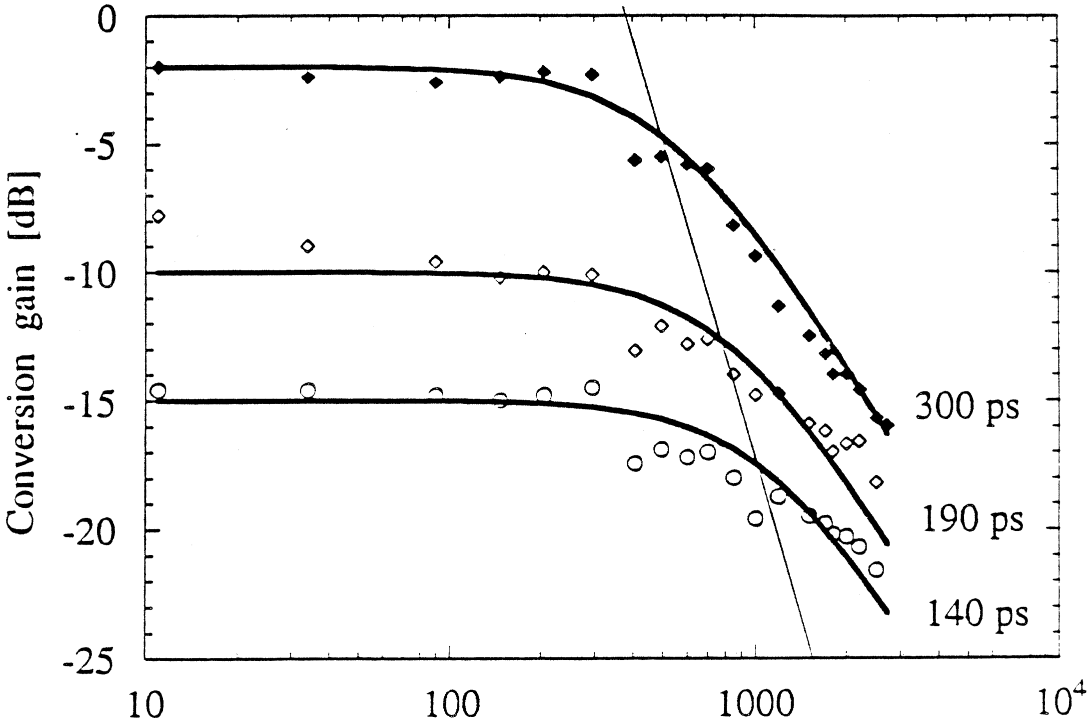

Fig. 7. Conversion gain versus intermediate frequency for three bias points, sample No. 1.