Fixed tuned waveguide mixers around 450 GHz, 670 GHz and 810 GHz for a dual channel receiver.

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We developed a series of three SIS waveguide mixers for the frequency bands 440-500 GHz, 630-690 GHz and 760-820 GHz. The mixers have noise temperatures of approximately 80 K in the 490 GHz band, 130 K around 660 GHz, and about 900 K from 770 GHz to 820 GHz. The waveguide mixer blocks are fixed tuned, robust and easily and quickly to fabricate. The waveguide horns are commercially available. We use $Nb\text{-}Al_2O_3\text{-}Nb$ SIS junctions with an area of approximately 0.8 μm^2, a current density of about 15 kA/cm^2 and an all niobium integrated tuning structure. The micro stripline tuning structure consists of a series resonant stub followed by an impedance transformer. The two lower frequency mixers cover the full bandwidth of the respective atmospheric windows . The operating band of the high frequency mixer is presently limited by the local oscillator. The 430-500 GHz, and the 760-820 GHz mixers have been used very recently in a two channel receiver for radio astronomic observations at the Submillimeter Telescope Observatory (SMTO) .

1 Introduction

In recent years SIS mixer technology has developed rapidly [1]. The frequency range of the mixers has been extended from a few hundred GHz until above 1 THz [2] and their sensitivity has been increased substantially. Up to 700 GHz a state of the art mixer now has a sensitivity of around five times the quantum limit.[3],[4]. Up to 1 THz the sensitivity of SIS mixers is now larger than that of the Schottky mixers that were in use until recently [5].

A crucial factor in this development is the niobium microstructure technology that is used to make the SIS junctions. Excellent quality of the $Nb\text{-}Al_2O_3\text{-}Nb$ SIS junctions is necessary for quantum limited mixer performance [6] The problem of the geometric capacitance of the SIS contact, which short circuits most of the high frequency signal, has been solved by a making the junction areas smaller and by using a variety of integrated tuning elements [1].

An important requirement for the tuning structures is that they have very low loss, as loss will degrade the mixer performance. Therefore these structures are usually also made of niobium, and become superconducting at the operating temperature of the junction. Above the gap-frequency of superconducting niobium, which is around 700 GHz, the losses in niobium tuning structures start to increase rapidly with frequency. At present it seems that up to approximately 800 GHz a niobium integrated tuning structure will show the best results, whereas at higher frequencies normal metal structures will have a lower loss.[7]

Contrary to integrated tuning structures , Nb-Al_2O_3-Nb SIS junctions continue to function as quantum mixers above the gap-frequency of niobium.[8]. They will in principle be usable until just below two times the niobium gap frequency.

As with the integrated tuning structures, the mixer mounts also have been developed in some variety. There are waveguide mounts [2], [4] and quasi-optical mounts [3] with and without additional adjustable tuning elements. General conclusions about the optimum mixer mount cannot be drawn. But an important aspect of the whole field developing in various directions at different institutes is that the understanding of how to build an SIS mixer has increased enormously. The comparison between design and reality has been tested more often. This has resulted in a more mature SIS mixer technology which facilitates designing a state of the art SIS mixer, tailored to the application, from scratch.

We present here design and measurements at a series of three waveguide mixers for the frequency bands , 430-500 GHz, 630-690 GHz, and 760-820 GHz. The mixers are made for use in a dual channel receiver with a permanent 430-500 GHz channel and alternately 630-690 GHz or 760-820 GHz. Requirements on the mixers were state of the art performance, robust quality and the possibility to be made in house at low cost. We developed waveguide mixer blocks without adjustable tuning elements, similar to a design presented by Blundell et al [9]. While the highest frequency is only just above 800 GHz, we use niobium integrated tuning structures to tune out the junctions geometric capacitance.

2 Mixer Design

2.1 Waveguide mixer blocks

Initially we choose a waveguide mixer mount, as opposed to a quasi optical one, because of the possibility to incorporate an adjustable tuning element. Adjustable tuning elements are used with great success in waveguide SIS mixers up to frequencies of 810 GHz [2], [10].

