SUBMILLIMETER WAVEGUIDE SIS MIXER WITH FULL NbN CIRCUIT

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Abstract

We have developed and tested a submillimeter waveguide SIS mixer with NbN-MgO-NbN quasiparticle tunnel junctions. The two junction array is integrated in a full NbN printed circuit. The NbN film critical temperature is 15 K and the junction gap voltage is 5 mV. The size of the junctions is 1.4 x 1.4 μm and Josephson critical current density is about 1.5 KA/cm² resulting in junction $R_N\omega C$ product about 40. The inductive tuning circuit in NbN is integrated with each junction in two junction array. A single non contacting backshort was tuned at each frequency in the mixer block.

At 306 GHz the minimum DSB receiver noise temperature is as low as 230 K. The sources of the receiver noise and of the limits of the NbN SIS submillimeter mixer improvement is discussed.

Keywords: superconductors; NbN; SIS junction; SIS mixer; SIS receiver; low noise; submillimeter waves; radioastronomy.

1. INTRODUCTION

An important effort for development of the SIS mixers with a circuit and quasiparticle tunnel junction electrodes in NbN [1,2] is motivated by the aim to overcome the frequency limit of existing SIS Nb devices around 1-1.2 THz. As known [3], the basic frequency limitation of SIS mixers is set below twice the gap frequency of superconductor about 1.3-1.4 THz for Nb and 2.4-2.5 THz for NbN. The mixer sensitivity starts to degrade at a half of this frequency due to reduction of the SIS mixer conversion gain and loss increase in superconductor circuit above the gap frequency. The new full NbN devices are of a special interest for radioastronomy and atmosphere monitoring in 1 to 2 THz frequency range where the Nb circuits may be less efficient.

Only few experiments were done up to date with a full NbN circuit SIS mixer at millimeter and submillimeter wavelength [4 - 6]. The best published DSB receiver noise with NbN SIS mixer circuit at submillimeter wavelength [4] is 500 K at 350 GHz with a junction $R_N\omega C$ product 11 and Josephson critical current density 3.8 KA/cm². At millimeter wavelength a 460 K DSB receiver noise was demonstrated around 200 GHz [5] and 65 K DSB noise temperature at 165 GHz [6].

2. MIXER DESIGN

In the mixer block with reduced height waveguide of 100 x 780 μm size a single backshort is used for adjustment. The SIS junctions and RF filters are located on suspended substrate made of a fused quartz. An L-C parallel micro strip impedance transformer is integrated with each junction as a part of the interconnection layer in the junction fabrication process. Inductive element is 27 μm long and 4 μm wide at 200 nm SiO2 layer and capacity element area is 2000 μm^2. The printed circuit of the mixer was optimized for individual junction normal resistance of about 30 Ohm and $R_N\omega C = 6$.

The NbN-MgO-NbN junctions and full NbN printed circuit used in this work was fabricated in IRAM. In more details the junction fabrication technology was presented in [7, 8]. The critical temperature of NbN used in our experiments is about 15 K and the gap voltage of the junction is about 5 mV.

The optimum $R_N\omega C$ product of NbN SIS junction for a mixer at frequency f may be estimated as 600 GHz/f [6]. At 300 GHz optimum junction $R_N\omega C$ is about 2. The size of NbN-Mg oxide-NbN junction available for the test was 1.4 x 1.4 μm with Josephson critical current density about 1.5 KA/cm^2 resulting in junction $R_N\omega C$ product about 40.

3. RECEIVER NOISE MEASUREMENT

The receiver comprises a liquid helium cryostat, a SIS mixer, a cooled HEMT IF amplifier, an ambient temperature amplifier and the local oscillator. The receiver output power is measured in the 500 MHz band around 1500 MHz IF. The noise temperature of the receiver IF chain is 4 K. The local oscillator consists of a Carlstrom Gunn oscillator and a quadrupler. The local oscillator power is injected at mixer input by a cooled waveguide directional coupler. The receiver input window is in polyethylene and an infrared filter in expanded polystyrene foam is fixed to the 77 K shield. The temperature of the mixer block in experiment with NbN junctions was about 4.5 K.

