Performances of Hot–Electron Superconducting Mixer for Frequencies Less than the Gap Energy: NbN Mixer for 100 GHz Operation

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Abstract

The possibilities to improve the parameters of the 100 GHz NbN HEB superconducting waveguide mixers have been studied. The device consists of a signal strip 1 μm wide by 2 μm long made of 40 Å thick NbN film. The best operation point was found at 5 K, where the mixer bandwidth made up 1.5-2 GHz and the total loss diminished down to 8 dB. The critical current density has been increased up to $\sim 10^6$ A/cm^2, the noise temperature of the receiver (DSB) has reduced down to 450 K and the local oscillator power has decreased down to $\sim$0.1 μW.

1 Introduction

Hot electron bolometric (HEB) mixers based on thin superconducting films have been given intensive consideration recently [1-5]. The purpose of such studies is to significantly reduce the noise temperature of the Terahertz waverange mixers. Since no visible results of these studies in the waverange higher than 1 THz have been achieved so far (which is due to considerable technical difficulties), it is essential that experimental studies aimed at defining the maximum achievable parameters of such mixers under lower frequencies be continued.

In [2] we reported the results of a study into HEB superconducting mixers based on thin NbN films in the 100 GHz waverange. The following characteristics were obtained: the noise temperature of the receiver $T_n \approx 1000$ K, the intermediate frequency band $\Delta f_{IF} \approx 0.6$ GHz, the optimal local oscillator power $P_{LO} \approx 1$ μW, the total conversion loss $\sim$10 dB. For a typical mixer chip, the latter value included a 2 dB loss in the transmitting waveguide, a 5 dB loss in the mixer block and a 3 dB loss in the mixer itself. Meanwhile, the theoretically calculated parameters for coupling factor α=1 for typical properties of NbN thin films currently used for fabrication of HEB mixers are as follows: the conversion gain +8 dB, $T_n \approx 70$ K, $\Delta f_{IF} \approx 5$ GHz. Although the calculated and the experimentally achieved characteristics differ quite significantly, one cannot pinpoint any one main factor which would account for these differences. Their analysis [2] helped define several possible ways to improve the characteristics.

One of the ways is connected with using quartz substrates being the most convenient for the commonly used mixer block design. The fact is that the thermal boundary resistance between the NbN film and the quartz substrate is greater and the quality of the NbN film is worse than those of sapphire or silicon. The former leads to a decrease in the intermediate frequency range, since a limited heat flow into the substrate for the films used gives an approximate equality of the time of phonon escape into the substrate τ_{es} and the time of electron-phonon interaction τ_{eph} at 4.2 K. The latter decreases the critical current density and consequently the bias current and the optimal local oscillator power, which does not allow to increase significantly the electron temperature above the lattice temperature and limits not only the IF bandwidth, but also the internal conversion gain. The greatest influence upon the loss is, however, exerted by the coupling factor. It is difficult to match an HEB mixer under the frequencies $f < 2\Delta/h$ (where 2Δ is the energy gap) because it is impossible to calculate the superconductor film impedance in the resistive state under the unequilibrium conditions with significant P_{LO} and bias current density. It seems that the only feasible way for these frequencies is to experimentally select the film geometry in order to achieve the best matching of the mixer block.

In the present work, we have made progress in all the directions mentioned.

2 Experimental

2.1 Design of Mixers and the Experimental Installation

The studied mixer structures were manufactured from thin NbN films made by reactive magnetron sputtering of Nb target in an argon-nitrogen mixture onto polished crystalline quartz substrates. The film quality is primarily defined by the gas pressure and the temperature of the substrate. The film thickness was checked by a profilometer-profilograph with a ±10 Å precision. A scanning electron microscope with a 100 Å resolution was used to make sure that there are no granules or heterogeneities. The mixers were produced as single NbN film strips. The contact pads and microwave filters were produced on the same substrate by photolithography. The mixer configuration and the design of the mixer block are shown in Fig. 1. The element produced was fastened in the centre of the 100 GHz waveguide. The film plane coincided with the E-plane of the waveguide. One contact pad was grounded in a mixer block. The IF signal through the microwave filter was removed from the mixer using a coaxial cable, which was also used to supply the constant bias current.

