Low noise mixer with the Nb-Al Oxide-Al-Nb tunnel junctions for a multibeam 345 GHz receiver

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Abstract

In this work we present for the first time a low-noise submillimeter receiver with a mixer using Superconductor-Insulator-Normal metal-Superconductor (SINS) junctions. Junctions containing a normal metal layer may be free of the Josephson current and of the related perturbations of mixer operation specific for the standard SIS mixers. This SINS mixer quality is important for the application in the multibeam receiver. The SINS mixer stability of operation and independence on the magnetic field have been confirmed in our experiment. Minimum SINS receiver noise in the 290 - 330 GHz band is about 135 K when the junction $R_N\omega C$ is about 30. Noise, conversion gain and thermal properties of the SINS mixer have been studied and compared with the SIS mixers. The limit of SINS mixer operation improvement is discussed in the end of the work.

Introduction

Improvement of the modern receivers used in radioastronomy at the submillimeter wavelength is based on the progress of the mixers with the Superconductor-Isolator-Superconductor (SIS) quasiparticle tunnel junctions [1, 2]. Quasiparticule current and pair current exist in this type of junctions. Problems related to the pair current in the SIS mixers are well known (instability, excessive noise)[3]. With the commonly used Nb-Al Oxide-Nb SIS junctions this problem is more pronounced at the submillimeter wavelength, where the low order Shapiro steps interfere with the first Tien-Gordon step. Magnetic field is normally used to suppress the pair current but in practice it is difficult to remove it completely. Even after adjustment of magnetic field the stability of operation may be lost due to the magnetic flux quanta trapping or simply to the instability of the magnetic field. Necessity of the periodical adjustment of the magnetic field in the numerous SIS mixers may be an important handicap of the mulitibeam SIS receiver at the submillimeter wavelength.

A Superconductor-Isolator-Normal metal (SIN) junction may be used as a version of the quasiparticle tunnel junction alternative to the SIS. Absence of the pair current in SIN junction simplifies the device behavior. It makes possible to avoid the Josephson effects related perturbations in the SIN devices and to use the mixer without applying the magnetic field to the tunnel junctions.

Up to now only few papers were published on the receivers with the SIN mixers. The best result is 220 - 300 K DSB receiver noise temperature in the 220-230 GHz range [4].

Theoretical analysis of a mixer performance with a tunnel SIN junction [5] is normally based on the same approach as the analysis of the SIS mixers [6], where the mixer performance is calculated using the Kramers-Kroning transform of the I-V curve. The I-V curve of a SIN junction is more smooth than that of the SIS junction resulting in the lowest mixer conversion gain [5]. Gap voltage of a SIN junction is a half of the gap of the SIS junction with the same superconductor. Nevertheless a gain about - 5 dB may be predicted for a SIN mixer [7].

Analysis of the experiments with the SIN mixers shows importance of the loss in the normal conductor electrode. At the submillimeter wavelength a tunnel junction typical resistance is well below 1 Ohm and a parasitic resistance of the same order of magnitude [4] may reduce in a few time conversion gain of a SIN mixer. Even a small loss in a parasitic resistance associated with a low conversion gain in a SIN junction degrades the receiver performance.

The idea of this work is to ameliorate performance of the mixer using a SINS junction instead of a SIN. In SINS junction the two electrodes are made in superconductor and the loss in a short Al layer is not important. At the same time the pair current through the SINS junction may be close to zero without an external magnetic field.

We introduce also an L-C impedance transformer integrated with the junction to prevent the degradation of the mixer gain related to the loss in the circuit.

Below we present an experiment in 290 - 330 GHz band with a low noise mixer with an Nb-Al Oxide-Al-Nb junction; we discuss the noise properties and the gain of the mixer, the thermal behavior of the mixer and the limit of the mixer optimization.

SINS junctions

The SINS junction was produced according to the method presented in [8]. Base electrode of the junction is in Nb 90 nm thick, the Al layer is 30 nm thick and the counter electrode is in Nb 300 nm thick. In the mixer we use an array of two junctions. Junction technology is in progress and up to the moment only few were accessible for the test. Junction definition is done with a mask with few different junction areas and with the same matching circuit. Only the junctions with the biggest area were usable. Junctions available for the test have the area 1.6*1.6 μm^2 and the individual normal resistance 72 Ohm resulting in a relatively important $R_N \omega C \approx 30$.