The receiver noise temperature is measured by the standard method using liquid nitrogen temperature and ambient temperature loads (77 K and 295 K).

4. RECEIVER OPERATION

4.1. Receiver noise

The current-voltage characteristic (CVC) of the two NbN SIS junction array is presented in Fig. 1. The gray and the black lines are measured respectively with and without 306 GHz local oscillator power (P_{LO}). The normal resistance of two junction array is 210 Ohm. The sub gap resistance of two junction array measured at 8 mV is about 4.7 time larger than the normal state resistance. The junction CVC may be compared with a normalized "Dull" characteristic used in [9] for modeling of Nb SIS mixer performance. In [9] the -5 dB conversion gain was predicted for a mixer with a dull CVC at 0.25 of the gap frequency, approaching 306 GHz if the junction electrodes are in NbN.

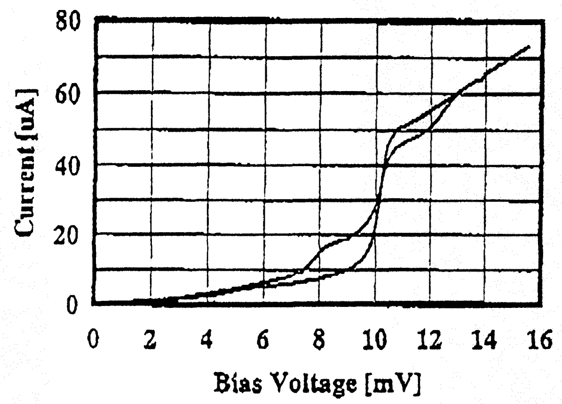

Figure 1. The Current-Voltage characteristics of the two NbN SIS junction array. Black line - without local oscillator power; gray line - with P_{LO}.

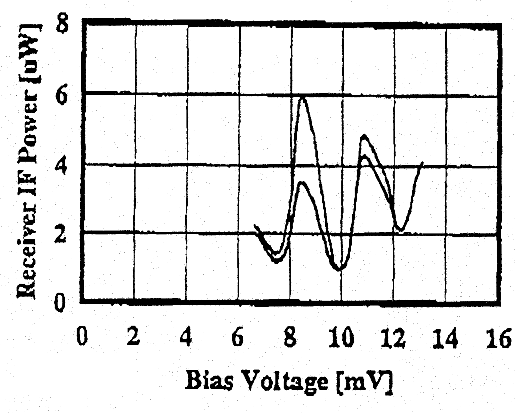

Figure 2. The output power of the SIS receiver at IF versus junction bias voltage. The gray line is measured with P_{LO} and with a nitrogen temperature load; black line - with P_{LO} with an ambient temperature load in front of receiver.