The parameters of the mixers were studied in the 100 GHz waverange using a setup whose block diagram is shown in Fig. 2. The working temperature of the mixer block could be varied between 4.2 K and 9 K. The RF power loss in the waveguide between the cryostat input and the input of the mixer block did not depend on the frequency in the 80–120 GHz range and amounted to 2 dB. A backward wave oscillator (BWO) was used as local oscillator. A discharge tube with noise temperature of 6000 K was used as a signal source. The local oscillator power and the radiation of the signal were combined into one channel using a directional coupler. The local oscillator power, previously measured with a thermistor, was varied by calibrated attenuators. A DC bias supply with an internal resistance of 50 Ohm produced a bias current through the sample.

While measuring the bandwidth of the mixers, a wideband amplifier with an amplifying range of 1-2000 MHz was included into the IF circuit. The IF signal amplitude after it was amplified by 50 dB was measured by a spectrum analyser. The noise temperature T_N of the device was measured in a waverange of 1.3-1.7 GHz using a low-noise amplifier. The amplifier and the isolator were placed near the mixer block with the same working temperature.

The setup allowed to measure the IV-curves using the 2-point scheme, the value and the IF-frequency dependence of the conversion gain, as well as the noise temperature of the mixers under working temperatures from 4.2 K to 9 K.

2.2 Results

Fig. 3 and Fig. 4 respectively show the IV-curves of the mixers No 1 and No 2 under LO power. HEB mixer No 1 was made of a NbN film of higher quality than those described in paper [2]. With the same film thickness of 50 Å the critical current and the bias current in the optimal working point are practically identical with the respective currents of multistrip mixer elements mentioned in [2], since the critical current density of the superconducting strip was now greater almost by an order of magnitude and amounted to $5 \bullet 10^6$ A/cm^2. The superconducting transition temperature is higher than 11 K, and the temperature transition width is lower than 0.3 K. The film of the HEB mixer No 2 is still thinner: $\sim$ 40 Å. Despite the decrease of the critical current density ($\sim 10^6$ A/cm^2), the IV-curve still has, in the absence of microwave radiation power, an N-shape with a peculiar nonstable interval. The series resistance between the film and the contact pads is reduced and is now less than 2 Ohm.

Under LO power the resistance of mixer strips increases and the IV-curves shift to the area of weaker currents and higher voltages. The IV-curve of mixer chip No 1 loses its N-shape under the power radiation higher than -25 dBm. The local oscillator power, optimal for the conversion gain, amounts to -29 dBm. At the same time the optimal bias working point is located near the current unstability on the IV-curve. The differential resistance R_d in the operating point for mixer chip No 1 is equal to 95 Ohm. The optimal local oscillator power for mixer chip No 2 is equal to -39 dBm. The IV-curve of this mixer chip loses its breaking character under a power higher than -45 dBm. Thus, the optimal local oscillator power is located on the IV-curve without a negative differential resistance.

The conversion gain measurements in the IF waverange from 1 MHz to 2 GHz have shown a decrease of no more than 3-5 dB for both mixer chips. Thus, the frequency range of the mixers under study is 1.5-2 GHz. The conversion loss of the mixer No 1 in the optimal point in respect to local oscillator power and to bias current is 10 dB, and that of the mixer No 2 is 8 dB. The noise temperature of the receiver with the mixer No 2 at an intermediate frequency of 1.7 GHz was equal to 450 K.

The mixer impedance at an intermediate frequency is approximately equal to the differential resistance of the mixer chip. The IF loss of the mixer No 1 associated with this fact is about 1 dB. The remaining losses are distributed among the coupling factor and the internal conversion loss. If one assumes that the strip resistance in the working area of P_{LO} and the bias current is a function of the electron temperature only, the coupling factor can be calculated as follows:

$$L = \frac{P_{R_a} - P_{R_b}}{P_{DC_b} - P_{DC_a}}$$

where P_{R_a} and P_{R_b} are the microwave powers in the input of the waveguide located in front of the mixer block, P_{DC_a} and P_{DC_b} are Joule powers of the bias current in the points a and b of IV-curves under P_{R_a} and P_{R_b}, corresponding to the same resistance in the DC current. For mixer No 1 the coupling factor values thus received varied from 9 dB at the optimal working point to 7 dB for the increased mixer resistance. Although the above calculation does not take into account the pair-breaking action of the bias current and the microwave power, the estimations obtained in this way show the dominating influence of the coupling factor. A similar estimation in the input of mixer No 2 shows that the losses vary from 10 dB in the optimal point to 7 dB when operating in the area of high resistances of the mixer chips. The conversion loss and the noise temperature mentioned above are obtained under the mixer block temperature of 5 K. As the working temperature approaches the temperature of the superconducting transition, the mixer parameters become worse.