Experiments at 800 GHz with a mixer block with an adjustable backshort fabricated at our institute [11] showed that reproducible fabrication of a reasonable quality backshort proved to be difficult and very time consuming. Furthermore the wear of the backshorts is one of the main causes of degradation or failure of the waveguide mixers at 230 GHz and 350 GHz that are used in the dual channel receiver at KOSMA, Gornergrat, Switzerland [12]. This problem is likely to become worse at higher operating frequencies. In addition, the quality of the backshort is always a problem in the simulation of the mixer performance. It generally cannot be measured independently from the mixer noise temperature. This caused, for example, a large uncertainty in the interpretation of our first noise measurements at 800 GHz .

This made us reconsider the use of an adjustable backshort. Excellent results have been reported on fixed tuned waveguide SIS receivers [4],[13]. The main concern of a fixed tuned design is that the bandwidth of the mixer has to be large enough. For ground based astronomy this means the bandwidth of the atmospheric window.

The general way to achieve a wide coupling bandwidth is to design the dimensions of the waveguide, the substrate channel and the detector substrate with metallization in such a way that the antenna impedance of the mixer mount is almost constant over a large bandwidth. For an SIS mixer this is preferably equal to a low real impedance, say 30 Ω. In order to achieve this, a reduction of the waveguide height is necessary. In addition, the dimensions of the substrate channel, and the metallization on the junction substrate forming the RF-filter and the probe in the waveguide have to be chosen appropriately.

For 600 GHz and 800 GHz the design of the mixerblock is made for the existing junction fabrication mask. With the mask, the metallization is determined and also the width and height of the substrate channel cannot be varied freely anymore. We found that we can still achieve a reasonably constant impedance over a 10 percent bandwidth if we bring the backshort close enough behind the junction. We use a reduced (half) height waveguide (330μm x 90μm) in the fundamental mode. For a backshort distance of 80 μm behind the junction the impedance is given in Fig. 1B. The impedance is measured in a 250 times larger scale model. Unlike Blundell et al.[9] we do not use a suspended substrate. The junction is glued at the bottom of the substrate channel.

After good experience with this mixer design at 660 GHz (section 4.2) we decided to scale the design to 450 GHz and 800 GHz. At the lower frequencies the design is more critical because the fractional bandwidth of the mixer is higher. Consequently the RF-filters and the metallization in the waveguide have been redesigned. The optimum antenna impedance, measured in the model for a backshort distance of 100 μm behind the junction substrate, is given in Fig. 1A.

2.2 Integrated tuning structures

To match the SIS junction impedance to the fairly constant impedance of the mount, a broad band integrated tuning structure is necessary. It was shown that a series inductive tuning of the junction geometric capacitance, followed by a two step quarter wavelength transformer is one of the broadest possibilities [10], [14].

This type of integrated tuning structure is used at 490 GHz and at 660 GHz. Both electrodes of the microstripline of the integrated tuning structure are made of niobium. At frequencies below approximately 700 GHz, the gap frequency of niobium, the superconducting line will in effect be lossless and the junction geometric capacitance will be compensated completely by a properly designed inductor. At 800 GHz the loss in the line reduces the tuning effect of the series inductor. To limit the transmission loss in the transformer at 800 GHz we reduced it to a single quarter wavelength section.

Starting at the junction, and giving the dimensions in pairs of width (w) and length(l), (w,l), the dimensions of the tuning structure at 490 GHz are: (2, 13.4), (17.8, 56.2), and (3.7, 52.2), in micrometer. For 660 GHz the dimensions are (4, 6),(19, 24) and (3, 27) for junction a21. At 800 GHz the total tuning structure has a length of 29μm at a width of 5μ. Detailed design considerations can be found in [15] for 450 GHz and 660 GHz, and in [16] for 800 GHz.

2.3 Embedding impedance, theoretical performance

The integrated tuning is optimized with the use of the antenna impedance measured in the scale model. The integrated tuning structure terminated by the antenna impedance parallel to the junction geometric capacitance forms the embedding impedance of the tunnel junction. This impedance is optimized in such a way that its real part is approximately equal to the junction normal state resistance and its imaginary part is zero, or slightly negative (capacitive) in the frequency band of interest.

In Fig. 1 the result of optimization is shown. The Smith chart is normalized to the junction normal state resistance. In each chart there are three traces, the embedding impedance indicated by the "x"s, the impedance measured in the scale model indicated by the "+"s, and the impedance of the integrated tuning structure terminated by the SIS junction.

