WIDE BAND FIXED TUNED AND TUNEABLE SIS MIXERS FOR 230 GHz AND 345 GHz RECEIVERS

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ABSTRACT

Extra-low noise SIS mixers have been developed for radioastronomy receivers in the 1.3 mm and 0.8 mm bands. A single backshort waveguide mixer design is used. The best receiver DSB noise temperatures achieved are about 55 K in the 1.3 mm band and about 72 K in the 0.8 mm band. The present mixer design uses SIS junctions in which parallel inductive tuning is implemented with quasi-lumped elements. The tuning structures have been optimized in order to allow to use the same junction area and current density for the submillimeter band as for the millimeter band. Experimental measurements agree with model predictions of the new SIS mixers performance. In particular, the same mixer can be used either in fixed-tuned, DSB mode, having an instantaneous bandwidth covering most of the waveguide band, or tuned to image band rejection (SSB) mode at each frequency. It has been found that if a mixer is tuned to SSB operation the minimum SSB receiver noise temperature is only about 75% of the SSB noise temperature in DSB regime. The new mixers have been installed at the IRAM 30-m telescope in Spain and at the telescope of the University of Grenoble in France.

INTRODUCTION

SIS mixer development is one of the main activities of the IRAM receiver group. The large investment made in the 30-m IRAM telescope at Pico Veleta and in the four 15-m antennas interferometer on Plateau de Bure gives a strong incentive for improving the receiver performance.

The objectives of the development are: to reduce the receiver noise, to extend the operating bandwidth, and to allow to tune the mixer either for single sideband (SSB) or for double sideband (DSB) operation. The reduction of the receiver noise temperature increases the data gathering efficiency of scheduled observations. An improved coverage of the atmospheric windows opens new possibilities for the observations. Mixer tuning with 10-15 dB image sideband rejection in all the mixer RF band improves the calibration accuracy of spectroscopic observations and the SSB system temperature through rejection of atmospheric noise.

Fixed tuned, wide band mixers are attractive for their simplicity of operation. This new kind of SIS mixer appeared some years ago and is currently an area of active development [1-3]. It is interesting for all the applications were DSB operation is acceptable or the tuning to SSB is impractical. The possible domains of application in radioastronomy are multibeam arrays or large interferometers. It may be also interesting for the installation on a satellite or airborne observatory.

The capability of fixed-tuned operation was one of the main design objectives of new mixer development in IRAM. The present design is universal. The same mixer may be used either fixed-tuned (DSB mode) or tuned to SSB mode. Single backshort tuning of this mixer allows one sideband rejection allover the mixer RF band

Below we present the new 1.3 and 0.8 mm SIS mixer developments. The principal mixer features are: reduced height waveguide, single backshort design, two SIS junctions array with individual tuning structures.

The use of this mixer in a receiver is simpler than the use of a mixer with two adjustable backshorts, but the stage of mixer circuit design is more complicated. If the RF band is relatively broad (25-30 %) and if the junction $R_N C\omega$ parameter is large an accurate mixer model is required to synthesize the mixer circuit allowing the correct mixer tuning (or tuneless operation) over all the band. A reduced height waveguide single backshort SIS mixer model reported before in [4] is used for the mixer circuit design.

The SIS junctions with the integrated inductive tuning let us use for the submillimeter band (0.8 mm) the same junction size and critical current density as for millimeter band (3-1.3 mm). For example it allows to get a good mixer performance in a 25% relative band with a factor $R_N C\omega$ about 14 at 350 GHz. It is about 14 times large then the value given by the well known relation for the optimal $R_N C\omega \approx \dfrac{400}{F[GHz]}$ [5].

In this work we first describe the receiver conversion gain measurements and the receiver and mixer noise estimation for a 345 GHz SIS receiver. Then a test of the noise temperature of the fixed tuned and the tuneable mixers over the 180-270 GHz and the 300-360 GHz band is presented. In the last section the operation of the new mixers on the telescopes is described.

SIS RECEIVER CONVERSION GAIN MEASUREMENT

The conversion gain measurement of an SIS receiver is important for the understanding of the mixer performance. Below we show how these measurements are used for the estimation of the mixer noise temperature.

The measured receiver conversion gain depends on the frequency, the mixer tuning, the junction current, the mixer block temperature etc. In our laboratory experiments the measured receiver minimum conversion gain (SSB) is normally between about 0 dB in the 3 mm band and -3 dB in the 0.8 mm band. The in situ measurement of the IF chain noise temperature is in a good agreement with the result of an independent measurement with a variable temperature load.

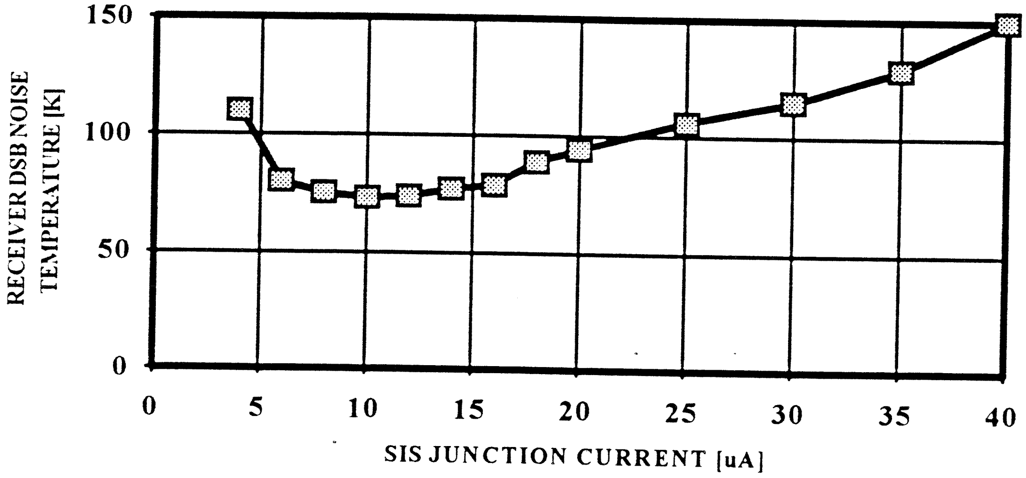


Fig. 1 SIS receiver DSB noise temperature at 318 GHz for different LO power levels as a function of the bias current. Junction bias voltage is fixed (4 mV). Junction temperature is 4.2 K.