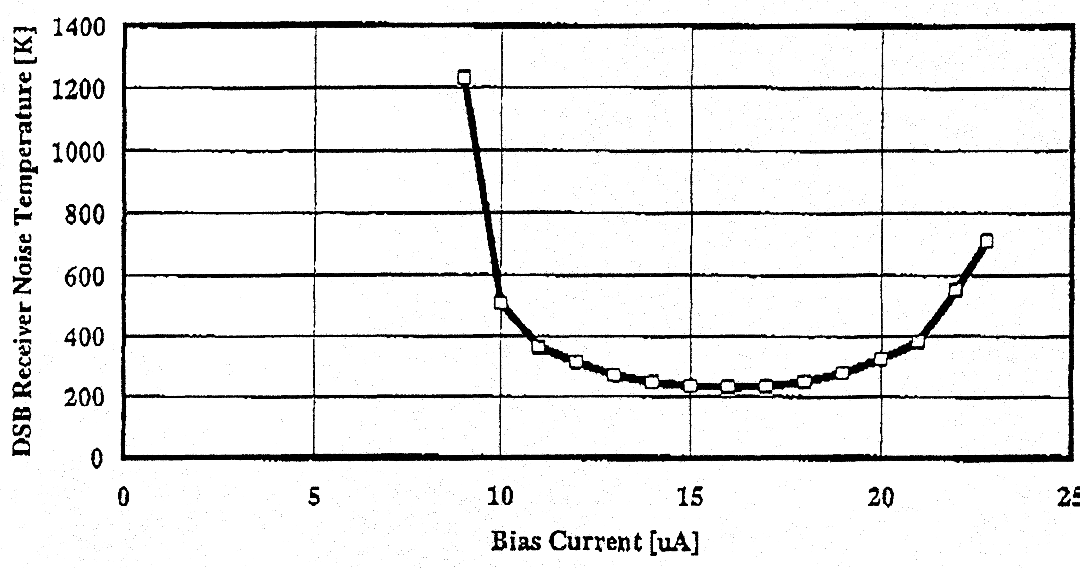

Figure 3. DSB SIS receiver noise temperature at 306 GHz at the different levels of the bias current. Bias voltage is fixed and current is controlled by the local oscillator power level. Minimum noise temperature is 230 K.

The quantum steps are visible in CVC of a junction when local oscillator power is applied (gray curve in Fig. 1). Even better the quantum steps are visible in the curves of the receiver output IF power versus bias voltage (Fig. 2). The receiver IF power measured with an ambient and nitrogen temperature loads in front of receiver is presented in Fig. 2 with black and gray lines respectively. The sizes of the quantum steps at the voltage axis are identical below and above gap voltage and no traces of the junction overheat where observed.

At 306 GHz the minimum measured DSB receiver noise temperature is 230 K. The measured DSB receiver noise temperature versus bias current is presented in Fig. 3. The bias voltage is fixed at 8.4 mV and current is controlled by the local oscillator power. The minimum receiver noise was measured with a 17 μA current.

Below are discussed the sources of receiver noise using the standard relations for receiver double sideband noise temperature:

$$T_{Rec}=T_{RF}+\frac{T_{OUT}+T_{IF}}{2G_M G_{RF}} \qquad (1)$$

Here T_{RF},T_{OUT} and T_{IF} are respectively the noise temperatures of the receiver input section, 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 $G_{Rec}=G_{RF}G_M$.

4.2. Mixer conversion gain

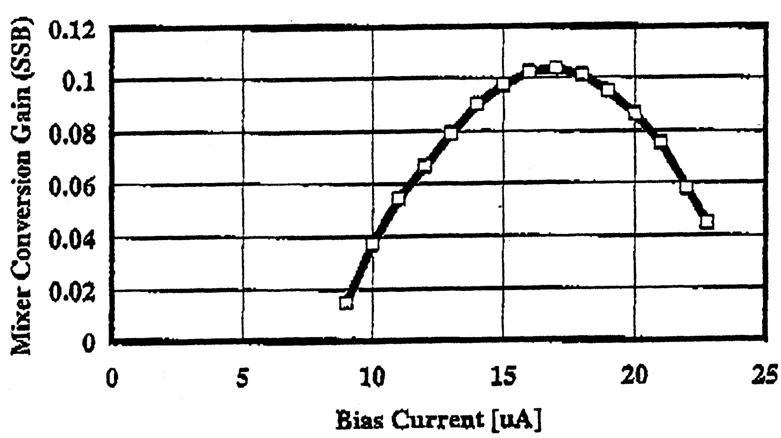

Figure 4. The mixer conversion gain versus bias current at 306 GHz. This curve is measured with the bias voltage fixed at 8.4 mV and with the different levels of the local oscillator power.

The mixer conversion 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 above the gap voltage according to [10]. The receiver conversion gain at 306 GHz versus bias current (bias voltage is fixed) is presented in Fig. 4. The maximum gain between the receiver input window and the output of the mixer IF isolator is about 0.1 (-10 dB). This gain is about 5 dB less than expected. Excessive loss in the mixer is due to the junction $R_N\omega C$ parameter about 20 times larger than the optimal value.

