NOISE PROPERTIES OF A MIXER WITH SIS NbN QUASIPARTICLE TUNNEL JUNCTIONS.

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Abstract

We present an analysis of the noise properties of a mixer with the full NbN tunnel junctions. Our work is based on experiment in 120 -180 GHz range with SIS mixer with the NbN-MgO-NbN tunnel junctions. Mixer circuit is totally in NbN. The mixer operates at 5.4 K temperature unacceptable with Nb junctions. Minimum DSB receiver noise temperature is about 65 K at 160 GHz and approaches the Nb SIS mixer performance in mm band. In the whole 50 % band receiver noise varied between 65 and 150 K with the middle value about 80 K.

It has been found that noise sources in the NbN junctions are comparable to the Nb junctions and that the receiver noise with the NbN SIS mixer may be only few times more than the quantum limit of noise in the frequency range below the gap frequency. Output noise of the SIS mixer has been found constant in a wide frequency band and within an important range of the local oscillator amplitudes.

Introduction

Progress of the millimeter and submillimeter ultra low noise receiver required for the radioastronomy programs and for the atmosphere monitoring was provided with the development of the new generation of the low noise Superconductor- Insulator- Superconductor (SIS) mixers with Nb-Al oxide-Nb quasiparticle tunnel junctions [1,2]. The upper frequency limit of Nb SIS devices about 700 GHz is settled by the increase of the loss behind the gap frequency of superconductor. The further progress in frequency of the SIS devices was currently related to the NbN junctions with the highest gap frequency around 1200 GHz. Only one experimental investigation was performed in the mm band with a full NbN SIS mixer at 200 - 208 GHz [3]. Up-to-date noise performance of the SIS NbN mixers was out of concurrence with the Nb devices. Presented in [3] receiver DSB noise was about 460 K and a minimum available mixer noise was estimated as 145 K. Origin of such a high noise in the NbN junctions was not clear. The aim of this work is to demonstrate a low noise operation of a SIS mixer with NbN tunnel junctions and to understand mixer noise properties.

NbN - Mg Oxide - NbN junctions

NbN-MgO-NbN junctions used in this work was produced with the tri-layers coming from the Electrotechnical Laboratory. Tri-layer deposition technology was presented in [4]. Junction etching and the deposition of the NbN wiring layer was performed in IRAM. Critical temperature of NbN used in our experiments is about 15 K and the gap voltage of the junction is about 5 mV.

Optimum $R_N\omega C$ for the use in the quasiparticle tunnel NbN junctions in the mm and submm mixers

Optimum $R_N\omega C$ for the Nb junctions is discussed in [5,6]. If the local oscillator frequency is well below the gup frequency of Nb ($F \ll \Delta/h$) and if the junction I-V curve is sharp the optimum is about or below $R_N\omega C \approx 4/F$, where F is the frequency in 100 GHz [5].

In the same conditions a similar relation may be outlined for the NbN junctions. This relation may be based on the estimation of the optimum RF impedance of the SIS junction $R_{RF\ OPT}$. Optimum coupling to the external circuit of the junction presented by a parallel connection of RF resistance and small junction reactance is expected when $R_{RF\ OPT}=|X_{RF}|$. Junction RF resistance may be estimated in the case $F \ll \Delta/h$ as $R_{RF}=2h\nu R_N/eVg$, leading to the expression for the optimum junction parameter $R_N\omega C=eVg/2h\nu$. In the case of the tunnel junction with the Nb electrodes it givés a known expression $R_N\omega C\approx 3.5/F[100\ GHz]$. In the case of the NbN junction with Vg=5 mV we arrive to:

$$R_N\omega C\approx 6/F[100\ GHz] \qquad (1)$$

This relation gives an approximate value of the optimum $R_N\omega C$ for the use of the NbN junction in a mixer. As in the case of the Nb junctions, optimum $R_N\omega C$ of the NbN junctions approaches 1 if I-V curve is not sharp or if the operation frequency comes closer to Δ/h.

Mixer design

SIS mixer comprises a multi layer NbN printed circuit with two tunnel junctions and a mixer block. It is a single backshort mixer block with a reduced height waveguide. An L-C microstrip impedance transformer is integrated with each junction as a part of the interconnection layer in the junction fabrication process. Printed circuit of the mixer was optimized for the individual junction normal resistance about 30 Ohm and $R_N\omega C\approx 6$. The junctions available for the test have $R_N\omega C\approx 50$ resulting in extra loss in the mixer circuit. Backshort position of this mixer with a relatively large junction $R_N\omega C$ product have to be adjusted at each frequency.

