Millimeter and Submillimeter SIS Mixers with the Noise Temperature Close to the Quantum Limit

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ABSTRACT

We report the ultra low noise SIS mixers built for the radio astronomy at millimeter wavelength (1.3 mm) and at submillimeter wavelength (0.8 mm). Mixers sensitivity is found to be close to one photon.

A mixer with the superconducting tunnel diode developed for 0.8 mm receiver is able to operate in 290-370 GHz band been fixed tuned. The receiver minimum DSB noise temperature of about 30 K corresponds to the 1.9hv/k level. Expressing this noise (or sensitivity) in photon number we get the four photons level. Measured mixer noise temperature in this receiver is about 10 K equal to 0.6hv/k level.

This receiver has been used for the observation in the winter 1994 period at 30 m IRAM radio telescope at Pico Veleta. Telescope system noise temperature of 500 K SSB has been achieved when the opacity was about 0.17.

In 1.3 mm band the minimum receiver noise is 32 K DSB (2.9hv/k level). Measured mixer DSB noise temperature is about 5 K (0.5hv/k level).

INTRODUCTION

The development of the ultra low noise receivers at submillimeter wave length is stimulated by the progress in radio astronomy instrumentation. In the present work we studied the possibility to reach quantum limited detection with the superconducting tunnel quasiparticle mixer

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receiver around 345 GHz and 230 GHz, the frequency of the CO 3-2 and CO 2-1 transitions often used for the observation in radio astronomy.

The quantum noise level (hv/k) or the number of photons $N=2T_{rec\ DSB}/(hv/k)$ may be used as a reference for comparison of the different receiver sensitivities at different frequencies. From the literature we know the DSB receiver results around 3hv/k (N≈6) at the lower frequencies. At 115 GHz the best published result is 17 K (3.1 hv/k) DSB receiver noise temperature [1]. Around 150 GHz the best result is 23 K DSB (3 hv/k) [2].

The aim of this work is to extent equivalent good quality of the receiver operation to higher frequencies.

345 GHz RECEIVER

RECEIVER DESIGN

The heterodyne receiver consist of the Superconducting Tunnel Diode mixer mounted with the first Intermediate Frequency amplifier at the 4 k stage of the liquid helium Infrared Laboratory cryostat, of the ambient temperature second IF amplifier and of the local oscillator. Local oscillator power is injected on the waveguide mixer input port through a cooled waveguide coupler. The mixer operates in all the receiver band without tuning and the only one tunable part of the receiver is the local oscillator.

SIS MIXER DESIGN

The goal of this mixer design was to get the fixed-tuned operation around 345 GHz (280-370 GHz band). It is a single backshort waveguide mixer. In the mixer block the waveguide height is reduced to the quarter of the standard size. In this mixer we use two 0.9 square micron seriesly connected Nb- Al oxide-Nb junctions with RωC≈6. Critical current density is about 8 KA/cm^2. The individual inductive tuning elements are integrated with the junctions. A new version of a non contacting backshort is developed for the reduced waveguide height mixer block. Magnetic field has been applied to the junctions in order to suppress the Josephson current.

The mixer backshort once fixed in the mixer block remains in the optimal positions. For this backshort position the receiver exhibits a low noise operation across ~30% band. Estimation of the SIS junctions mach calculated for the optimal backshort position is presented in Fig. 1. Mixer operation is in a good accord with the model prediction. The standard equvalent circuit of the mixer block has been used to optimize the mixer circuit without the scale-model experiments.

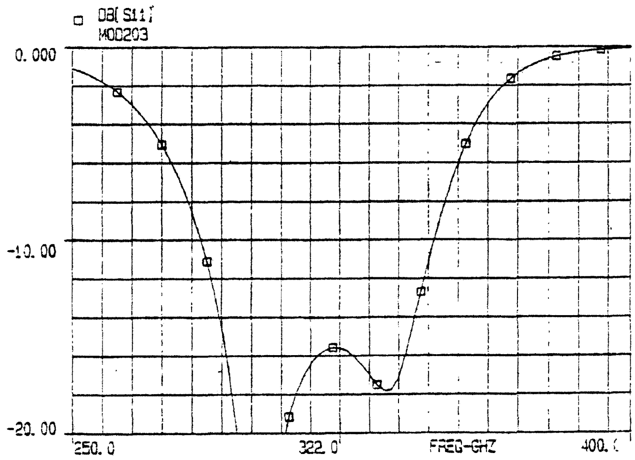

Fig. 1. Estimation of the SIS junction mach for the optimal backshort position in the fixed tuned mixer.