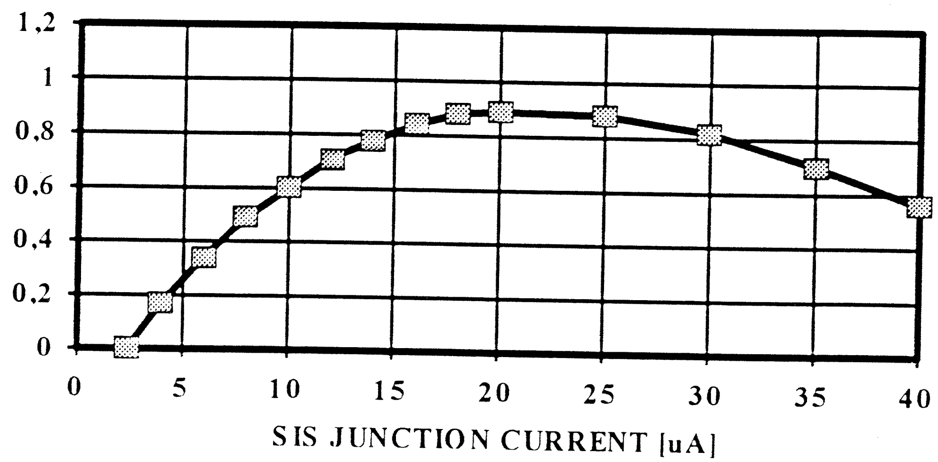


Fig. 2 SIS receiver SSB conversion gain at 318 GHz for different LO power levels as a function of the bias current. Junction bias voltage is fixed (4 mV). Junction temperature is 4.2 K.

The receiver conversion gain between the quasioptical input port and the input port of the first IF amplifier (behind an isolator) is determined in the same hot-cold loads experiment as the receiver noise temperature by a "shot noise" method [6]. In the same procedure the IF chain noise temperature is measured.

The conversion gain is calculated from the receiver IF power (P_{IF}) variation which occurs when the room temperature load (black body at T_{HOT}=295 K) is substituted at the receiver input port by the liquid nitrogen load (T_{COLD}=77 K). Then the temperature variation at the receiver input is 218 K and the equivalent noise temperature variation at the mixer output is proportional to receiver IF power variation. For the receiver in DSB operation the conversion gain (SSB) is calculated from the ratio of noise source temperature variations at the mixer output and at the receiver input.

$$Gr = \frac{1}{2}\frac{K*(P_{IFH} - P_{IFC})}{T_{HOT} - T_{COLD}} \tag{1}$$

The IF chain should be calibrated to determine the coefficient (K) of the equivalent temperature variation at mixer output to the IF power (P_{IF}) variation.

In our experiment the IF amplifier chain between mixer output and the IF power measurement plane is calibrated in situ using as a controlled noise source the unpumped SIS junction biased beyond the gap voltage. An SIS junction biased behind the gap voltage is in a normal state and may be considered as a parallel connection of the junction normal resistance and the junction capacitance. The junction normal resistance equivalent noise temperature is calculated for the different bias current levels from the resistance shot noise density converted to an equivalent temperature T ($h\nu << kT$). The coefficient (K) relating the temperature variation at mixer output to the IF power variation is determined from two IF power measurements with different junction current levels I_{J1} , I_{J2} as :

$$K = \frac{T_2 - T_1}{P_{IF2} - P_{IF1}} , \tag{2}$$

where T_1 and T_2 are the equivalent noise temperatures corresponding to the shot noise power available at the IF chain input for bias current levels I_{J1} and I_{J2}. The noise power available at the cooled amplifier input (behind an isolator) is calculated from the noise power available at the terminals of the SIS junction. The mixer block and IF chain equivalent circuit is used to calculate the junction coupling to the IF amplifier input port.

The IF chain noise temperature is calculated from the same data in a standard way as:

$$T_{IF} = \frac{T_2 * P_{IF1} - T_1 * P_{IF2}}{P_{IF2} - P_{IF1}} . \tag{3}$$

Figures 1-3 show the results of a 0.8 mm receiver test. In this test the receiver noise temperature Tr and conversion gain Gr are measured for the different local oscillator power levels at a fixed frequency (318 GHz). The junctions bias voltage is fixed (4 mV) and the bias current is controlled by the local oscillator power. Measured values Tr, Gr are presented as a function of the bias current. The test has been performed at the altitude of 2850 m, where the mixer block temperature is about 4.2 K instead of 4.8 K at the sea level, resulting in performances which are better than in laboratory.

The 1.2-1.8 GHz IF chain noise temperature measured in situ is 3.5-4 K The independent test gives 3.8 K..

