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A three photon noise SIS heterodyne receiver at sub millimeter wavelength

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***Abstract*—An ultra low noise single sideband SIS receiver has been prepared for radio astronomy at the sub millimeter wavelength λ≈0.85 mm. The minimum single sideband receiver noise temperature of 48 K corresponds to 3 ħω/k or equivalent number of 3 photon of noise. The minimum single sideband SIS mixer noise temperature is about 20 K, close to 1.2 ħω/k, or one photon of noise. The SIS mixer uses Nb/AlOx/Nb junctions with a Josephson critical current density of 9 KA/cm² and with the area of about 0.9 μm².**

The receiver has been tested at the 30 meter IRAM radio telescope in the winter seasons of 1997 and 1998. The observations at the radio telescope are speeded up by a factor of two to three with the new receiver.

I. INTRODUCTION

The possibility of approaching the quantum limited sensitivity for heterodyne detection using a quasi particle tunnel Superconductor Insulator Superconductor (SIS) junction was predicted by J. R. Tucker in 1979 [1]. With the progress of the receivers developed for the radio astronomy at millimeter and sub millimeter waves in the last years [2] the possibility to reach this sensitivity become a question not only of a theoretical interest, but also of a big practical importance [3].

The push for the most efficient use of the radio telescopes, the high cost of observing time, and the high pressure factor on observing time are motivating a further improvement of receiver sensitivity in submm wave radio astronomy.

The importance of a further progress in receiver sensitivity for ground based radio astronomy is illustrated in Fig. 1 using typical parameters of the IRAM 30 meter radio telescope at 345 GHz. The telescope is situated at 2850 m altitude in the mountains of Sierra Nevada, Spain. In Fig. 1 the relative increase of observing time required for detection of an astronomical signal is presented as function of receiver noise temperature. The radio telescope observation time is normalized to the time expected with a zero receiver noise. We use a standard relation for estimation of observation time t required to achieve a certain precision ΔT of measurement of the brightness temperature of a radio source:

$$t = \frac{1}{B}\left(T^*_{Sys} / \Delta T\right)^2 \qquad (1)$$

where B is the predetection bandwidth and T^*_{Sys} is the telescope system noise temperature referred outside the atmosphere. System noise T^*_{Sys} at 345 GHz is calculated for

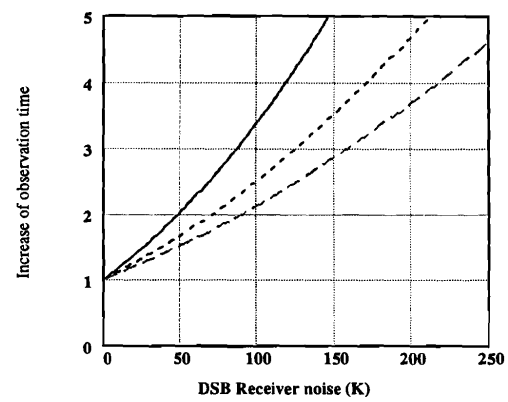

Figure 1. Estimation of the IRAM 30 meter radio telescope observation time versus receiver noise at 345 GHz in different weather: solid line - precipitable water vapor in is 0.5 mm (excellent winter weather), dotted line - 2 mm (good winter conditions), and dashed line - 4 mm (average winter conditions). Radio telescope observation time is normalized to the time expected for the telescope with zero receiver noise. Observation time strongly depends on the receiver noise down to 25 K receiver noise, comparable with the quantum limit ħω/k=16 K.

excellent winter conditions (0.5 mm precipitable water vapor (PWV)), for good winter weather (2 mm PWV), and for typical winter/good summer conditions at the IRAM 30 m telescope (4 mm PWV). The telescope forward efficiency is 0.75 and the elevation has been assumed to be 45°.

One can see a strong influence of the receiver sensitivity on the observation time needed in these typical weather conditions down to below a 30 K receiver noise temperature (figure 1), close to 1.8 ħω/k. In working on the development of receivers with a sensitivity so close to the theoretical limit it is important to know the exact value minimum possible receiver noise.