From 400GHz to 500 GHz we achieve a good embedding impedance over the whole band. Because of the less optimal antenna impedance we do not achieve such a wide band around 660 GHz. In Fig. 1 B it can be seen that a good embedding impedance can be expected from about 630 GHz to 700 GHz.

Around 800 GHz the simulation depends very much on the loss that is estimated for the niobium striplines above the gap frequency. In Fig. 1C we show the result of a simulation that estimates the loss by using the Mattis Bardeen theory in the extreme anomalous limit. In the calculation the normal state conductance of the niobium is chosen equal to the actual value for our fabrication process. It can be seen that with a series resonant tuning structure followed by a transformer matching to the antenna impedance is very well possible (in fact the loss in the line is part of the matching circuit). The embedding impedance is clearly worse than in the lossless case. Assuming the same loss in the striplines a better embedding impedance can probably be achieved using a parallel resonant stub [11], but this would considerably worsen the matching to our type of waveguide mount.

3 Fabrication

3.1 Mixer blocks

The mixerblocks are fabricated at the University of Cologne in the mechanical shop of our institute. A detailed description of the mixerblock fabrication can be found in [15]. The mixer consists of a copper block with outer dimensions of (20 x 20 x 10) mm^3 (Fig. 2). A rectangular cavity (1) with the dimensions of a half height waveguide (100 x 330) $\mu m^2$for 660 GHz and 800 GHz, and (135 x 540) μm^2 for 490 GHz) is punched into the copper block with a special steel tool of suitable dimensions. The depth of this cavity is initially 160 µm (800 GHz), 180 µm (660 GHz) or 200 µm (490 GHz).

After punching the backshort section, the junction substrate channel (100 µm wide, 100 µm deep for 800 GHz and 660 GHz, and 165 µm wide, 100 µm deep for 490 GHz) (2) is sawed across the cavity. The distance of the backshort behind the substrate channel is 60 µm (800 GHz), 80 µm (690 GHz) or 100 µm (490 GHz) afterwards.

The recesses (6) (70 µm deep) at the ends of the substrate channel are made to facilitate the contacting of the junction. The SMA-connector (4) for the DC/IF contact is fastened to the back of the block. Its center conductor extends perpendicular to the substrate channel until just behind the junction substrate

All manufacturing steps including holes and threads for clamping a horn antenna to the block are made in a single run on the lathe under computer control. This guarantees the high relative positioning precision of the waveguide, substrate channel, and mounting holes for a horn antenna. The depth of the cavity is reproducible to within 5µm.

We use commercially available corrugated feed horns at 450 GHz and 660 GHz, and a modified Potter horn at 800 GHz. [17]

3.2 SIS junctions

Nb-Al_2O_3-Nb SIS junctions are manufactured at the University of Cologne using a variation of the common self aligned niobium etch process (SNEP).The junctions have an area of 0.8 μm^2 and a current density of approximately 15 kA/cm^2. The ratio between the subgap resistance and the normal state resistance is generally close to 20. The integrated tuning structure is made of niobium with an SiO dielectric.

The junctions are fabricated on 100 µm thick SUPRASIL fused-quartz substrates. The quartz wafers are lapped to 50 µm thickness for 490 GHz, 40 µm thickness for 660 GHz, and 35 µm thickness for 800 GHz. The mechanical stress of the lapped quartz is released with a short etch in buffered hydrofluoric acid. The wafer is diced into junction chips of size 80 µm x 2400 µm for 660 GHz and 800 GHz, and 120 µm x 2700 µm for 490 GHz

Because the inductive tuning section is short, for example 6 µm at 670 GHz for a line width of 3 µm, the alignment inaccuracy during fabrication (approx. 1 µm) has a large effect on the actual frequency characteristic of the tuning structure. Fortunately the high current density facilitates matching over a larger bandwidth than there is available in the waveguide mount, especially around 660 GHz. The "extra" bandwidth partly compensates the alignment limits.

The definition accuracy of the junction area is about 0.2 μm^2. This also has a large influence on the band of the tuning structure. The inaccuracy in area definition, which mainly varies per fabrication batch, is counteracted by putting area variations on the photo masks.