Experimental set - up

Experiments with the NbN SIS mixer were hold in the receiver developed for the SIS Nb mixers. Receiver comprises a liquid helium cryostat, SIS mixer, cooled HEMT IF amplifier, ambient temperature amplifier and the local oscillator. Local oscillator consists of the Carlstrom Gunn oscillator and a doubler developed in IRAM by F. Mattiocco. Local oscillator power is injected at the mixer input by a commercial cooled waveguide coupler. Receiver input window is in milar and an infrared filter in expended polystyrene form is fixed at the 77 K shield. Temperature at the mixer block in experiment with NbN junctions was about 5.4 K. This temperature is not acceptable with the Nb junctions but in the case of the NbN junction is still below 0.4 Tc.

Operation of the SIS receiver with the NbN tunnel junctions in the mixer

Current-voltage characteristics (CVC) of the two NbN SIS junction array with and without local oscillator power (P_{LO}) are presented in Fig. 1. Normal resistance of the two junction array is 260 Ohm and the Josephson critical current density is about 1.3 KA/cm². The subgup resistance of these junctions is about 4 time lager then the normal state resistance. Junction CVC may be compared with a "Dull" characteristic used in [6] for the calculation of the SIS mixer performance. Conversion gain -5 dB is predicted in [6] for a mixer with the dull CVC at 150 GHz, corresponding to 0.12 of the NbN gup frequency.

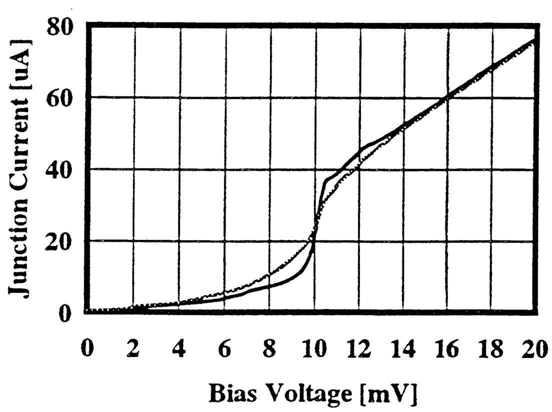

Figure 1. Current-Voltage characteristics of the two NbN SIS junction array. Black line - without local oscillator power; gray line - with P_{LO}.

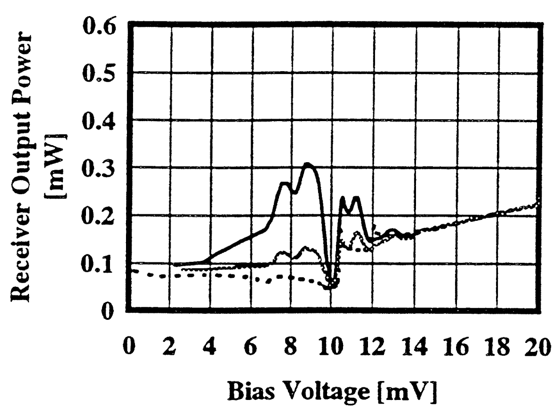

Figure 2. Output power of the SIS receiver versus junction bias voltage. Dotted line - without P_{LO}. The gray line is measured with P_{LO} and with a nitrogen temperature load; black line - with P_{LO} with an ambient temperature load.

Tien - Gordon steps are not obvious at the CVC in the presence of the local oscillator power (gray curve in Fig. 1). It may be a common effect of a very smooth CVC and of a relatively low frequency of operation in our experiment. The quantum structures are better visible in the curves of the output power of receiver versus bias voltage presented in Fig. 2. Output power of the receiver is measured in the 500 MHz band around 1500 MHz with an ambient and nitrogen temperature loads in front of receiver (black and gray lines in Fig. 2 respectively). Dotted line in Fig. 2 presents the receiver output power without local oscillator.

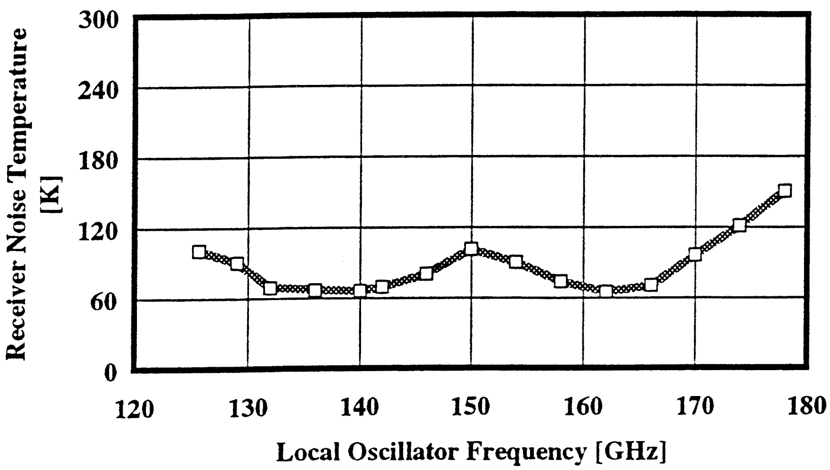

Figure 3. DSB receiver noise temperature with the NbN SIS junctions in the mixer.