The quantum limit of heterodyne receiver noise temperature was recently studied taking into account the zero-point fluctuations according to the model of black body radiation of Callen and Welton [4]. It has been found [5] and lately confirmed in [6] that the basic limitation to the heterodyne SIS receiver equivalent noise temperature in single sideband (SSB) observation is:

$$T_{RecSSB\,\min} = \hbar\omega / k \qquad (3)$$

Whereas the minimum noise of a double sideband (DSB) mode of observation is:

$$T_{RecDSB\,\min} = \hbar\omega / 2k, \qquad (3)$$

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contrary to the levels $\hbar\omega/k$ and zero predicted before with the Planck black body model for single and double sideband receiver operation respectively.

The receiver noise Trec may be expressed as a number N of incident photons, doubling the output signal of the receiver [7]. The ratio N serves to compare the different low noise receivers operating in the different bands. The same value for N is obtained by comparing the receiver noise with the quantum limit of receiver noise: $N=T_{rec\ SSB}/(h\nu/k)$.

In our previous work we presented a four photon noise double sideband SIS receiver [8] used at the IRAM 30 m radio telescope in 1993-1995. It was a double sideband receiver with a broad band fixed-tuned SIS mixer. For the new receiver descibed here the SSB noise is about three photons, *i.e.* only three times above the quantum limit of $\hbar\omega/k$. This improvement of receiver sensitivity is due to the rejection of the image band in the new SIS mixer.

The importance of the SSB mode of operation of SIS receivers for radio telescope performance is illustrated in Fig. 2. Here is shown an estimation of the speed-up of observations at the IRAM radio telescope with a SIS mixer tuned for single sideband operation as compared with double sideband operation. The receiver noise is calculated as the sum of the receiver optics noise and of the noise of the mixer with IF chain. Here we suppose a low noise contribution from the receiver optics of T_{opt}=20 K. The noise contribution of the SIS mixer with IF chain is supposed to be doubled, when tuned for single sideband operation [9]. This gives a relation between the receiver noise under single and double sideband tuning used to obtain the data of Fig. 2:

$$T_{RecSSB} = 2T_{RecDSB} - T_{Opt} \qquad (4)$$

The system noise is calculated for the same telescope parameters and for the same typical weather conditions as in Fig. 1.

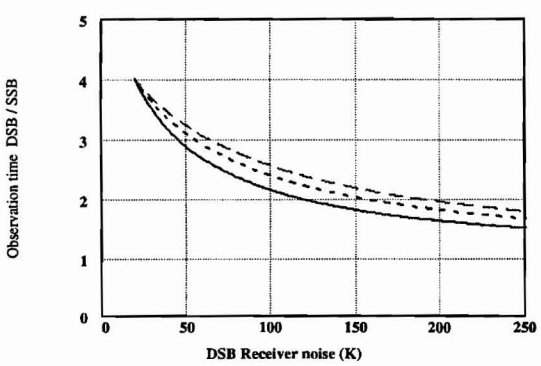

Fig. 2. The speed-up of the observations at a radio telescope with a SIS mixer tuned for SSB operation in comparison to the observation time with the same SIS mixer tuned for DSB operation. The parameters of the radio telescope and atmospheric conditions at 345 GHz are the same as in the Fig. 1. An important speed-up of the observations with the SSB tuning of the SIS mixer is expected only for SIS receivers with a relatively low initial DSB noise, below 80 K.

The possible improvement of the radio telescope observing time is not strongly dependent on the weather and is far from an "evident" factor of four (figure 2). The observation speed-up with SSB tuning is between three and two for a reasonably good DSB SIS receiver noise, below 80 K. The best radio telescope system operation improvement with the SSB tuning occurs for the same DSB receiver noise temperature of about 30 - 40 K, as achieved in our previous work on DSB SIS receiver [8]. This observation gives a motivation of the present work on the single sideband SIS receiver.