3 Discussion

The unpumped IV-curve of the mixer No 1 can be divided into 4 sections. In the low voltage region the strip is in superconducting state and the resistance observed arises due to the contact pads. The second part of the curve is a region of current instability. Then the curve remains relatively horizontal until the strip enters its normal state. The horizontal fragment of the IV-curve for a homogeneous film under temperature well below T_c takes place due to the formation of a resistive domain region.

As the voltage sinks, the normal section size reduces. When the domain size reaches the thermal length level, its edges draw together, and the film becomes entirely superconducting. The 100 GHz microwave radiation is mostly absorbed by the normal region. The electron heating as a result of P_{LO} and signal radiation causes an intermediate frequency response by shifting the domain edges. The maximal conversion gain is achieved close to the rupture point, where the length of the strip part in normal conducting state reaches its minimum. There the mixer impedance is low, thus increasing the coupling factor. One could expect to reduce it rising the working temperature. This provided, the energy gap narrows while the P_{LO} absorption in the superconducting areas intensifies. Besides, the bias current value at the optimal point and the critical current density diminish. If under higher temperature the latter becomes stronger than the current of depinning vortices in the superconducting regions, the mixer strip in the whole turns into resistive state which takes place because of the viscous flux flow (i.e. more spatially homogeneous). This case must be better described by the hot electron theory. Moreover, it is more convenient to achieve a better matching, since the pumped IV-curves are smooth and the optimal bias region is considerably wide.

The HEB superconducting mixer theory, however, assumes a sharp deterioration of the mixer parameters as the temperature approaches Tc [1]. Whether the situation described above holds already under temperatures not so close to Tc, where the internal conversion loss increases only a little, or this is not the case until very close to Tc, depends on the $hf / 2\Delta$ ratio. The latter must be the case under lower frequencies, i.e. when holds $hf / 2\Delta << 1$. Whether the 100 GHz frequency is high enough, can only be found out experimentally, while the appropriate calculation is too complex. The current experiment proves, indeed, that under temperature near 5 K the conversion loss and the noise temperature reach their minimum values.

In order to diminish the coupling factor, a single strip proved useful as the mixer form. Although the resistance in normal state is high and amounts to 1.1 kOhm and 3 kOhm for the mixers No 1 and No 2 correspondingly, their impedance under 100 GHz at the optimal working point (see above) is though significantly lower, but it still seems better matching in the mixer block than the multistrip mixers used in the previous work [2]. Those mixers could be probably more suitable for higher frequencies.

Finally, a reduction of the NbN film thickness together with a certain increase of the working temperature helped expand the IF band up to 1.5-2 GHz.

Acknowledgment

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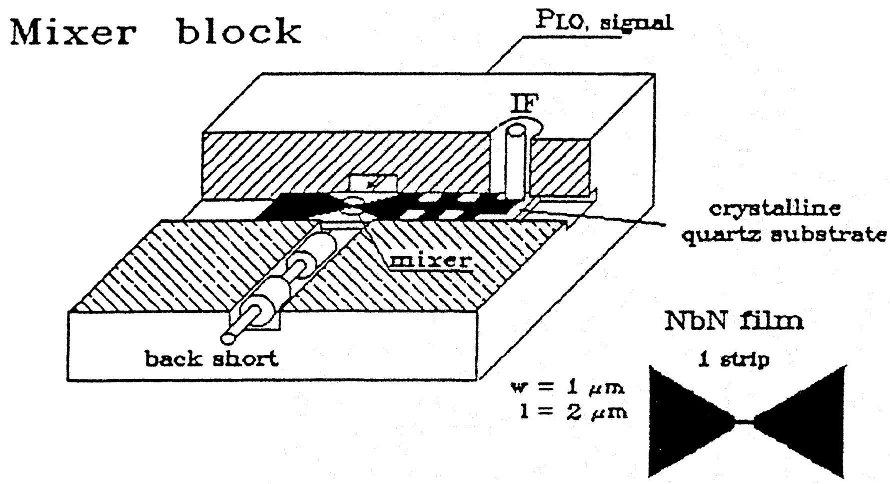

Fig.1. Design of the mixer block and configuration of mixer chip.