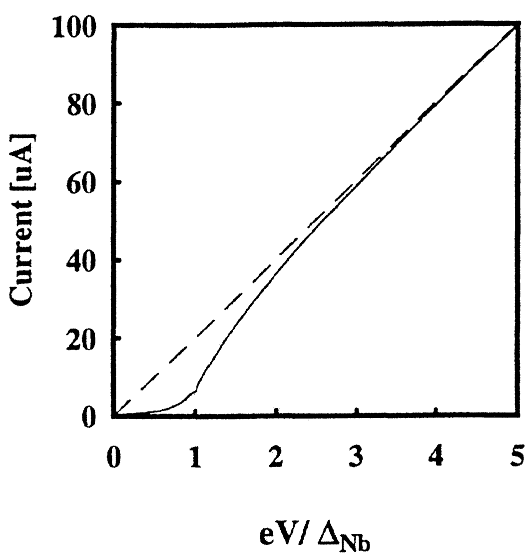

Figure 1. I-V characteristic of the SINS junction used in a mixer. Bias voltage is normalized to Δ_{Nb}/e. Junction is at 3 K. A dashed line corresponds to the normal resistance of the junction.

Gap voltage of a tunnel junction is important for the estimation of the frequency limit of the operation of a mixer $f_{MAX} \approx 2Vg/eh$ [6]. It is known that in SIN junctions $Vg = \Delta_S/e$ resulting in $f_{MAX} \approx 700$ GHz for Nb superconductor electrode; for the SIS junctions the gap voltage is two times larger $Vg = 2\Delta_S/e$ with $f_{MAX} \approx 1400$ GHz for Nb. The SINS junctions have some intermediary properties and a limit frequency is between 700 and 1400 GHz.

Theoretical and experimental consideration of the Nb\Al junctions with a similar structure presented in [9] gives the gap voltage for the different thickness of the Al layer. When Al layer is about 30 nm thick a gap voltage according to [9, 10] is $Vg \approx 1.48\Delta_{Nb}/e$ mV at 4.2 K and $Vg \approx 1.52\Delta_{Nb}/e$ at 1.6 K. Using this data one can expect the limit frequency of our SINS mixer as $f_{MAX} \approx 1000$ GHz convenient for the application at the submillimeter wavelength. In practice the junction gap voltage depends strongly on the conductivity of the metals in the Nb and Al layers and on the interface between the layers and so on the technology of the junction fabrication.

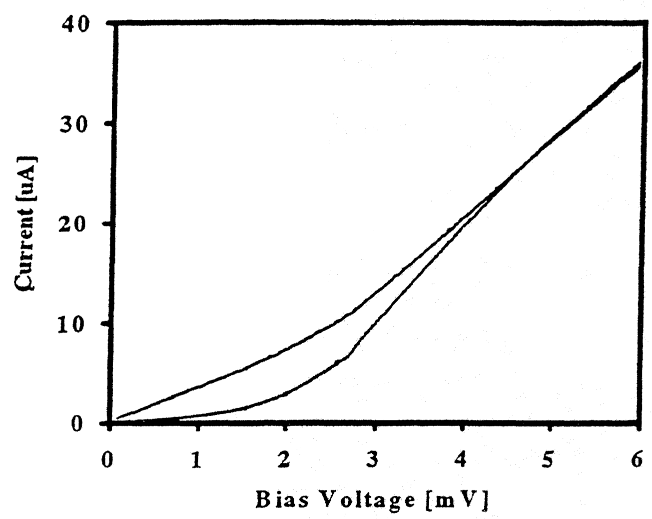

Figure 2. The details of the I-V characteristics of the SINS junction without local oscillator power (below) and with the local oscillator at 300 GHz.