3.3. Mixer assembly

The construction of the mixerblock is such that building a junction into the mixerblock is made as easy as possible. The recesses (7) in Fig. 2 facilitate a good access to the junction substrate. Experience has shown that after some practice every graduate student can build a junction into the mixerblock.

The substrate with the junction (3) is glued into the substrate channel using Crystalbond^{TM}, which is soluble in acetone. One end of the IF-filter is ultrasonically wire-bonded to the centre pin of the SMA-connector assembly (4), the other end to the block with 25 µm diameter aluminum wire (5). The junction faces the horn antenna. The horn is flanged to the mixerblock and is carefully adjusted to centre position under a microscope.

4. Measurements

4.1 DC IV-curves

The DC IV-curve of all junctions fabricated is measured at 4.2K. A typical example of a DC IV-curve is given in Fig. 3. The current density is about 15 kA/cm and the subgap current at 2 mV is approximately 5 µA.

As mentioned in paragraph 3.2 we expect a rather large spread in the fabrication due to the alignment accuracy and the junction area definition. This spread is investigated in the DC IV-curves on the basis of the self resonant current steps. Due to the AC Josephson effect an SIS junction without a magnetic field functions as a (bias)voltage controlled oscillator with 483 GHz/mV: At certain frequencies the impedance of the integrated tuning structure parallel to the junction geometric capacitance and terminated by the antenna impedance has a resonance condition. At the bias voltages corresponding to these frequencies a current rise will be seen in the DC IV-curve.

Generally the current rise extends over a small region of bias voltage. It is also rather unstable. With an appropriate bias supply we try to monitor as much as possible of the resonance, and take the highest voltage we measure as the voltage characterizing the fabrication of the tuning structure.

This is of course a rather inaccurate measure of the possible frequency characteristic of the tuning structure. A comparison with Fourier Transform Spectrometer measurements, which will give more accurate information, will be done at a later stage. Generally we can say that we observe a spread in the resonant steps consistent with a fabrication alignment accuracy of 1 µm, and a junction area definition accuracy of 0.2 μm^2.

4.2 Noise measurements

All noise temperature measurements are done in a liquid helium dewar at a temperature of 4.2K. The vacuum window of the dewar and the 77K infrared filter are sealed with teflon or mylar foils. The thickness of the foils is optimized to achieve a transmission of about 98% in the current frequency band.

The center frequency of the cooled HEMT amplifier is 1.4 GHz and its noise temperature is about 5K. The IF-output power is measured in a 100 MHz bandwidth around the center frequency.

For 450 GHz and 660 GHz the local oscillator and the signal are combined with a beamsplitter. The calculated reflection of the beamsplitter used at 450 GHz is 2%, and that at 660 GHz is 5%. At 800 GHz we use a diplexer with a transmission loss of about 5%.

At present we have only measured two different junctions in each frequency band. The junctions have been mounted in different, but nominally identical, mixerblocks. The two blocks are the mixer and the spare mixer for the dual channel receiver. At 490 GHz and 800 GHz two nominally identical junctions are used. At 660 GHz we measured two junctions with slightly different integrated tuning structures.

The junctions have been chosen on the basis of their self pump resonance in the DC IV-curve. The resonance voltage for the two 490 GHz junctions is 0.85mV for junction b54, and 0.78mV for junction b53 (numbering of the different junction according to fabrication; also given in figures 4-6). for 800 GHz we measured 1.63mV for junction e19 and 1.65mV for junction e21. At 660 GHz, structure a21, which has the best receiver noise temperatures, showed a resonance at 1.33mV, while structure b21 showed a resonance at 1.45mV.

A typical example of a measurement at 816 GHz is given in Fig. 3. The noise temperature is directly calculated from the hot/cold load IF output power, thus including beamsplitter/diplexer, and dewar windows. The level of local oscillator power is adjusted for optimum conversion. Although the suppression of the Cooper pair tunneling is not complete there is still a sufficient bias region.

The noise temperatures for the six different mixers are given in Fig.'s 4-6. For the 490 GHz mixers and the 800 GHz mixers the temperatures should have been the same. Apparently at 490 GHz the actual frequency characteristic of the tuning structure of the two junctions is not the same. This can already be concluded from the resonance voltage observed in the DC IV-curve. For 800 GHz the resonances of the two tuning structures are closer together and so are the measured noise temperatures. Contrary to the results reported in [18] the noise temperatures are fairly constant across the 800 GHz band. At 660 GHz the frequency band of tuning structure b21 is clearly shifted to higher frequencies compared to structure a21.