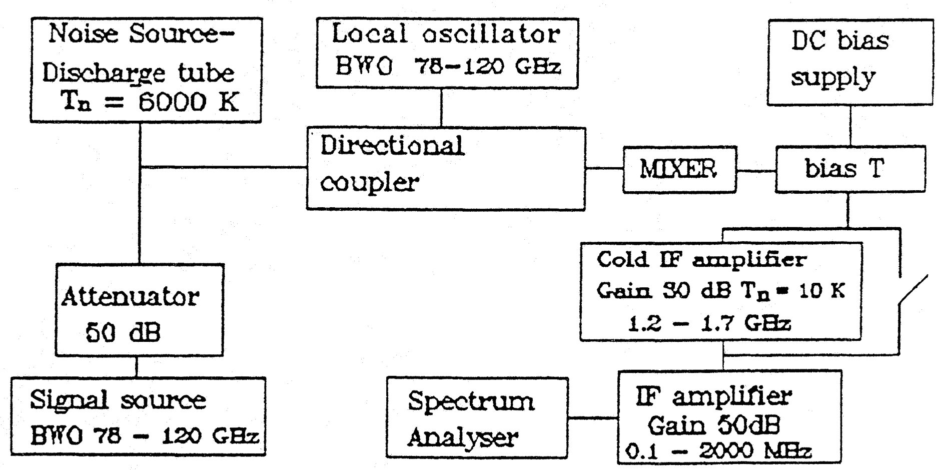

Fig. 2, Experimental set up.

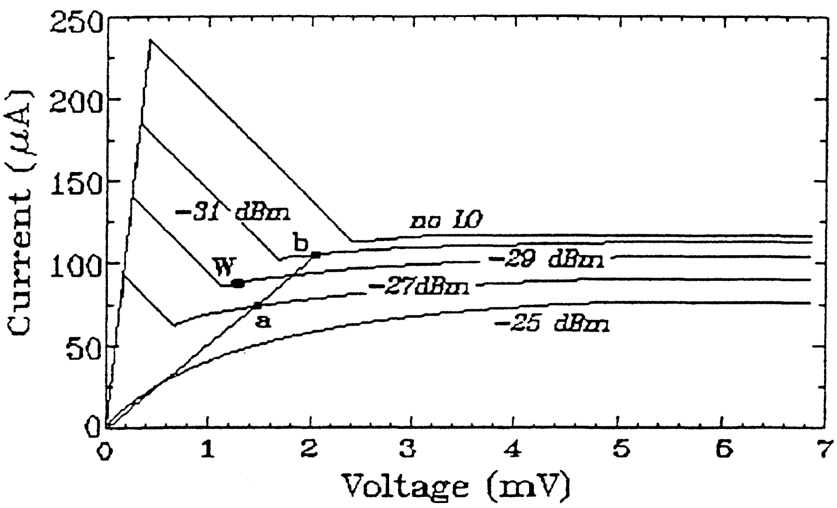

Fig. 3. I−V curves under LO power for sample No. 1.
W − is the optimal bias working point.

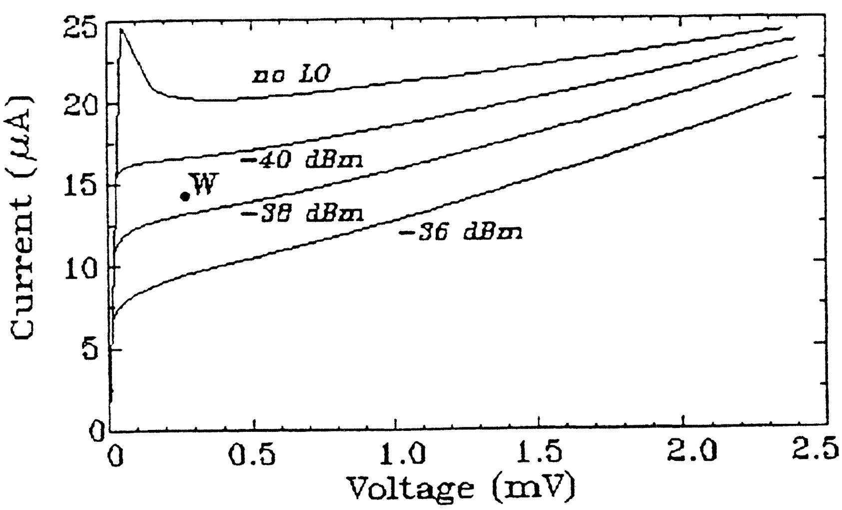

Fig. 4. I−V curves under LO power for sample No. 2.
W − is the optimal bias working point.