The minimum receiver DSB noise temperature is 73 K and maximum receiver conversion gain (SSB) is as high as 0.9 (- 0.5 dB). It is the best result observed in our 0.8 mm receiver test. Junction mismatch to the receiver input and mixer output ports accounts for a loss about -1.5 dB at this frequency. Therefore, the mixer available gain about 1 dB. It is close to the theoretical prediction in [7] of the gain in optimum regime at this frequency.

In our experiments the minimum receiver noise temperature occurs at a lower local oscillator power level than the maximum gain. It can be explained by the increase of the shot noise contribution in the receiver noise temperature when the junction current follows the increase of the local oscillator power.

In fig. 3 the receiver gain corrected for the junction coupling to the IF chain is presented. The maximum of the curve is relatively flat and corresponds to a current about 5-6 times larger than the leakage current at the operating point. It is interesting to note that the gain may be rather large (0.7) down to a current of about only 1.5 times more than the leakage current.

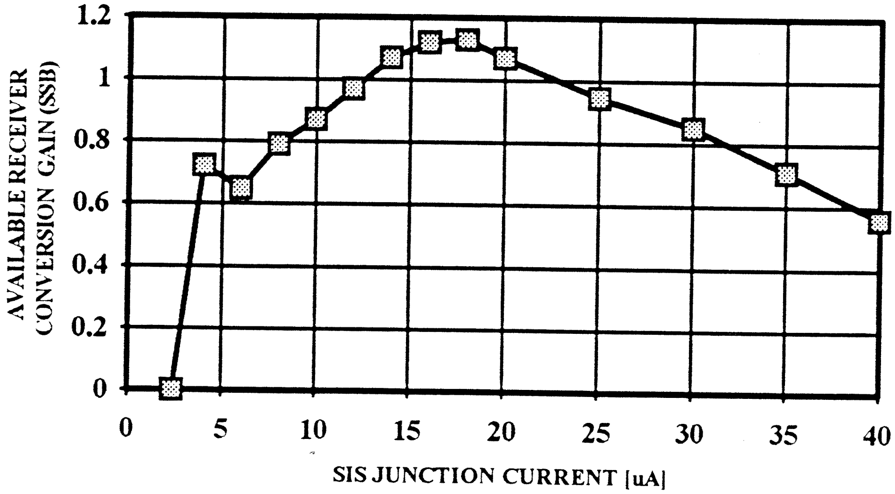


Fig. 3 SIS receiver SSB conversion gain at 318 GHz corrected for the junction to IF chain coupling.

SIS RECEIVER NOISE ESTIMATION

We use the standard relation for the receiver DSB noise

$$T_R = T_{ANT} + T_{MIX} + \frac{T_{IF}}{2G_R} \tag{4}$$

Where:

T_{ANT} is the equivalent noise temperature of the quasioptical system at the receiver entrance before the mixer. Usually a dual beam interferometer diplexer is used in IRAM receivers for the local oscillator power injection. The loss of this element is about 0.2 dB (15 K contribution in T_{ANT}). The plastic lens loss contribution (if it is not cooled) is similar. A cooled scalar corn contribution in T_{ANT} may be neglected.

T_{MIX} is the mixer DSB noise temperature.

T_{IF} is the IF chain noise temperature.

G_R is the receiver SSB conversion gain.

The receiver noise measured at 318 GHz can be broken down as follow:

T_{ANT} is about 25 K (15 K from the diplexer and 10 K from the plastic cryostat window; the mixer horn and lens are inside of the cryostat at 4.2 K stage); the measurement of T_{IF} gives 4 K; at optimal bias current (10 μA) SSB receiver conversion gain is G_R=0.6.

So, the minimum mixer DSB noise in this experiment is $T_{MIX} \approx 45$ K ($T_{MIX} = T_R - T_{ANT} - T_{IF}/2G_R$).

This value is about one order of magnitude larger than the minimum mixer noise at 345 GHz predicted in [7, 8]. Available mixer noise temperature remains still more than prediction, even corrected for the SIS junction to antenna coupling.. Corrected (available) mixer noise temperature $T_{MIX\,AV} \approx 38$ K is estimated according to:

$$T_R = T_{ANT} + \frac{T_{MIX\,AV}}{2G_C} + \frac{T_{IF}}{2G_C{*}G_M} \tag{5}$$

Where:

$T_{MIX\,AV}$ is the available mixer noise temperature.

G_C is the SIS junction coupling to the antenna. The coupling of the junction has been calculated using the mixer equivalent circuit for the different backshort positions and frequencies. At 318 GHz G_C it is estimated as 0.7 (SSB)

G_M is the mixer conversion gain; ($G_R = G_C \cdot G_M$).

The difference between the prediction of the optimal mixer noise and measured data may be related to the junction shot noise power injected in the IF chain. An estimate of the maximum shot noise can be derived by applying the standard shot nose formula, using DC bias current and the differential resistance of the pumped IV curve at the bias point. In the condition of the test at 318 GHz (fig. 1-3) it gives the equivalent noise temperature about 70

K injected in the IF chain and about 50 K contribution in the available mixer noise. The approximate agreement with the measured noise lends some support to our hypothesis.

JOSEPHSON EFFECT PROBLEM IN THE SIS MIXER

At some frequencies the Josephson effect may perturb the SIS mixer operation. If the $R_N C\omega$ product is large enough this happens when the Josephson oscillation fundamental frequency or one of its harmonics coincides with the mixer operating frequency. It results in a receiver noise increase and a perturbation of the pumped I-V curve. Usually these oscillations in the SIS junction may be suppressed if a magnetic field is applied. When a junction array is used, Josephson oscillations suppression may be more difficult due to possible asymmetries in the circuit. In this situation the oscillations in the different junctions are suppressed at slightly different field intensities and the mixer operation perturbation may be reduced but remains present.