II. SIS JUNCTIONS

For frequencies exceeding about 300 GHz junction areas below 1 μm^2 are desirable. In the fabrication process the junction area is commonly defined by square or round resist stencils. To work with stencil size below 1 μm^2 is troublesome. Such small round or square stencils are often not stable enough to withstand the various fabrication steps, in particular the reactive ion etching. Damaged stencils result in too large variation of the individual junction size on the wafer. In addition, the lift-off process after SiO or SiO_2 sputter deposition is difficult or even not possible.

Sub micron devices have been fabricated using special techniques. One is to replace the simple resist stencil by a more stable two-layer stencil consisting of electron beam resist with an SiO_2 layer on top of it [10]. Another technique employs well defined underetching of a larger photoresist stencil [11]. We have adopted the use of photoresist lines of sub micron width which are more stable than corresponding round or square stencils [12]. A good test of this method is that square junctions of sub micron size can be obtained which is almost impossible when square resist stencils are employed.

The fabrication of the SIS mixer chip circuit starts with the deposition of a Nb1-Al/Aloxide-Nb2 trilayer in a photoresist mask defining the low-pass filter for the IF output. The Nb1 layer is 120 nm thick. Twenty minutes after its

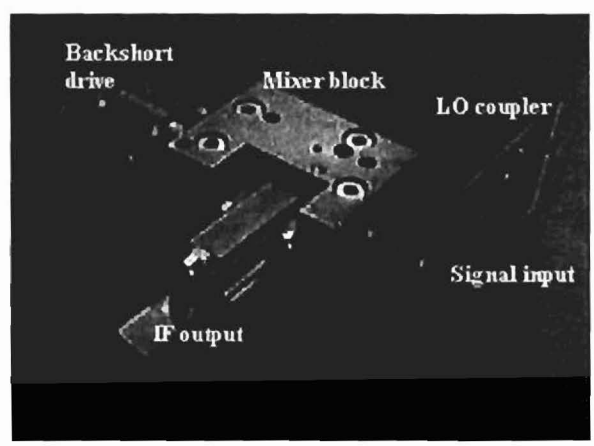

Figure 3. SIS receiver module with the mixer block, the waveguide coupler for the local oscillator power injection and the mixer backshort drive.

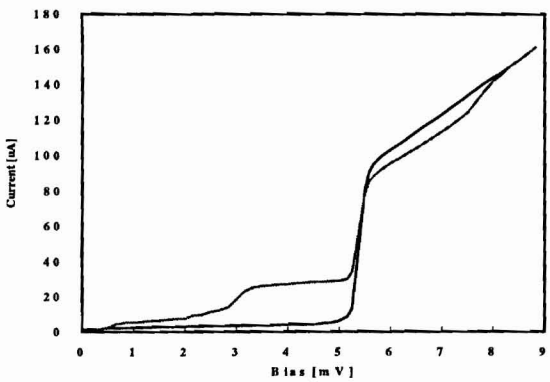

Fig. 4. SIS junction Current - Voltage characteristics with and without LO power at 330 GHz.

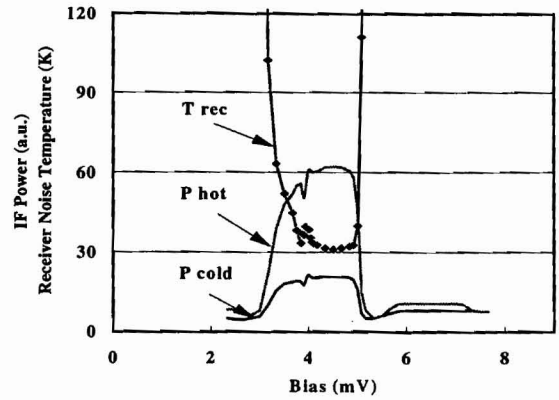

Fig. 5. Operation of the DSB SIS receiver at 330 GHz.