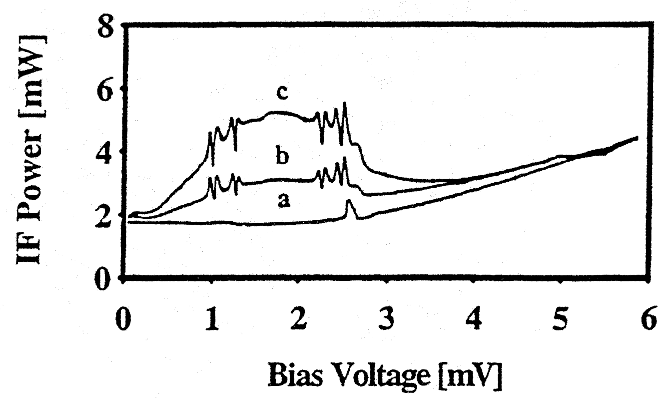

Figure 3. Receiver output power at the intermediate frequency 1.5 GHz a) without the local oscillator power P_{LO}, b) with the P_{LO} and with the nitrogen temperature load in front of the receiver, C) with P_{LO} and with the ambient temperature loads.

Experimental I-V characteristic of a SINS junction measured in our mixer at 3 K temperature is presented in Fig. 1. Bias voltage of the two junction array is devised by 2 and than normalized to Δ_{Nb}/e=1.4 mV; a dashed line corresponds to the normal resistance of the junction. Critical Josephson current in this junction was not observed. The I-V curve is very smooth. Gap voltage of the junction may be referred to the on-set of the current situated just behind Δ_{Nb}/e. Normally a knee-like structure on the I-V curve specific for the proximity effect in the SINS tunnel junctions exceeds the line of the junction normal resistance on the I-V plane. In I-V characteristic of our junction knee-like structure is not visible in a broad round slop behind the gap voltage. In the terms of [9] this I-V curve corresponds to the case of the a large proximity parameter of the SINS junction electrodes related with a low conductivity of the Nb layer. An other possible explication of this smooth I-V curve is a low transparency of the Nb/Al interface [9]. Small structure just below the gap voltage may be referred to a small gap induced in Al through an additional barrier between the top Nb electrode and Al layer, produced accidentally before deposition of the top electrode. Smooth form of this structure indicates the simultaneous existence of both effects - low transparency of the Al/Nb interface and reduced conductivity of Nb electrode. One can conclude that junction used in our experiment is nearly SIN contact with a gap voltage corresponding to the frequency limit of the mixer about $f_{MAX} \approx 700$ GHz.

Characteristics of an array of the two SINS junctions with and without local oscillator radiation at 300 GHz are presented in Fig. 2. Receiver output power at the intermediate frequency 1.5 GHz (P_{IF}) is presented in Fig. 3. Curve a) in Fig. 3 is measured without local oscillator power (P_{LO}). Curve b) is measured with P_{LO} and with a nitrogen load in front of the receiver. Curve c) is measured with P_{LO} and with an ambient temperature load. Mixer is at 3 K temperature; no magnetic field is applied to the junction. Pair currents are very small in this junction. No traces of the critical Josephson current or of the Schapiro steps are visible on the I-V curve. Only at the curve of the output power of the receiver one can mentioned some structures related to the excessive power generation by the Josephson effects at the I-V curve regions with a larger dynamic resistance. The amplitude of these perturbations is of the same order of magnitude as may be currently observed with an SIS mixer after optimization of the magnetic field. The presence of these structures does not restrain to use the mixer in the receiver. With the central voltages 1.24 mV and 2.48 mV the structures correspond to the voltage of the first and the second Schapiro steps on the I-V curve of the junction irradiated at 300 GHz. Separation of this structures in the two substructures may be explained by a 15-20% difference in the individual junction area.

A structure at the output power curve without local oscillator power (Fig. 3 a) at 2.7 mV may be explained by the increase of the differential resistance just below the current on-set at the I-V characteristic of the junction. An other smooth maximum at the curve a) Fig. 3 may be mentioned around 1.3 mV. It may be associated with the traces of the two particles tunneling structure.

The Tien-Gordon steps are not obvious at a very smooth I-V curve of the SINS junction when the local oscillator power is applied. However in the dependence of the IF power versus bias voltage a structure corresponding to the quantum step with the size about 2hv/e = 2.5 mV is visible. It confirms the existence of the quantum assisted tunneling in the tested junctions.

Mixer design

Mixer design is based on our experience with the SIS junctions [11]. It is a single backshort mixer with a reduced height waveguide. An L-C resonant microstrip impedance transformer is integrated with the each junction as a part of the interconnection layer in the junction fabrication process (Fig. 4). Printed circuit of the mixer was optimized for the individual junction normal resistance about 30 Ohm, the junction capacitance 0.15 pF and $R_N\omega C \approx 9$. This mixer design with a relatively large $R_N\omega C$ product of the junctions presumes the adjustment of the backshort position at each frequency.