A correct junction bias choice may improve the situation. It allows to use an SIS mixer with incomplete suppression of the Josephson effect by magnetic field and makes the choice of magnetic field density less critical. Diagram in the fig. 4 illustrates this. This drawing shows the frequency of the Josephson oscillation and its harmonics (up to 6 th) versus the bias voltage of a two junction array. Here we can choose fixed bias voltage to keep the Josephson oscillation frequency outside the RF mixer band.

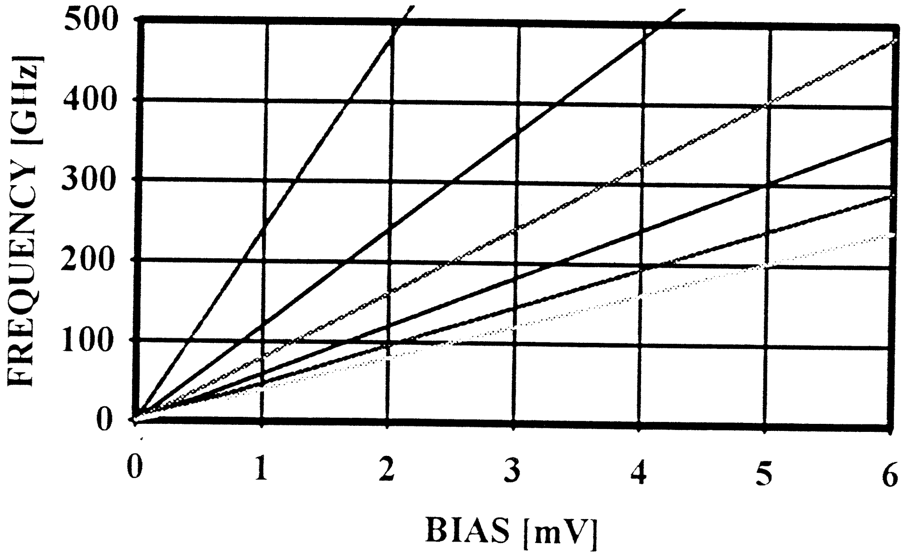
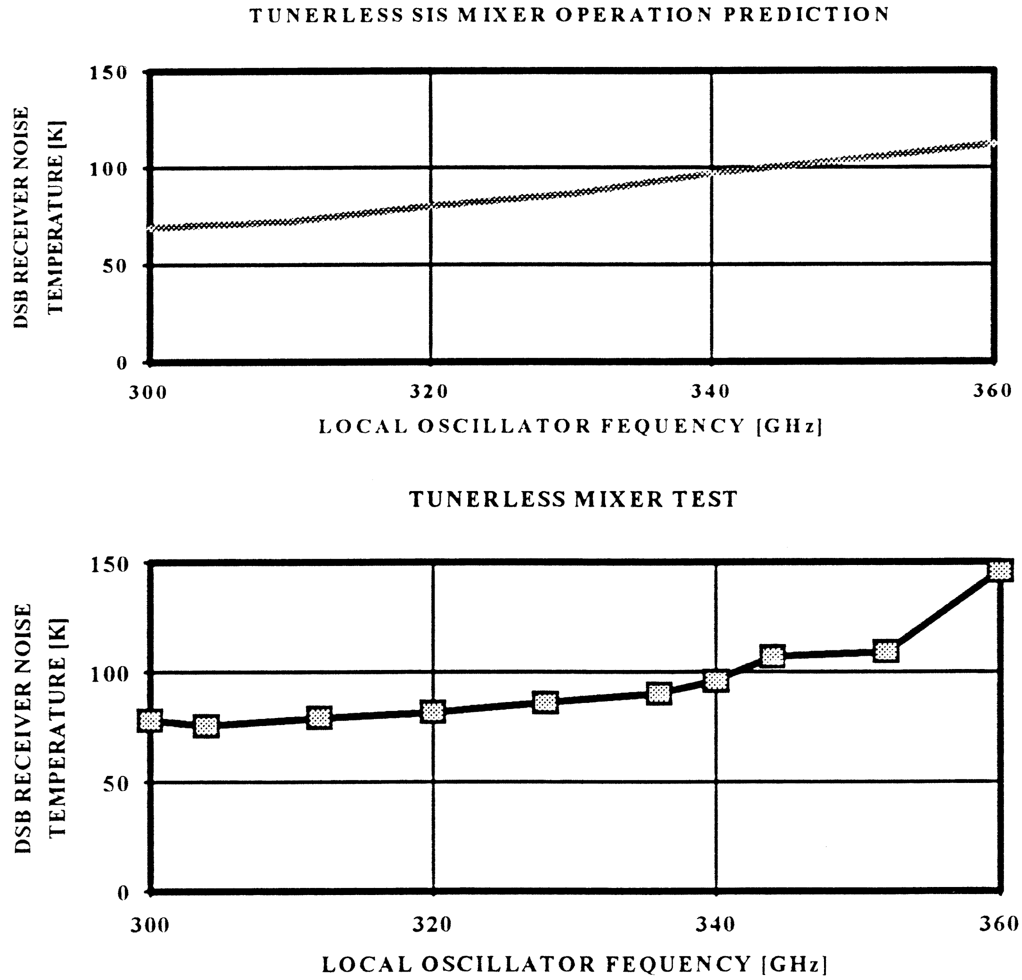


Fig. 4 Frequency of the first six harmonics of the Josephson oscillation.