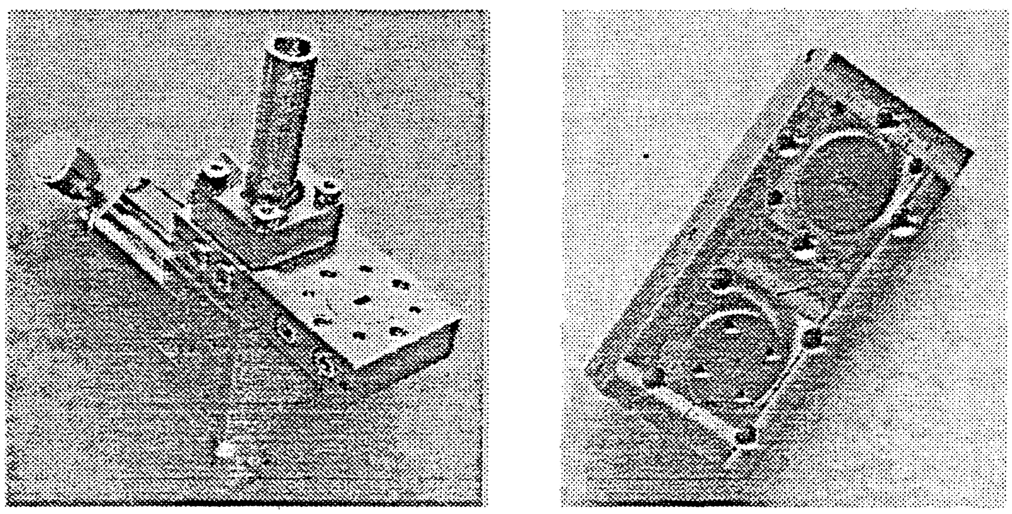

Fig 2. The 280-370 GHz mixer with the corrugated horn and the LO coupler (left) and the waveguide coupler prepared for the local oscillator power injection (right).

Mixer with the corrugated horn and the LO waveguide coupler is presented in Fig 2 (left). The waveguide 17 dB coupler for 260-380 GHz is presented in Fig 2 (right).

Measured mixer DSB noise temperature is 10 K (0.6hv/k level). According to this data mixer sensitivity may be estimated as one photon.

MIXER NOISE MEASUREMENT

In the mixer test we measured the receiver conversion gain G_R, using the calibration by the junction shot noise, and the receiver optics contribution to the receiver noise T_{FE} according to [3],[4]. Measured receiver noise temperature and conversion gain are presented in Fig. 3 as the function of the junction current. In this experiment the bias voltage is fixed and the current is tuned by the local oscillator power

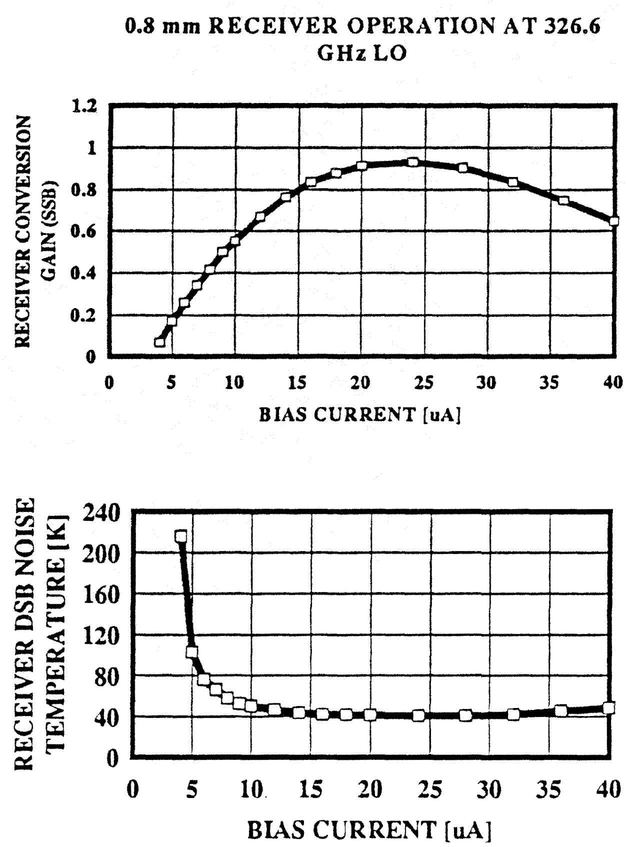

Fig. 3 Laboratory test of the receiver gain and noise(mixer at 4.8 K). Bias voltage is fixed and the current is tuned by the local oscillator power