4.3 Spectroscopic Measurements

The mixers are developed for a dual channel receiver. The two channels have a 90 degree difference in polarization. They are built into a standard Hybrid dewar [19] with a 10" cold plate, with a cold elliptical mirror for each channel to couple the beam outside the dewar. In operation the dewar has a hold time of about 10 days for 10 liters of helium. Both channels have an IF center frequency of 1.5 GHz. We use two AOS backends with a bandwidth of 1.1 GHz, designed at the University of Cologne. For a first observing run at the SubMillimeter Telescope Observatory (SMTO) the 490 GHz and the 800 GHz mixer were selected. For the 490 GHz channel a Single Side Band (SSB) filter was implemented.

The main objective of the observing run was the *simultaneous* measurement of the atomic carbon $[CI]^3P_1 \rightarrow {}^3P_0$ and $[CI]^3P_2 \rightarrow {}^3P_1$ lines and/or the CO $4 \rightarrow 3$ and the CO $7 \rightarrow 6$ molecular rotational lines. In that way a good relative calibration of the two line intensities, of relevance to the astrophysical interpretation of the data, is possible. An example of such a detection in the source W3 IRS5 is given in Fig. 7. It is the average of just a few scans made on line during observing, and as such the calibration is preliminary. The detection was done at a SSB receiver noise temperature of 1200 K for 492 GHz channel and 2200 K for the 809 GHz channel.

The high receiver noise temperature of the 490 GHz channel is caused by the increased noise temperature of the cooled HEMT amplifier in that channel, which developed problems during observing and finally reached a noise temperature of only around 200 K. This also caused some instability in the 490 GHz channel. The 800 GHz channel was stable, showing an Allan variance minimum time of 40 s. A big advantage of the fixed tuned mixers, demonstrated during this observing run is the fact that the IF bandpass was almost constant, independent of the tuning of the local oscillator frequency, thus facilitating the future implementation of an equalizer for the IF band, leveling the passband to about 3 dB .

The telescope site (weather conditions) and the quality of the telescope dish met all expectations for submillimeter observing, culminating in a first extra galactic detection of the $[CI]^3P_2 \rightarrow {}^3P_1$ line in the starburst galaxy M82 [20].

5 Conclusion

We developed a series of fixed tuned mixers for astronomical observations with state of the art noise temperatures. The mixers have proven to be robust, and easy to handle. Around 450 GHz and 660 GHz the whole bandwidth of the atmospheric window is covered by the mixer. The design of the mixers is rather well understood, as is documented by the almost constant receiver noise temperature across the respective bands, as well as the fact that we were able to select appropriate junctions for the actual mixer and its spare without further tries from the batch of junctions produced on one wafer.

The 15 kA/cm^2 current density of the high quality SIS junctions facilitates matching and good noise temperatures over a large bandwidth. Because we use rather large area SIS junctions the alignment accuracy during fabrication causes a rather large spread in the actual devices. Although not a very precise criterium, the self resonance frequency in the DC IV-curve is a helpful tool in choosing the appropriate mixer junction.

At 800 GHz all niobium integrated tuning structures can still be used successfully. An almost constant noise temperature over the band from 770 GHz to 820 GHz is achieved.

The mixers were successfully used in astronomical observations. Thanks to the fixed tuned characteristic the IF bandpass is almost independent of the observing frequency. The receiver showed excellent stability, documented by an spectroscopic Allan variance minimum time reaching about 40 s.