For the 0.8 mm mixer fixed 4.0 mV junctions bias has been selected. The 4 mV vertical line in fig. 4 has the crossing points at 242, 323 and 484 GHz. Near these frequencies mixer operation may be perturbed by the 4th, the 3th and the 2th Josephson oscillation harmonics excitation. The 322 GHz frequency coincides with the absorption line in the atmosphere and is not of interest for the radioastronomy. So, the 4 mV fixed bias allows to use a two junctions SIS mixer in 260-370 GHz band without important Josephson effect perturbations. On the other hand in this frequency range the 4 mV bias is sufficiently close to the middle of the first photon step, the optimal operation point.

LABORATORY RECEIVERS TEST

Fig. 5 shows a comparison of predicted performance and laboratory measurements for the 0.8 mm fixed tuned mixer. Receiver DSB noise temperature varied between 75 K and 145 K in the 300-360 GHz range. For the receiver noise estimation the junction coupling to the antenna is calculated over the band. A mixer available noise temperature estimation from the preceding section is used. In fig. 6 the measured receiver conversion gain is presented.



TUNERLESS SIS MIXER OPERATION PREDICTION

TUNERLESS MIXER TEST

Fig. 5 Fixed tuned operation of the 0:8 mm SIS mixer.

The predicted mixer operation is in a good accord with the test result in all the 300-360 GHz band. Model prediction gives the band of the operation with the receiver DSB noise temperature below 150 K between 280 and 370 GHz but in the test the local oscillator was not available in the band 280-300 GHz. In this mixer a two Nb-Al oxide-Nb junctions array with the individual junction surface about 1 μm^2 and $RnC\omega \approx 5$ is used.

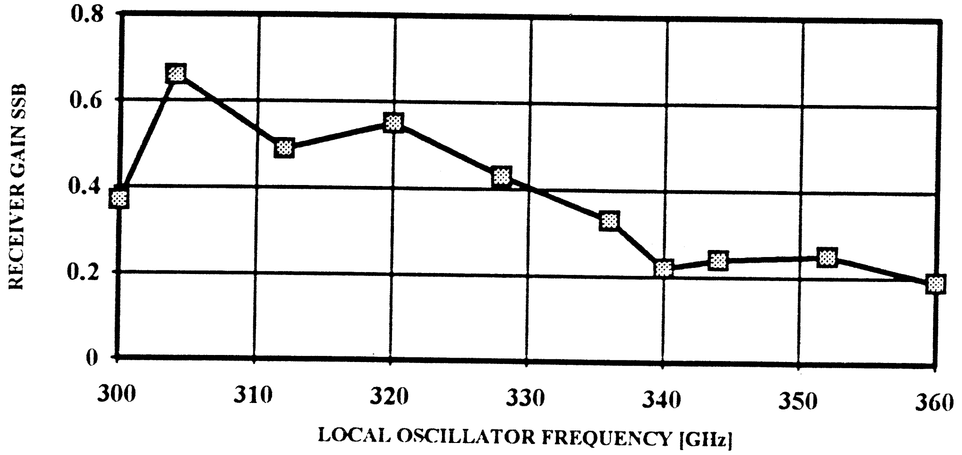


Fig. 6 Receiver conversion gain in 0.8 mm band (fixed tuned operation).

A similar design of the tuneable mixer allows to use in the same frequency range (320-360 GHz) the junctions with an individual area of about 2 μm^2 and $RnC\omega \approx 14$. The tuneable 0.8 mm mixer test is presented in fig. 7. Even though the bandwidth of this mixer is less than with smaller junctions, it is sufficient to cower the atmospheric transparency band around 345 GHz. This result is particularly interesting, because the fabrication of such junctions with traditional photolithography is relatively easy.

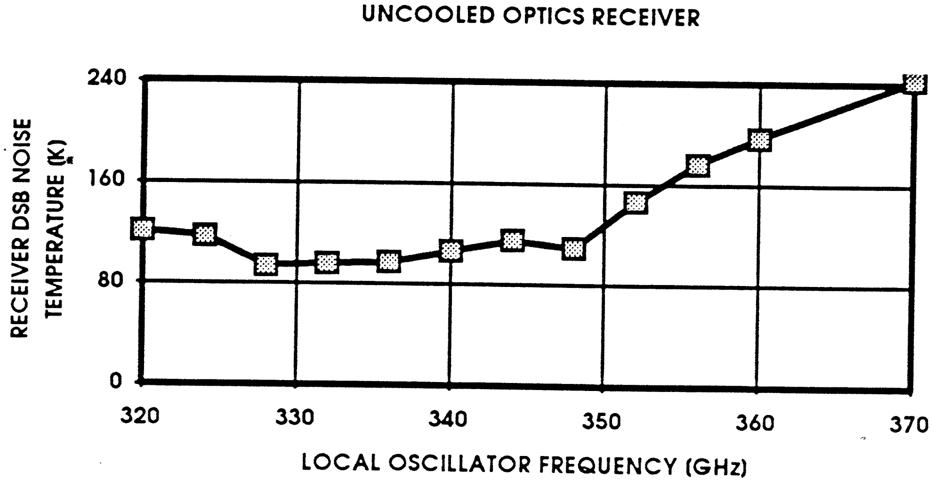


Fig. 7 A tunaeble 0;8 mm receiver operation. The junctionwith an individual area of about 2 μm^2 and $RnC\omega \approx 14$.