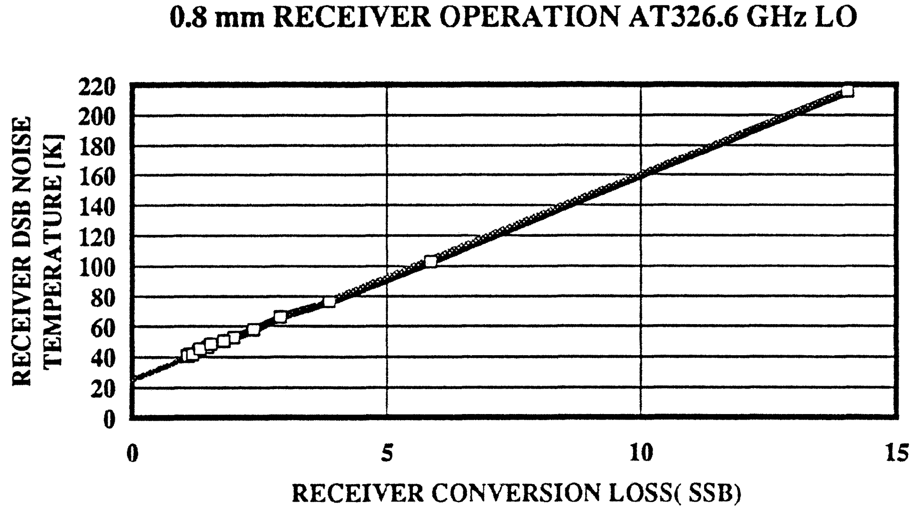

Fig. 4 Receiver noise versus receiver loss for the different local oscillator power levels. Bias voltage is fixed.

Relation between the receiver noise temperature and the receiver loss is nearly linear for all values of the junction current (Fig. 4). Receiver optics contribution to the noise according to this data is about T_{FE}=27 K [4]. The minimum receiver noise in this test is T_R=39 K (mixer at 4.8 K), receiver conversion gain is about G=1 and the IF chain noise is T_{IF}=4 K. Mixer noise is determined as usually:

$$T_M=T_R-T_{FE}-T_{IF}/2G$$

and T_M=10 K.

RECEIVER TEST

In the receiver test the equivalent noise temperature has been determined in the standard ambient load and nitrogen load experiments. At the telescope (Pico Veleta 2850 m) the cold load temperature drops with the nitrogen temperature, to 75 K. The best receiver sensitivity has been achieved at the telescope (2850 m altitude) where the mixer physical temperature was 4.2 K about 0.5 K lower then in laboratory at the sea level. Minimum receiver DSB noise temperatures are presented in the Fig 5. In the Fig 6 the receiver sensitivity is given in the photons.

For the noise measurements, the output receiver power is integrated over the whole 500 MHz wide IF band. The best measured value of the Y factor in this experiment was about 3. It corresponds to the receiver DSB noise temperature 30 K (1.9hv/k level at 325 GHz). Expressing this noise (or sensitivity) in photon number we get the four photons level N=4.

The cold and hot load temperatures have to be corrected for the first order term coming from the Planck relation

$$\Delta T_{H,C} \approx -\frac{1}{2}\frac{h\nu}{k}.$$

It gives at 330 GHz correction in the receiver noise: $\Delta T_{R_H} = -\Delta T_{H,C} = +8K$

The reflections on the surface of the cold load give the opposite effect:

if Y=3 and reflection is of about -17 dB $\quad \Delta T_C \approx +6K$ and $\quad \Delta T_{R_C} \approx -9K$

The receiver noise corrections coming from the last two cold and ambient load temperature corrections seems to be nearly in balance in the conditions of our receiver test.