Receiver noise temperature is measured in the standard nitrogen and ambient temperature load experiments. Mixer was tuned at each frequency. Minimum DSB receiver noise temperature is 65 K when the average noise in the 125 - 180 GHz band is about 80 K (Fig.). The noise level of this receiver is comparable with the performance of a receiver with the Nb SIS junctions.

Below we discuss the sources of the receiver noise using a standard relation for the receiver double sideband noise temperature:

$$T_{Rec} = T_{RF} + \frac{T_M}{G_{RF}} + \frac{T_{OUT} + T_{IF}}{2G_M \cdot G_{RF}} \qquad (2)$$

Here T_{RF}, T_M, T_{OUT} and T_{IF} are respectively the noise temperatures of the receiver input section, of the mixer, the output mixer temperature and the IF amplifier temperature. Terms G_{RF} and G_M denote the gains of the receiver input section and the mixer respectively. Receiver conversion gain is $G_R = G_{RF}G_M$.

Receiver and mixer conversion gain

Receiver gain was measured in situ in the hot and cold load experiments. Receiver IF chain was calibrated with the shot noise of the junction normal resistance biased behind the gup voltage according to [6]. Receiver conversion gain versus bias current (bias voltage is fixed) is presented in Fig. 4. Maximum gain between the receiver input window and the output of the IF isolator of the mixer is about 0.25 (-6 dB). In this receiver we used the junctions with the $R_N\omega C$ parameter more than 10 times large the optimal value. Analysis of the mixer circuit shows that at least 2 dB of loss may be explained by the junction mismatch.

Measured IF chain noise temperature is 6.5 K.

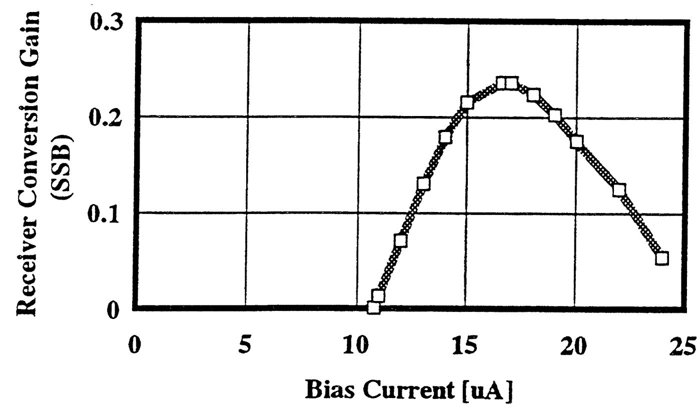

Figure 4. Receiver conversion gain versus bias current at 166 GHz. This curve is measured with the bias voltage fixed at 9 mV and with the different levels of the local oscillator power.

Noise of the input section of the SIS receiver

Input section noise of this receiver was determined according to [7, 8] in the experiment with a SIS mixer with Nb junctions. It has been found that $T_{FE}+T_M/G_{FE}$ is about 7 K. Here we present in Fig. 5 SIS NbN receiver gain versus receiver loss dependence measured at 166 GHz with at the different local oscillator power levels between zero and a level superior to the optimum working P_{LO}. Experimental points are situated on the strait line. This behavior corresponds to a constant output mixer noise temperature if T_{IF}, T_{FE} and T_M are constant. In this experiment mixer CVC does not change significantly with the P_{LO} and we can expect constant SIS junction coupling to the mixer circuit at RF and IF. Extrapolation of the measured data to zero conversion loss gives according to expression (2): $T_{FE}+T_M/G_{FE}$=8 K. Receiver front end section noise measured with NbN and Nb junctions are identical.