The test of a 1.3 mm fixed tuned mixer with uncooled optics is presented in fig. 8 (curve 1). In this receiver the diplexer and the lens are at the ambient temperature. Junctions with an area of about 2 μm^2 and RnCω≈5 are used in this mixer. The minimum DSB receiver noise temperature (70-80 K) achieved in fixed tuned operation (curve 1) may be improved by the mixer tuning only in a small fraction of the band (curve 2).

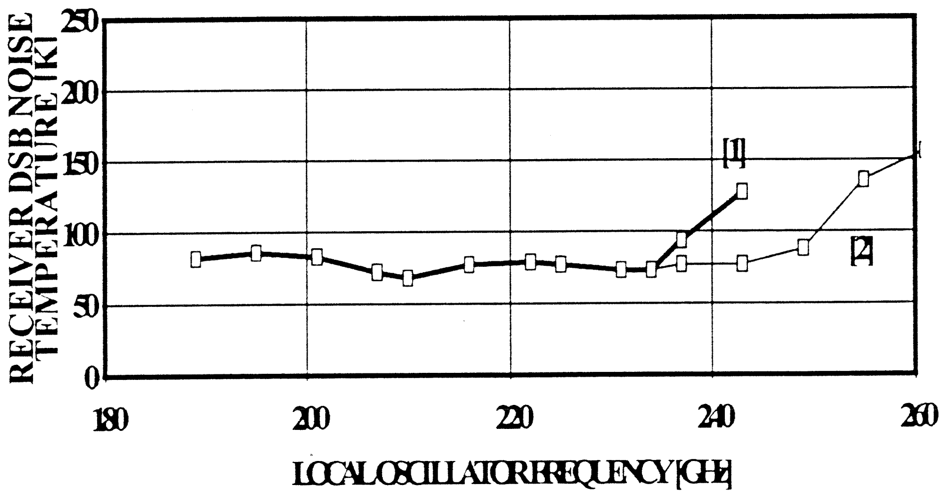


Fig. 8 Noise temperature of a 1.3 mm SIS mixer with a fixed backshort position (1) and with tuning (2)

When the cooled optics is used in the receiver noise temperature drops to the value of about 55 K in the 1.3 mm band (fig.9). In this receiver the local oscillator power is injected at the mixer input throw a cooled waveguide coupler. A plastic correcting lens of the mixer antenna is also cooled.

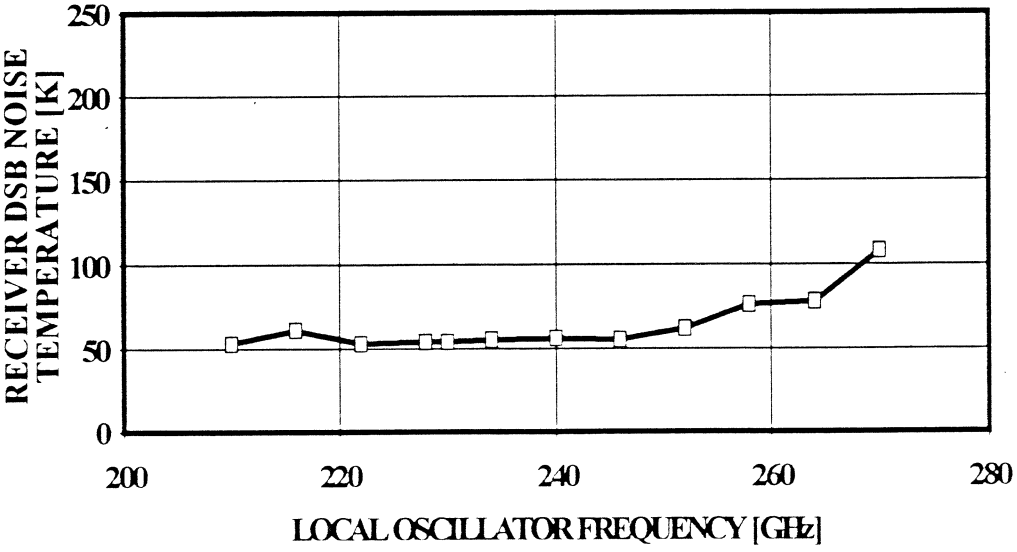


Fig. 9 The 1.3 mm receiver with a cooled optics and local oscillator power injection throw a cooled coupler.

The 1.3 mm receiver tuning to the SSB or DSB operation is presented in fig. 10 for a room temperature optics receiver. In this figure the DSB receiver noise temperature is given for the double sideband mixer operation and the SSB noise temperature for the mixer tuned for the single sideband operation. The SSB receiver noise temperature in SSB operation is about 150 % of the DSB noise temperature in DSB mode (or the SSB noise temperature of the tuned receiver is about 75% of SSB noise temperature of the receiver in wide band operation).