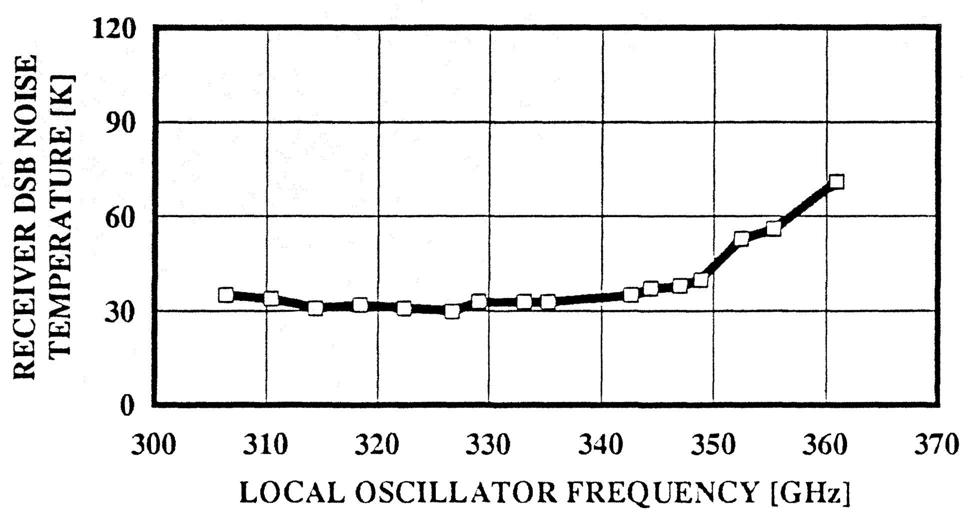

Fig 5. Fixed tuned receiver DSB noise temperature

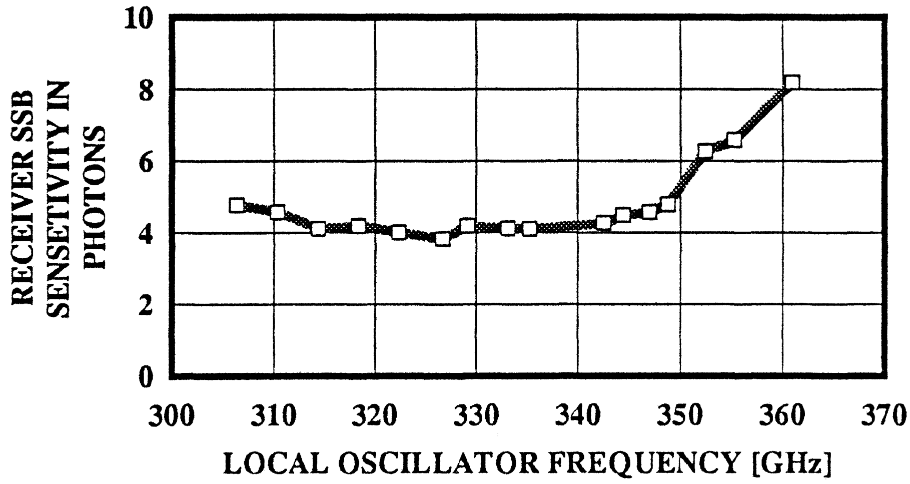

Fig 6. Fixed tuned receiver sensitivity in photons.

An example of the receiver DSB noise behavior in the intermediate frequency band 1250-1750 MHz is given in the Fig 7 for the 325 GHz LO. This curve is measured at the radio telescope with an autocorrelator. In the curve we can see a subdivision of the band to the regions with a small difference in noise level, specific imperfection in the autocorrelator measurements (so called "platforming"). In this measurement the middle DSB noise temperature is about 32 K. The receiver response in the 500 MHz IF band is rather constant (variation of about ±1K).

0.8 mm RECEIVER OPERATION ON THE 30 M RADIOTELESCOPE

Receiver has been used for the observation at IRAM 30 m radio telescope at Pico Veleta in the mountains of Sierra Nevada (Spain) in February 1994. The 30 m telescope is equipped with the multiplexing quasioptical system for the parallel observation in 3 frequency bands. It was possible to operate in parallel in 0.8 mm, 1.3 mm and in 3 mm bands. The system noise temperature out of the atmosphere in 0.8 mm band is strongly dependent on the frequency, the weather and the telescope orientation. The best SSB system noise temperature during the observation period was 500 K at 330 GHz.

In Fig 8 is presented an example of the 13CO(3-2) transition spectrum of the IC342 measured with the new receiver at the telescope (by courtesy of Andreas Schulz et al).