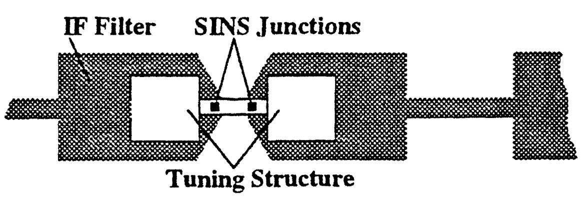

Fig. 4. SINS junctions with the individual tuning structures. An L-C microstrip circuit is used to compensate the junction capacity.

Coupling loss between the mixer input port and the junction depends on the junction impedance, frequency, position of the backshort in the mixer and the loss in the circuit. A mixer model [12] was used for the estimation of the minimum coupling loss for the expected junction parameters (R_N=30 Ohm, C= 0.15 pF) and for the junction used in the experiment (R_N=72 Ohm, C=0.22 pF) in the 290 - 360 GHz band (Fig. 5). Minimum coupling loss of the junction used in this experiment is expected about 7 dB in the band 290 -320 GHz and degrades quickly out of this range (black line in Fig. 5). With a lower junction area and a larger current density minimum coupling loss may be expected 0.5 - 1 dB in a 30 GHz band around 345 GHz (gray line in Fig. 5).

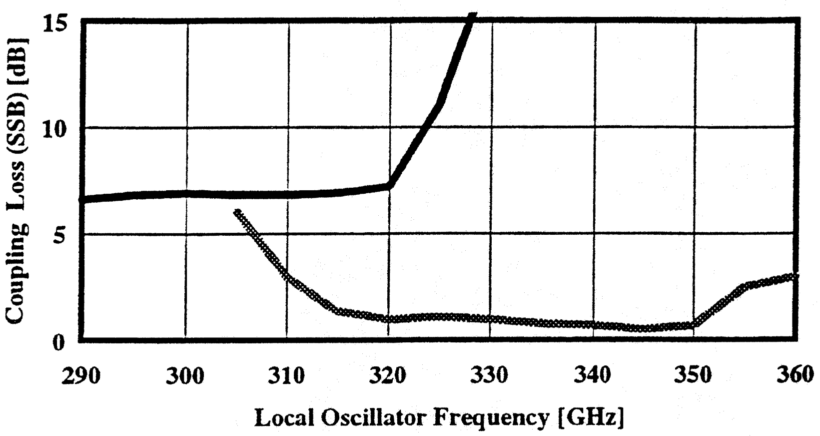

Fig 5 Coupling loss between the junction and the mixer input port calculated for the actual junction area and normal resistance (black line) and for the parameters used for the design of the mixer (gray line).

Experimental set-up

Experiments with the SINS mixer were hold in the receiver developed for the SIS Nb mixers. Receiver comprises an Infrared Laboratory liquid helium cryostat, SINS mixer, cooled HEMT IF amplifier, ambient temperature amplifier and the local oscillator. Local oscillator consists of the Carlstrom Gunn oscillator and Millitech quadrupler. Local oscillator power is injected at the mixer input by a cooled waveguide coupler. Receiver input window is in polyethylene and an infrared filter fixed at the 77 K shield is made in expended polystyrene form.

Receiver operation

Receiver noise temperature was measured in the standard ambient and nitrogen loads experiments. Minimum DSB receiver noise temperature 135 K was measured at 312 GHz when the junction was at 2.7 K temperature. An example of the receiver noise dependence on the local oscillator power is given in the Fig. 6. In this experiment the bias voltage is constant (1.8 mV) and the P_{LO} varied. This leads to a variation of the junction bias current. Current induced in the junction may be expected to be proportional to the LO power. One can mention an excellent 50 % allowance to the local oscillator power around the optimum noise point. Independence of the SINS receiver noise on the P_{LO} may give in the multibeam receiver a good tolerance to the coupling of the different mixers with a common LO source.