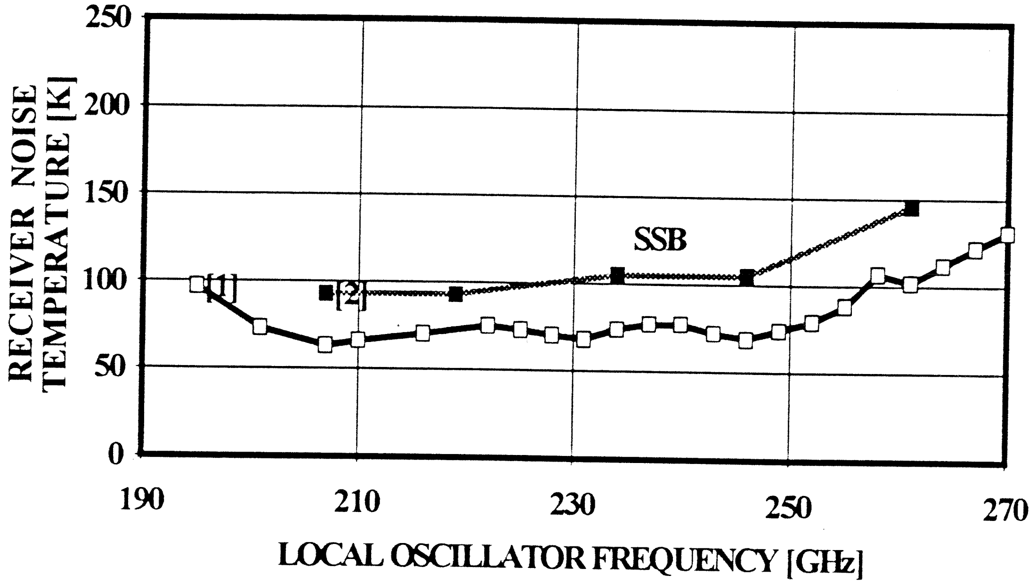


Fig 10 The tuning of a 1.3 mm receiver to the DSB and SSB operation

RECEIVERS ON THE TELESCOPES

Actually the new 230 GHz mixers are in use at two telescopes.

One SIS mixer is installed in September 1992 as a replacement of the Schottky-diode mixer at the Grenoble university telescope POM-2 [9] on Plateau de Bure in French Alps at 2500 m of altitude. It is a tuneable single-backshort mixer. Mixer is situated on the 4 K stage of the closed-cycle vacuum cryostat. Signal and local oscillator power are injected at the mixer entrance through the diplexer and uncooled lens. Measured at the telescope receiver DSB noise temperature is presented in fig. 11. In the band of receiver operation typical noise temperature is nearby 80 K.

The next 230 GHz mixer is installed at the beginning of 1993 at IRAM 30 M telescope at Pico Veleta in Spain as a replacement of the lead-junctions SIS mixer developed by R. Blundel [10]. The mixer is at 3.4 K stage in a helium gaze chamber of a traditional IRAM liquid helium cryostat with the uncooled optics [11]. For the needs of the spectrum observations the sideband rejections is required. Using the mixer model the distance between the backshort and the junction is optimised. It has been found that a far backshort position (about 5-6th resonance) is convenient to provide a sufficient variation of the junction to waveguide coupling in the frequency range between the two sidebands. Receiver SSB noise temperature achieved during the performed observations is presented in fig. 12. Normally the SSB receiver noise temperature is between 80 and 100 K. In SSB operation the upper sideband is rejected by -7-10 dB.

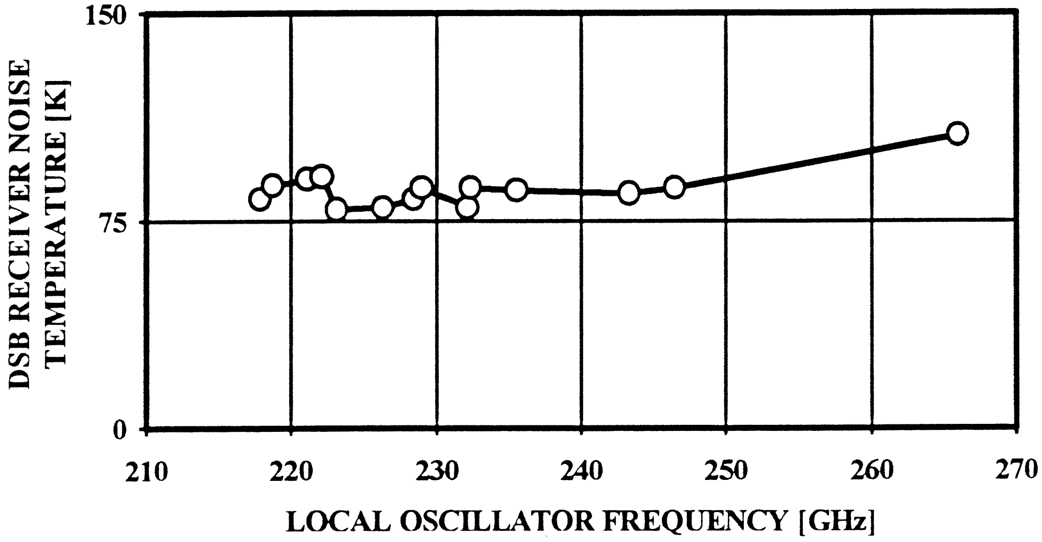


Fig. 11 Receiver with a developed SIS mixer at the telescope of Grenoble University.