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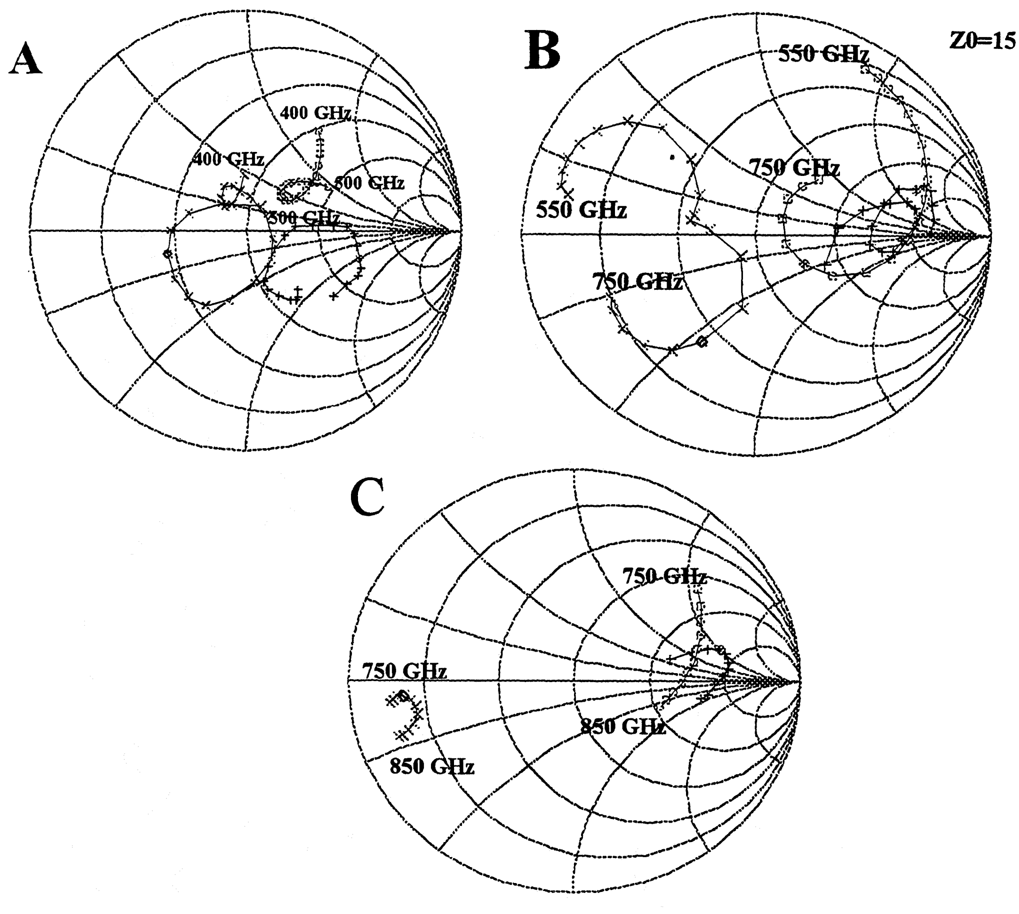
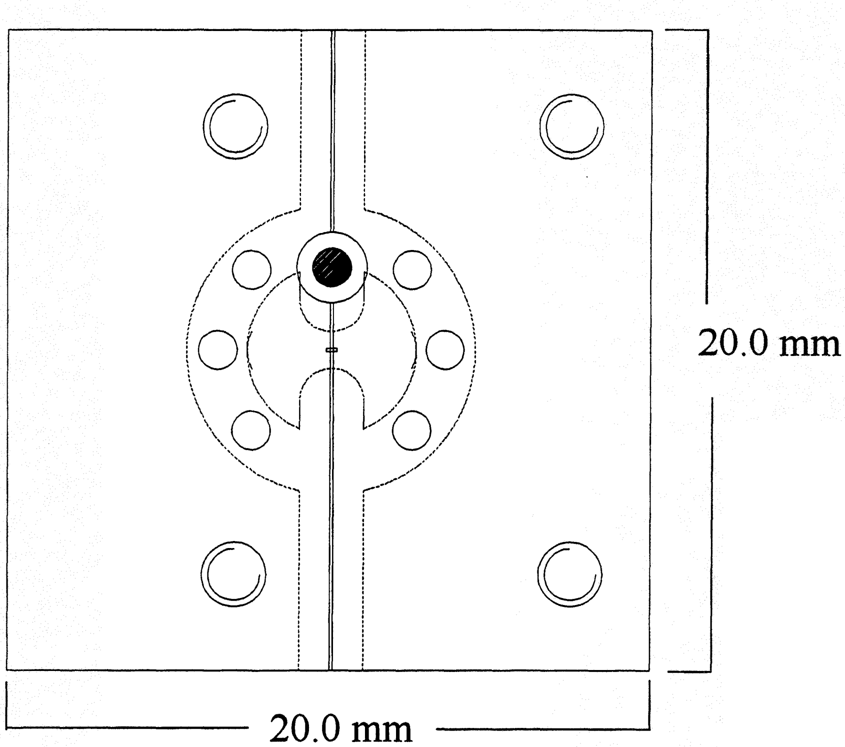