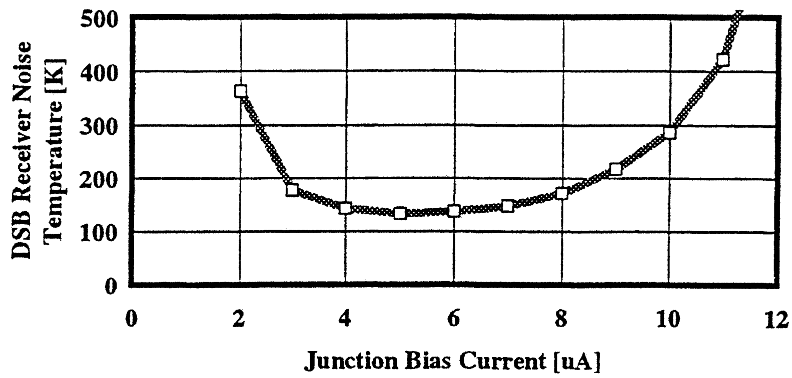

Figure 6. SINS DSB receiver noise for the different levels of the local oscillator power at 312 GHz. Bias voltage is fixed at 1.8 mV and the current in the junction follows the local oscillator power.

In the 290 - 320 GHz band measured DSB receiver noise temperature is quite uniform with the minimum about 135 K and the average level of 150 K (Fig. 7). SINS Mixer was tuned at each frequency to the minimum receiver noise. The frequency band of the low noise receiver operation is shifted to the lower frequency due to the junction large capacitance. It is the first demonstration of the low noise operation of a SIN mixer at the submillimeter wavelength.

Contributions of the different sources to the DSB receiver noise T_{Rec} may be discussed using a standard relation:

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

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 $G_M = G_C G_J$ denote the gains of the receiver input section and the mixer respectively; G_C and G_J the coupling of the junction with the mixer input and the junction conversion gain respectively. Receiver conversion gain is $G_R = G_{RF} G_M$.

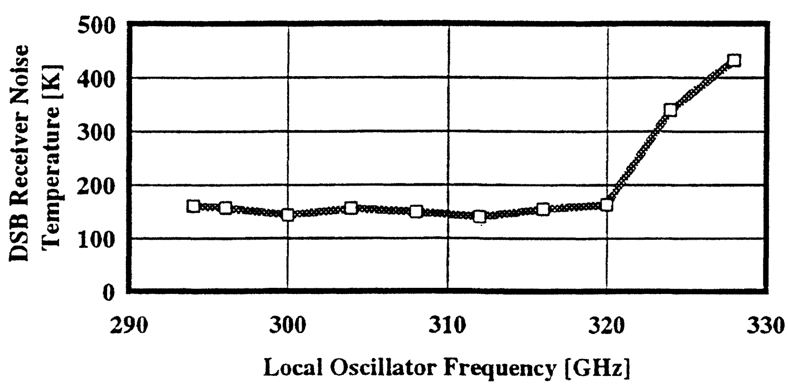

Figure 7. Measured DSB receiver noise temperature.

We measured receiver conversion gain and IF amplifier noise temperature in situ using the junction at the bias voltage behind the gap as a noise source for the calibration of the circuit [13]. Intermediate frequency chain noise temperature in the 1.25-1.75 GHz band is about 4 K. Maximum measured receiver conversion gain between the receiver input port and the IF port of the mixer is about -12 dB.

Measured SSB receiver conversion gain versus frequency dependence $G_{Rec}(F)$ between the reference plane at the cryostat window and the IF port of the mixer is presented in Fig. 8 by a black line. Receiver conversion gain in the 290 -320 GHz band is -12 ÷ -13 dB. Out of this band the mixer matching circuit is no more efficient and the reflection loss and loss in the mixer circuit becomes too important. The gray line in this figure is a calculated coupling gain G_C between the RF input of the mixer and the junction from the Fig. 5. Junction capacitance is included in the mixer circuit. Calculated variation of the coupling explains well the measured frequency dependence of the gain. One can note a nearly constant difference of 5 - 6 dB between the experimental data and the model prediction of the coupling. We may estimate the available mixing conversion gain $G_J = G_{Rec}/(G_C G_{RF})$ in the SINS junction as -5 ÷ -5.5 dB expecting the loss in the input section of this receiver $G_{RF} \approx -0.5$ dB. This estimation of the mixer conversion gain is in a good agreement with the G_J =-6 dB at 320 GHz predicted in [7] for a SIN junction with a similar I-V characteristic. However the noise of our receiver is larger than 10 K minimum predicted at 320 GHz in the same work.