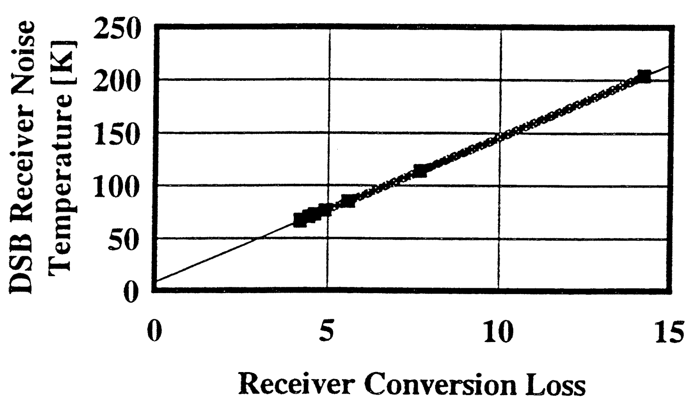

Figure 5. Receiver DSB noise temperature versus conversion loss measured at the different levels of the local oscillator power. Experimental points are located on a strait line.

Output noise of the mixer with NbN SIS junctions

Output noise of the mixer was determined according to (2) as:

$$T_{OUT} = (T_{Rec}-T_{FE})2G_{Rec}- T_{IF} \quad (3)$$

Measured output noise versus bias current is presented in Fig. 6. Minimum receiver noise was measured with a 17 μA current. Output mixer noise is perfectly stable up to 20 μA current, superior to the optimum level. In this experiment mixer tuning was fixed and bias current was changed by P_{LO}. Observed in our experiment Constant output noise at the different amplitudes of the local oscillator is in a good accord with the theoretical prediction in [9] for the low P_{LO} level.

Frequency dependence of the output mixer noise is presented in Fig. 7. Mixer tuning and P_{LO} are optimized at each frequency. Output noise is stable in the 50% frequency band, except some points with a difficult tuning. Frequency independent output noise of the SIS mixer was predicted in [6, 9].

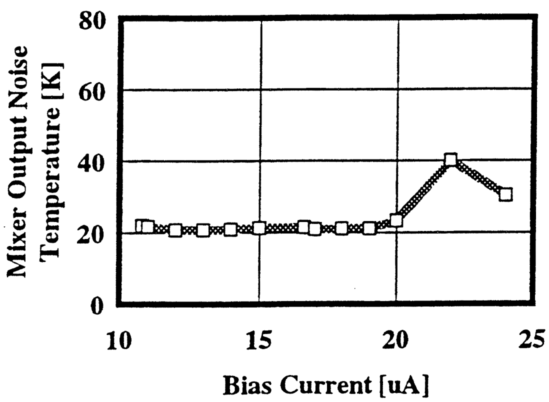

Figure 6. SIS mixer output noise dependence on the bias current measured at 166 GHz local oscillator frequency. Mixer tuning is fixed and the bias current changes with the local oscillator power.

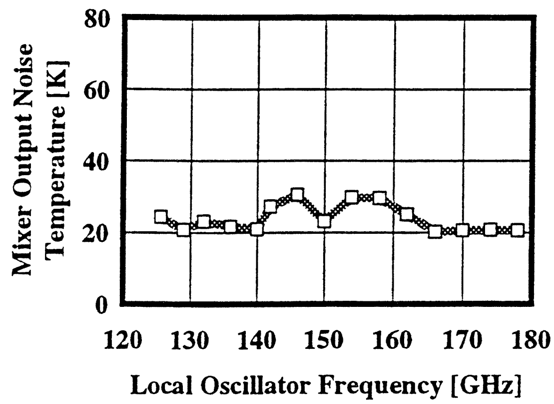

Figure 7. SIS mixer output noise temperature versus frequency. Mixer tuning and local oscillator power are optimized at each frequency.

Conclusion

We demopnstrated for the first time the low noise operation of the SIS mixer with a full NbN tunnel junction. Minimum receiver noise temperature of 65 K was measured at 162 GHz. Average noise temperature over all the 125 - 180 GHz band is about 80 K. Presented in this paper receiver noise with the NbN tunnel junctions in the mixer is comparable with the typical results with Nb junctions.

In our experiment the NbN SIS junction was at 5.4 K temperature unacceptable with the Nb devices. Introduction of the low noise NbN mixers may simplify the receiver cryogenics, especially the closed-cycle refrigerators.

For operation in the mixer the optimum $R_N\omega C$ NbN junction product is different from the Nb junctions. The optimum with NbN is $R_N\omega C \approx 600$GHz/F if the junction current-voltage characteristic is not smooth and if the frequency of operation does not approach to the gap frequency. In our experiment the junctions with $R_N\omega C=50$ have been used. A further improvement in the receiver noise with NbN tunnel junctions is possible with the progress in the junction parameters and mixer circuit design.

It has been demonstrated that in a good agreement with the theoretical prediction [6,9] the SIS mixer output noise is nearly independent on frequency and on the local oscillator power. Relative frequency band in our experiment was 50%; local oscillator power was between zero and optimum working level. According to our experiment the output noise level may be used as a basic characteristic of a SIS mixer.

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