4.2. Receiver input section noise

The receiver input section noise contribution was determined according to [11, 12]. We present in Fig. 5 receiver gain versus receiver loss dependence measured at 306 GHz at the different local oscillator power levels up to the optimum working P_{LO}. The experimental points are located on a strait line. This behavior corresponds to a constant output mixer noise temperature if T_{IF} and T_{RF} are constant. In experiment the mixer CVC does not change significantly with P_{LO} and one can expect constant SIS junction coupling to the mixer circuit at RF and IF. The extrapolation of the measured data $T_{Rec}(1/G_{Rec})$ down to zero conversion loss gives, according to expression (1), the value of T_{RF}. The receiver front end section noise measured with NbN junctions (Fig. 5) is about 60 K.

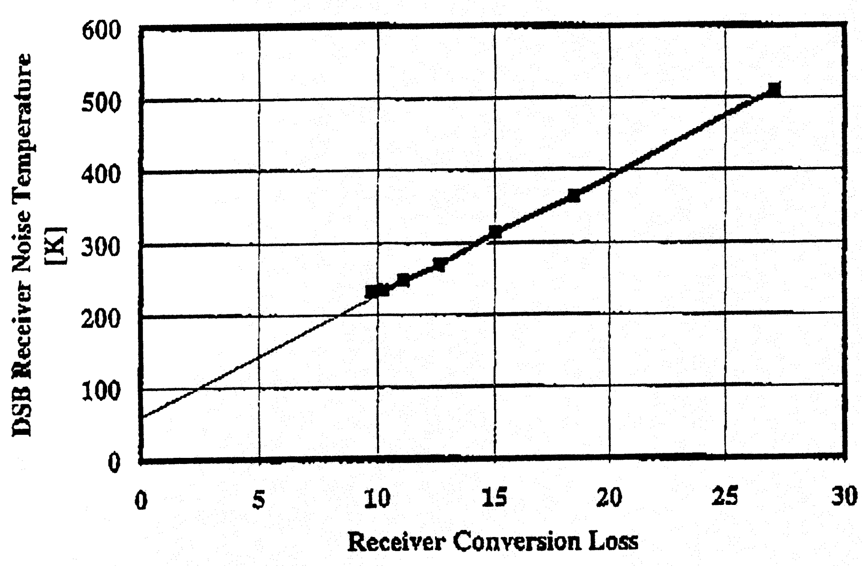

Figure 5. The receiver DSB noise temperature versus conversion loss measured at different levels of local oscillator power. The experimental points are located on a strait line.

4.3 Receiver noise budget

Receiver noise of 230 K at 306 GHz may be developed according expression (1) as follow:
- 60 K contribution of the quasi optical elements at receiver input
- 170 K contribution of the mixer with IF chain, where
- 20 K is contribution of the IF chain
- 150 K mixer contribution

The output mixer noise T_{OUT} is about 30 K.

In actual receiver the mixer contribution to receiver noise dominates. With improvement of the junction parameters, particularly with reduction of the $R_N\omega C$ product, one can expect reduce the junction mismatch and the loss in mixer circuit, approaching predicted mixer conversion gain of -5 dB [9]. With optimized NbN SIS junction size and critical current density and without changes in mixer output noise the mixer contribution to receiver DSB noise temperature may be reduced to 45 K according this prediction of gain.

5. SUMMARY

We demonstrated a low noise operation of the SIS mixer with a full NbN tunnel junction at submillimeter wavelength. The minimum DSB receiver noise temperature of 230 K was measured at 306 GHz.

Waveguide single backshort mixer with SIS NbN-Mg oxide-NbN junctions was at 4.5 K temperature. Mixer operation at 306 GHz is stable without suppression of the Josephson current with magnetic field.

The mixer conversion gain is about -10 dB (SSB); the mixer output noise temperature is 30 K. In our experiment the junction $R_N \omega C$ product was 40, considerably larger than the optimum $R_N \omega C$ value of about 2. One can expect after optimization of NbN junction $R_N \omega C$ product to reduce the mixer loss and extend the frequency band of SIS mixer operation.

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