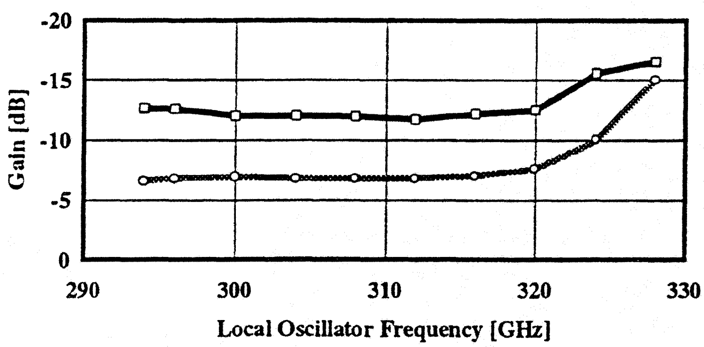

Figure 8. Measured receiver conversion gain (black line) and calculated coupling loss between the mixer waveguide input flange and the SINS junction RF resistance (gray line). The difference between this gain let us estimate the available conversion gain of about -6 dB in the SINS junction.

The first term of expression (1) $T_{RF}+T_M/G_{RF}$ is determined by a method proposed by R. Blundell et al [14] and Qing Ke and M. Feldman [15] for an SIS mixer. Receiver input section contribution in the receiver noise ($T_{RF}+T_M/G_{RF}$) is evaluated as a constant component in the linear relation between the SIS receiver noise and the receiver gain at a low level of the local oscillator power. This rule is based on the independence of the mixer output noise from the local oscillator amplitude at the tunnel junction predicted in [16].

Relation between the receiver gain $G_{Rec} = G_M G_{RF}$ and T_{Rec} measured with SINS mixer at 312 GHz is presented in Fig. 9. Receiver noise versus junction bias current for this experiment is given in Fig. 6. As with the SIS mixer the SINS mixer experimental $T_{Rec}(1/G_{Rec})$ may be well explained by linear function up to the local oscillator amplitude providing the minimum receiver noise temperature (135 K). Black line in Fig. 9 is a linear fit of $T_{Rec}(1/G_{Rec})$. Intersection of this line with the T_{Rec} axis gives $T_{RF}+T_M/G_{RF}$ = 30 K. In experiment with SIS mixer in the same receiver we find a similar value of $T_{RF}+T_M/G_{RF}$. All this confirms the validity of the methods proposed in [14, 15] for the case of the SINS mixer.

Output noise of the SINS mixer is determined according (1) with the measured $T_{RF}+T_M/G_{RF}$, T_{IF} and $G_R = G_{RF}G_M$. Output noise measured at the different frequencies is presented in Fig. 10. In a good agreement with prediction in [16] it is almost frequency independent. Moderate level of the SINS mixer output noise measured in our experiment ~13 K is very encouraging for the use of this devices in the low noise receivers.

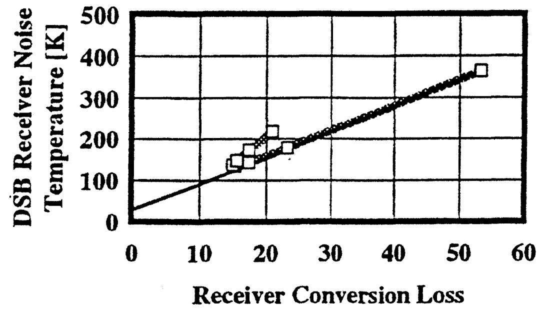

Figure 9. Measured SINS receiver DSB noise temperature versus receiver conversion loss. Noise to loss dependence is nearly linear at the local oscillator power below optimum.

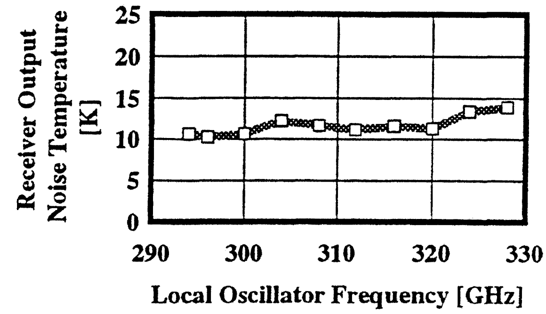

Figure 10. Measured receiver output noise temperature versus frequency. In a mixer with SINS junction T_{OUT} is nearly frequency independent when the mixer is tuned at the minimum of the receiver noise.