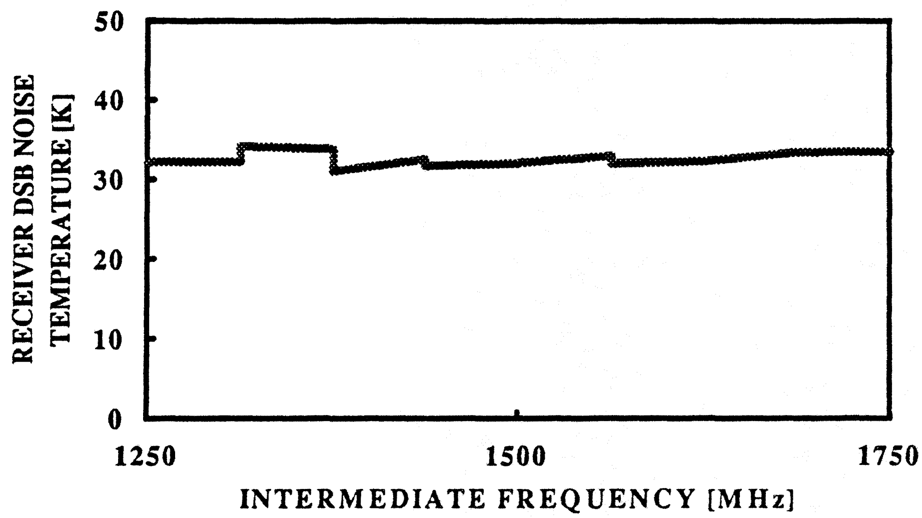

Fig 7. Receiver DSB noise temperature in the 500 MHz intermediate frequency band measured with an autocorrelator at the 30 m IRAM radiotelescope.

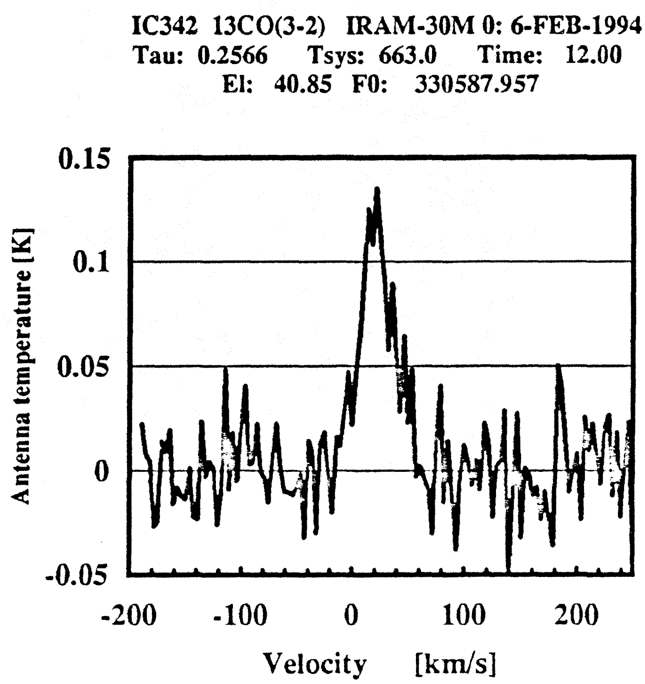

Fig 8. The 13CO(3-2) transition spectrum of the IC342 measured with the new receiver at the telescope (by courtesy of Andreas Schulz et al)

230 GHz RECEIVER

SIS MIXER AND RECEIVER DESIGN

The 1.3 mm mixer was tested in laboratory in the receiver similar to the 0.8 mm receiver. It is a receiver with the cooled optics, with the local oscillator injection through the cooled waveguide coupler, and with the 1.2-1.8 GHz IF 5 K amplifier.

The goal of this mixer design was to get the low noise operation in 205-250 GHz band. It is a single backshort waveguide mixer. In the mixer block the waveguide height is reduced to the quarter of the standard size. In this mixer we use two 2 square micron seriesly connected Nb-Al oxide-Nb junctions with $R\omega C \approx 6$. Critical current density is about 3.5 KA/cm^2. The individual inductive tuning elements are integrated with the junctions.

RECEIVER AND MIXER PERFORMANCE

1.3 mm receiver noise temperature is presented in the Fig. 9. The minimum receiver DSB noise temperature is 32 K at 230 GHz.