deposition a 6 to 8 nm thick Al film is sputtered in 6 s at 240 W. The oxidation of the Al film is then performed in the sputter chamber using pure oxygen. The junctions prepared for this work are from a wafer which was oxidized at 1 Pa for 10 min. The current density is about 9000 A/cm². The oxidation is followed by the deposition of a 60 nm thick Nb2 film. For the definition of the junctions lines are first patterned on top of the trilayer using Höchst AZ5214E as positive resist and the Karl Süß contact mask aligner operating at 400 nm light wavelength. Then the unprotected parts of the Nb2 film are etched away to obtain long junctions. They are passivated by liquid anodization and a sputter-deposited 180 nm thick SiO_2 film. After lift-off resist lines are patterned orthogonal to the long junctions, and liquid anodization as well as SiO_2 deposition is repeated. The last step involves the deposition of a tuning structure whose center part serves as a wiring layer.

III. SIS RECEIVER DESIGN

The receiver comprises a liquid helium cryostat, a SIS mixer, a cooled HEMT IF amplifier, an ambient temperature amplifier and the local oscillator. The local oscillator consists of a Gunn oscillator and a tripler. The local oscillator power is injected at the mixer input by a cooled waveguide coupler. The cooled intermediate frequency amplifier used in experiment has about 7 K noise temperature in the frequency range of 3.5-4.5 GHz [13]. An isolator is fixed between each SIS mixer and its first IF amplifier. The receiver input window with anti reflection grooves is made of polyethylene and an infrared filter in expanded polystyrene foam is fixed to the 77 K shield. The mixer block is at physical temperature of about 4.5 K.

In the new receiver the upper sideband is rejected using the tuning of a single backshort in the SIS mixer. Compared to a quasi optical image band filter this technique allows one to reject the image band noise with a minimum increase of the receiver noise. In order to simplify the sideband rejection we

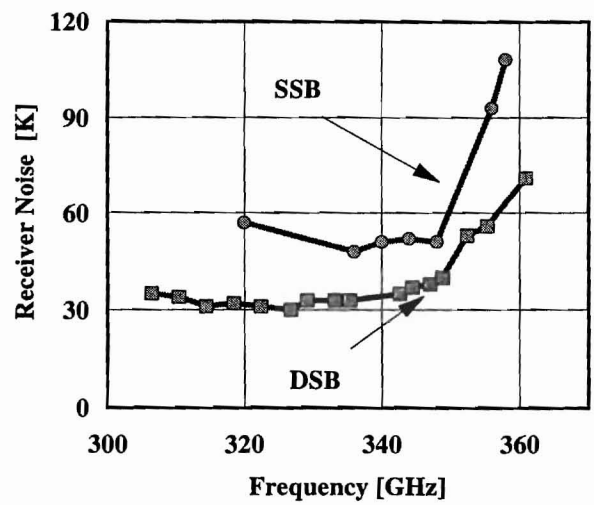

Fig. 6. Double and single sideband SIS receiver noise temperature measured in front of the cryostat window.

increased the central frequency of the IF band from 1.5 GHz to 4 GHz. The 4 GHz IF amplifier developed by D. Gallego in Centro Astronomico de Yebes (Spain) has a 1 GHz bandwidth and the 7 K noise temperature. A general view of the SIS receiver is presented in Fig. 3.

The new receiver single sideband noise temperature is 48 K at 330 GHz when the double sideband noise is about 30 K around 320 - 340 GHz (Fig. 4-6).

IV. SINGLE SIDEBAND SIS RECEIVER AT THE RADIO TELESCOPE

The single sideband SIS receiver was used at the IRAM 30 m radio telescope in the mountains of Sierra Nevada, Spain in the winter seasons of 1997 and 1998. With the new receiver the minimum radio telescope system noise was significantly reduced. In the reference plane above the atmosphere (at the star scale) Ta^* it is about 400 K (Fig.7).