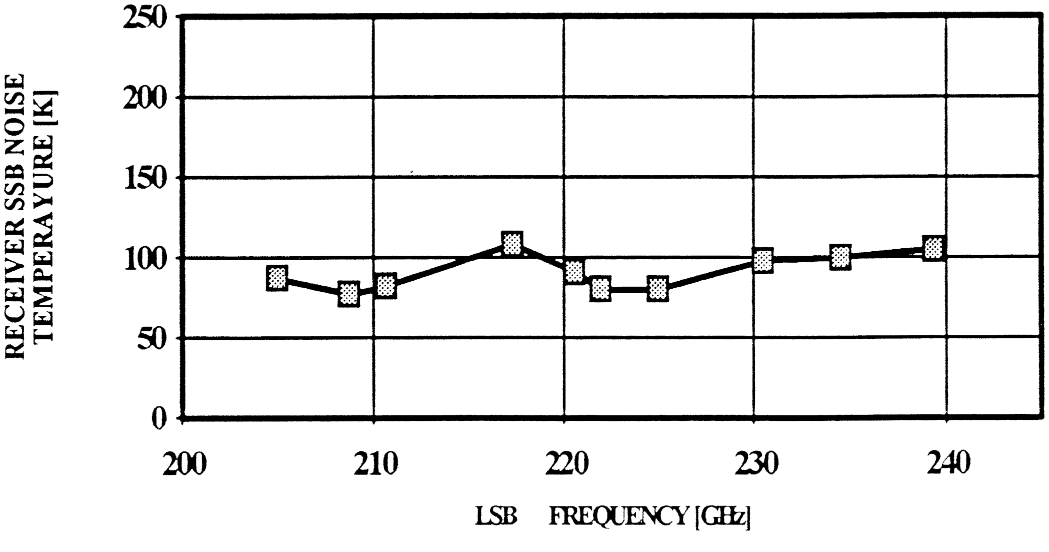


Fig. 12 Receiver with a new 1.3 mm mixer at IRAM 30-m telescope.

In the end of march 1993 a 345 GHz receiver with the new fixed tuned SIS mixer has been installed and tested at IRAM 30-m telescope. The receiver consists of the SIS mixer installed in the liquid helium Infrared Laboratory cryostat, the cooled IF amplifier situated in the same cryostat, the room temperature IF amplifier and the local oscillator. In this receiver we use the local oscillator earlier developed in MPIFR for the Schottky 345 GHz receiver. Local oscillator power is injected at the entrance of the mixer through dual beam interferometer diplexer. The mixer horn and the lens are at the 4 K stage of the cryostat. Intermediate frequency chain noise temperature is about 4K in the range 1.25-1.75 GHz.

At the telescope the fixed tuned receiver is tested in 320-360 GHz band (fig. 13). The noise temperature is found to be close to the laboratory test results (Fig. 5) and varied between 70 K and 130 K. Junction bias has been fixed at 4 mV. During the test no problem beard by the Josephson effect have been occurred. The minimum noise temperature of 70 K DSB is measured at 332 GHz. The system temperature (at the limit of the atmosphere) as low as 650 K has been achieved. Having the possibility of the low noise operation in the band between 280 and 360 GHz the new fixed tuned SIS mixer may be used as a supplement of the 1.3 mm mixer for the complete covering of the 190-310 GHz atmospheric window or for the operation in 330-360 GHz band.

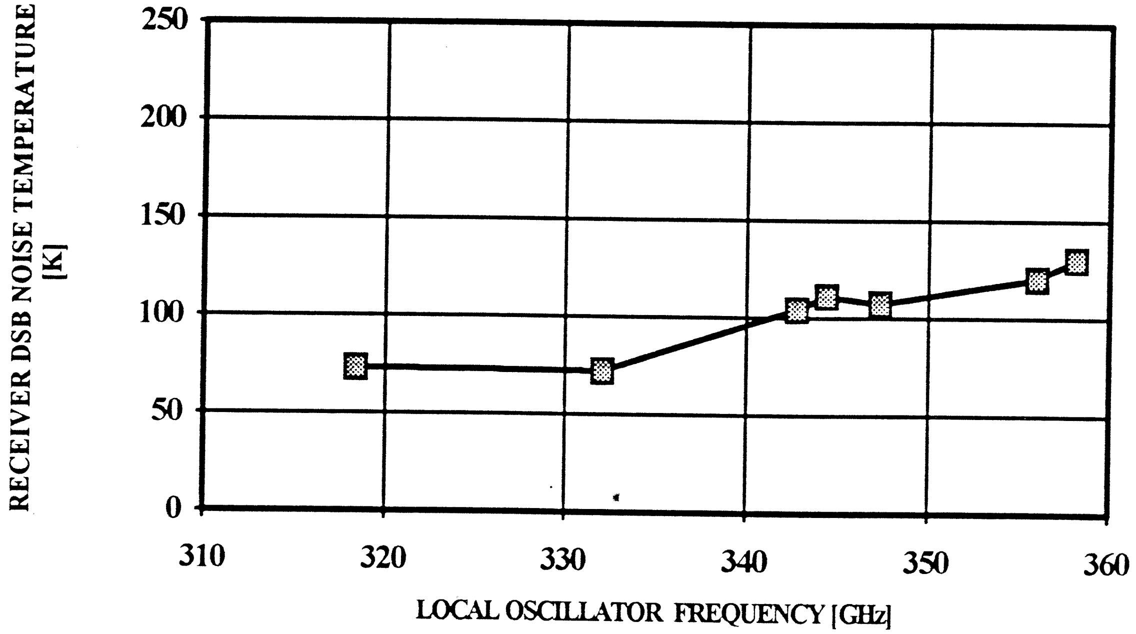


Fig. 13 Fixed tuned operation of the 0;8 mm SIS mixer on the IRAM 30-m telescope.

The junctions structures developed for a fixed-tuned 0.8 mm mixer have been provided to MPIFR (Bonn) and tested in their tunaeble two-backshort mixer being prepared for the

SMT (Arizona). Measured receiver noise temperature is close to 120 K over all the 320-370 GHz band.

CONCLUSION

The fixed tuned and tuneable SIS mixers for radioastronomy in 0.8 mm and 1.3 mm bands are developed. The receivers with this mixers are in use on the radiotelescopes. Receiver DSB noise temperature as low as 55 K and 72 K have been achieved in 1.3 mm and 0.8 mm bands.

The developed fixed tuned mixers may be used in futures multibeam arrays receivers.

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