Fig 1: The calculated embedding impedance (x), the measured antenna impedance (+) and the calculated impedance of the integrated tuning structure terminated by the SIS junction for the 450 GHz mixer (A), the 660 GHz mixer(B), and the 800 GHz mixer(C). The marked frequencies are 450 GHz in A, 700 GHz in B and 800 GHz in plot C

A



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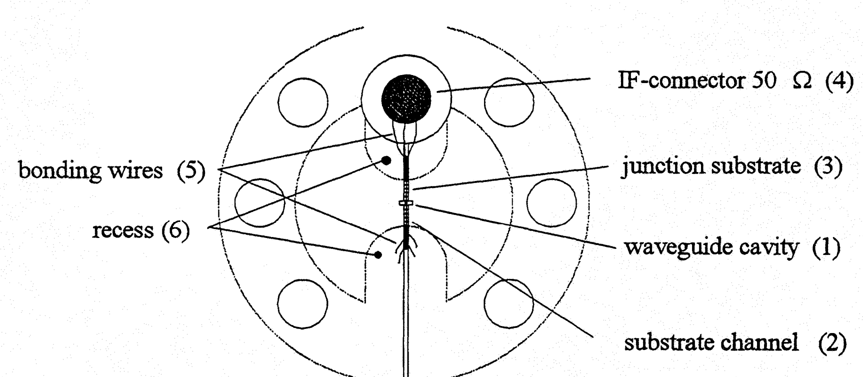

Fig. 2: A) Face-on view of the mixerblock with fixed backshort, B) detail of the central part.

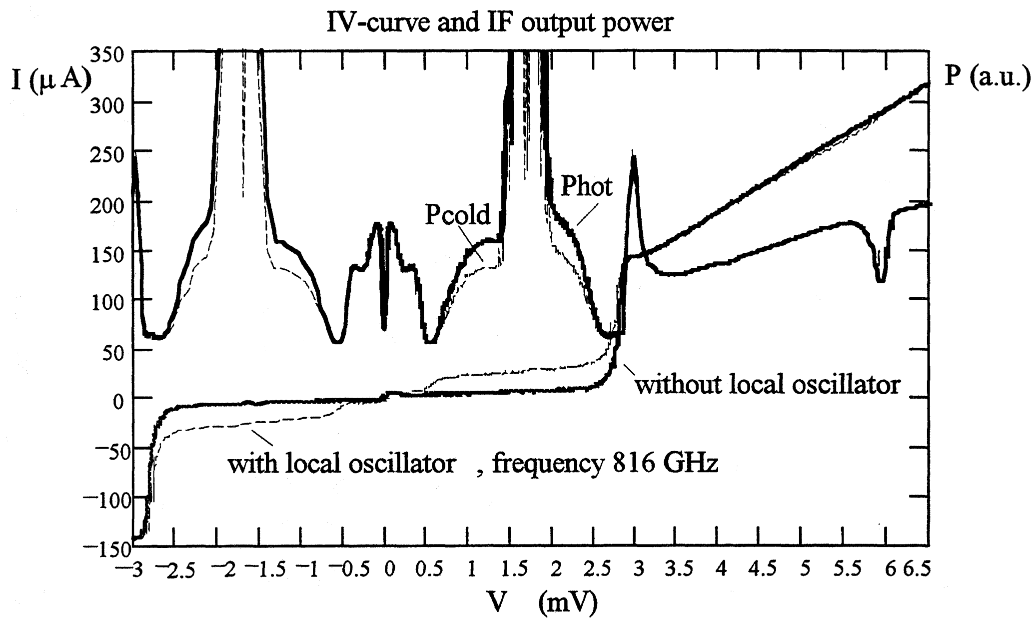

Fig. 3 DC IV curve of junction e 21 with and without local oscillator power at 816 GHz. Additionally the simultaneously measured IF output power at a hot (300K) and cold (77K) load input is shown for optimum conversion.