Comparison of the different components of the SINS receiver noise measured in our experiments shows that the SINS receiver noise is dominated by the term depended on the mixer output noise and receiver conversion gain. If the SINS mixer output noise is comparable with that of the SIS mixers, the receiver conversion gain may be improved. Actually the 135 K receiver noise comprises a dominate contribution of about 100 K produced by the output noise and multiplied by the receiver loss. Even a moderate reduction of the receiver loss may give an important improvement of the receiver noise. With the optimum SINS junction area and with a lower normal junction resistance the coupling loss and the receiver loss may be reduced for about 5 dB (Fig. 8). In these conditions the SINS receiver with the noise of about 60 K will be competitive with the best SIS receivers.

Thermal behavior of an SINS mixer

Thermal properties of the SINS junction are substantial for the use of the mixer with this device. If the absence of the pair current is a clear advantage of SINS against the SIS, an operation temperature well below 4.2 K normally used in SIN receiver [4] is a serious handicap. Architecture of a receiver with the cryogenics providing the temperature below the liquid helium temperature is complex and it use on the radiotelescope is more difficult.

For the best understanding of the optimum temperature for the SINS receiver operation the performance of a SINS mixer was studied in the 2.7 - 5.5 K range experiments. This range corresponds to the possible conditions in cryostats with and without He pumping. In all the 290 - 330 GHz frequency range it has been found that the receiver noise temperature strongly depends on the temperature.

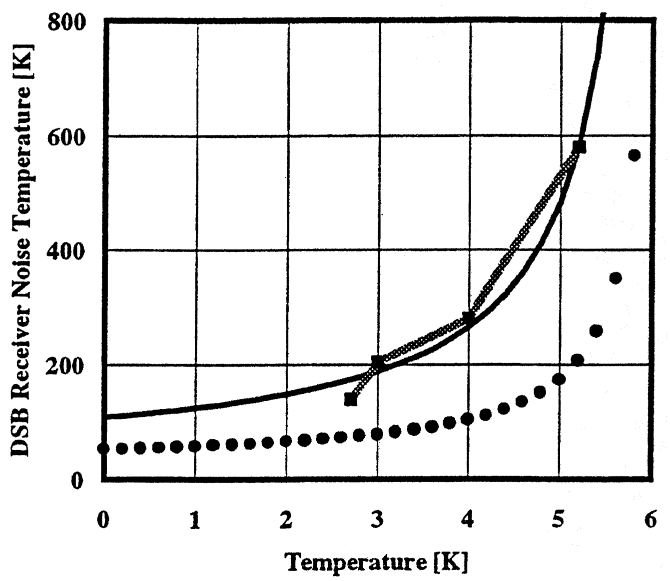

Figure 11. SINS Receiver DSB noise temperature at 312 GHz versus temperature of the junction. Experimental data (gray line) are in a good accord with the model (black line). Junction used in experiment has $R_N\omega C=30$. Dotted line is the model estimation of the receiver was noise with a better SINS junction with $R_N\omega C=9$. Note a smaller difference in the receiver noise temperature expected at 3 K and 4.2 K after optimization of the junction $R_N\omega C$.

In more details we present a typical temperature behavior of the SINS mixer measured in experiment at 312 GHz (Fig. 11). Mixer tuning and P_{LO} were optimized at each temperature in this test. In a 2.7 - 5.5 K temperature range DSB receiver temperature varied between 600 K and 135 K. The sources of this 450% receiver noise variation may be classified in terms of parameters of equation (1).

Receiver input section noise, receiver conversion gain and the SINS mixer conversion gain were measured at each temperature. Input section contribution is constant about 30 K except 2.7 K point where infrared filter was changed and RF loss in the filter reduced. Output noise of the SIN mixer has been found in this temperature range almost temperature independent (Fig. 12). The most part of the receiver noise temperature variation may be explained by the thermal dependence of the SINS mixer conversion gain. Mixer conversion gain temperature dependence is presented in Fig. 13. In the 2.7 - 5.5 K range G(T) dependence is quasi linear function. This understanding of the SINS mixer temperature behavior is illustrated in Fig. 11. In this figure we compare the measured DSB receiver noise temperature (gray line) and the receiver noise evaluated according (1) using a linear interpolation for G(T), a constant value for the mixer output noise temperature $T_{OUT}=14$ K, $T_{IF}=4$ K and a constant contribution of the receiver front-end section $T_{RF}+T_M/G_{RF} = 30$ K (black line). Interpolation is in a good agreement with experimental $T_{Rec}(T)$.