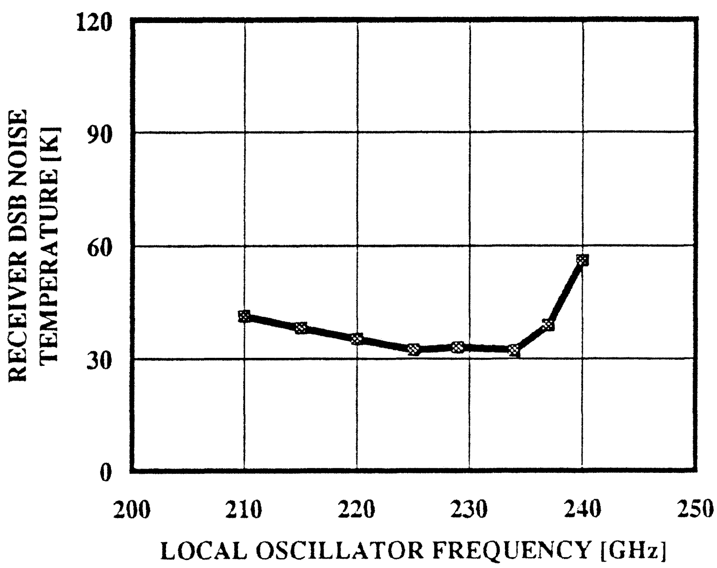

Fig. 9. Receiver DSB noise temperature in the 1.3 mm band. Cooled optics receiver with the IF amplifier noise temperature 5 K.

Mixer noise temperature was measured with the IF amplifier noise temperature 10 K. In this test at 230 GHz receiver noise is 36 K and IF chain contribution to receiver noise is 5 K. Receiver optics contribution at 230 GHz is found to be close to 27 K according [3,4] (Fig. 10). Mixer noise temperature is about 5 K

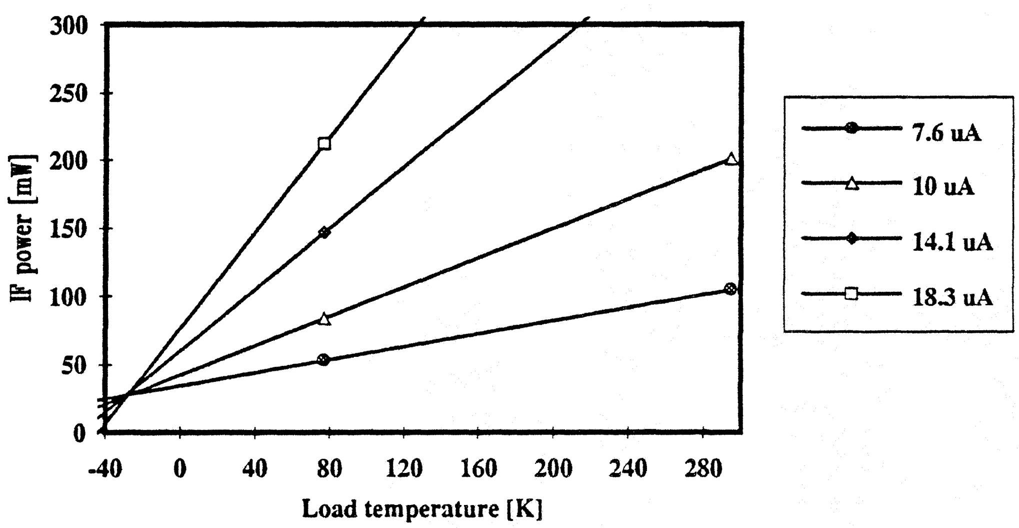

Fig 10. Receiver IF output power for the different junction currents and the different noise temperatures of the load before the receiver. According to [3,4] the intersection point gives the contribution of the optics to the receiver noise.

CONCLUSION

In this work the possibility to achieve the four photon receiver sensitivity at submillimeter wavelength has been shown. The minimum receiver DSB noise temperature is 30 K at 330 GHz

The mixers sensitivity about one photon was demonstrated around 230 GHz and 345 GHz.

The new version of the fixed tuned superconducting tunneling diode mixer covering the relative band of 30% around 345 GHz seems to be useful for the application in ground-based and airborne radioastronomy receivers.

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