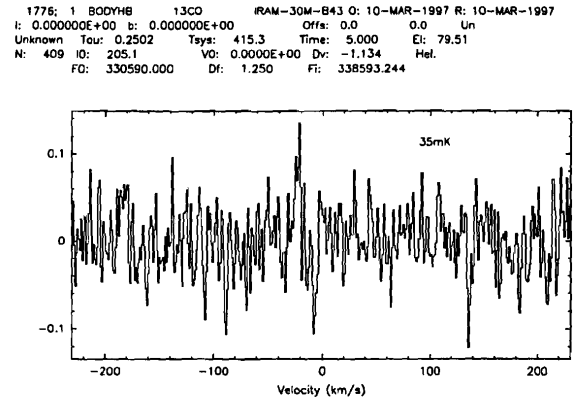

Figure 7. SSB receiver operation at the IRAM 30 m radio telescope. The radio telescope system noise at the star scale is 415 K. The r.m.s. noise level is 35 mK after 5 minutes of integration time.

An example of two radioastronomical spectra obtained from the same source with the new receiver in DSB and SSB mode of operation are plotted in Fig. 8. This data serves to measure the sideband rejection in the receiver. At 330 GHz we used as a reference source the $^{13}CO(3\text{-}2)$ spectral line of the Orion-IRC2 star forming region. The two spectra are measured with and without upper sideband (USB) rejection. The spectral lines coming from the upper sideband, such as CH_3OH at 338.4 GHz, are rejected by about 7 dB.

The speedup of the observations with the new receiver is between two and three, dependent on the weather.

V. Summary

We present a single sideband SIS receiver developed for 0.85 mm wavelength and tested at the 30 m diameter IRAM radio telescope. For the first time the single sideband receiver noise of 48 K measured at 330 GHz is only three times above the quantum limit to the sensitivity of a heterodyne receiver. In the SIS mixer we used a Nb/Al oxide/Nb two junction array with individual inductive tuning. The individual junction area is 0.9 μm^2 and the critical current density is 9 KA/cm^2. In the new receiver the upper sideband is rejected using the tuning of a single backshort in the SIS mixer. The receiver sideband ratio is measured at 330 GHz using as a calibration source the $^{13}CO(3\text{-}2)$ spectral line in the Orion-IRC2 star forming region. The speedup of observations with the new receiver is between two and three, dependent on the weather. The receiver noise Trec may be expressed as a number N of incident photons, doubling the output signal of receiver. The ratio N serves to compare different low noise receivers operating in different bands. The same value is obtained by comparing the receiver noise with the quantum limit of receiver noise: $N = Trec\ SSB/(\hbar\omega/k)$. The new receiver SSB noise is about three times above the quantum limit of $\hbar\omega/k$, *i.e.* only three photons.

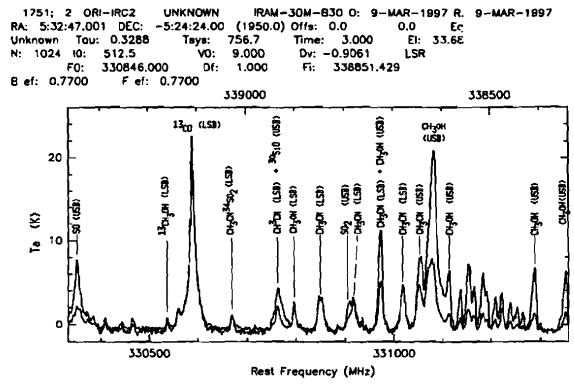

Figure 6. The SSB receiver at the IRAM 30 m radio telescope. The two superposed spectrum are measured with and without upper sideband rejection.The receiver sideband rejection at 330 GHz is measured using as a reference source the $^{13}CO(3\text{-}2)$ spectral line of Orion-IRC2. The spectral lines coming from the upper sideband, such as CH_3OH at 338.4 GHz, are rejected by about 7 dB.

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