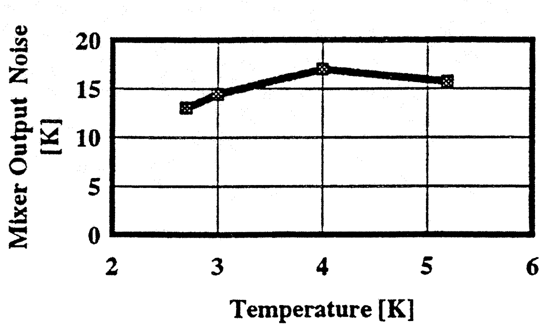

Figure 12. SINS mixer output noise temperature versus temperature of the junction at 312 GHz.

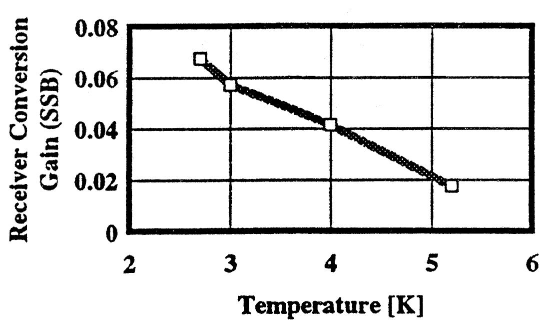

Figure 13. SINS receiver conversion gain versus junction temperature at 312 GHz.

Estimation of the SINS mixer possible thermal behavior with improved junction area definition ($R_N\omega C \approx 9$) is presented by a dotted line in Fig. 11. We expect the same quality of the I-V curve and the same thermal dependence of the mixer noise and gain as in our experiment. As before (Fig. 8) receiver conversion gain is expected to be improved by 5 dB after improvement of the junction $R_N\omega C$. In this conditions the SINS receiver noise is no more dominated by the term depended from the receiver conversion gain. Receiver noise thermal dependence with $R_N\omega C \approx 9$ may be less pronounced than in our experiment with $R_N\omega C \approx 30$ where the receiver gain is the main source of the receiver noise variation with the temperature. In Fig. 11 receiver noise calculated for a SINS junction with an improved $R_N\omega C$ is nearly the same at the liquid helium temperature (4.2 K) and at 3 K temperature. Improvement of the junction $R_N\omega C$ may not only reduce the SINS receiver noise but also may allow to use the SINS mixers at the liquid helium temperature without loosing the receiver sensitivity.

Conclusion

A low noise mixer with the SINS quasiparticule Nb/Al Oxide/Al/Nb junction is prepared and tested in the 290 -330 GHz band. Minimum DSB receiver noise temperature with the new mixer is about 135 K. No magnetic field was necessary to suppress the pair currents in the junction. Mixer operations may be stable, without Josephson effect related perturbations.

Available conversion gain of the RF signal in the tested junctions has been found to be close to -6 dB in a good accord with the theoretical predictions in literature for the mixer with a similar I-V characteristic [7].

SINS mixer output noise has been found to be constant and to be quite low (~13 K). Combination of a low output noise and a moderate conversion loss in the SINS mixer may allow to built the low-noise submillimeter receivers with the SINS mixers.

Junction technology is in progress and only the SIN junction with a quite large $R_N\omega C \approx 30$ was accessible for the test. With the SIN junctions having a moderate $R_N\omega C$ about 8-9 one can expect a significant improvement of the receiver performance up to 60 K DSB receiver noise temperature. Improvement of the SIN junction parameters may allow to built a low noise receiver with the SINS mixer at the liquid helium temperature.

Low noise operations of the SINS mixers at the submillimeter wavelength and the absence of the Josephson related perturbations are promising for the use of these mixers in the radioastronomy multibeam receivers in the 300 - 700 GHz range.

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