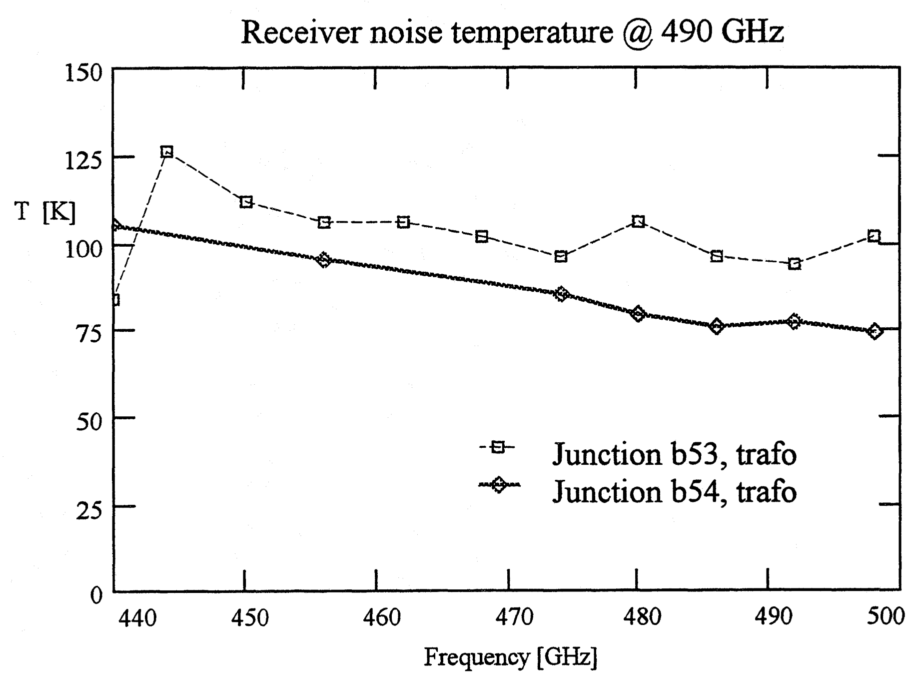

Fig. 4 Receiver noise temperature around 470 GHz of two nominally identical junctions in two nominally identical mixerblocks.

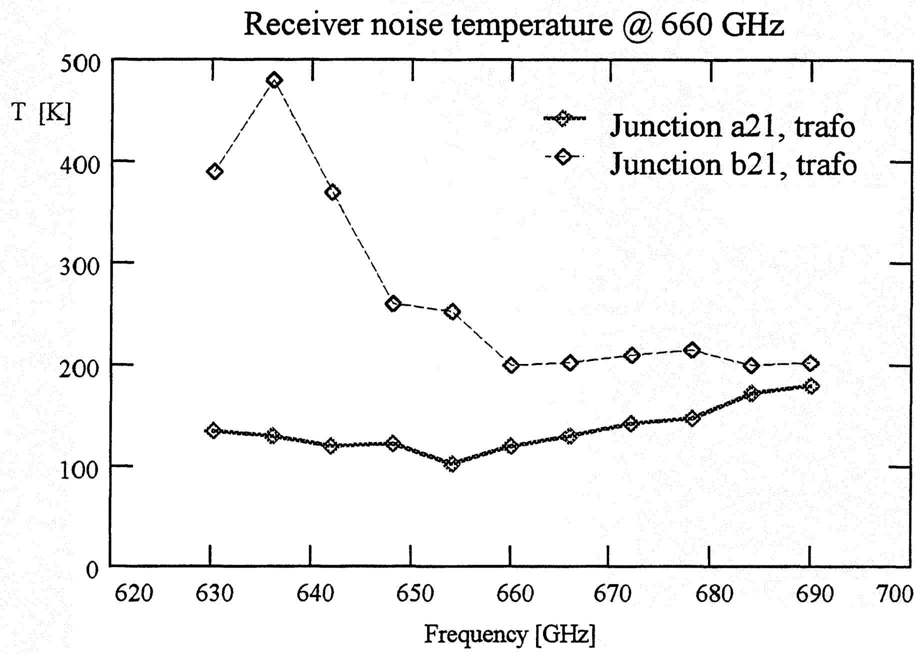

Fig 5. Receiver noise temperature around 660 GHz for an optimum junction (a21), and for a junction with a tuning structure designed for a somewhat higher frequency band (b21).

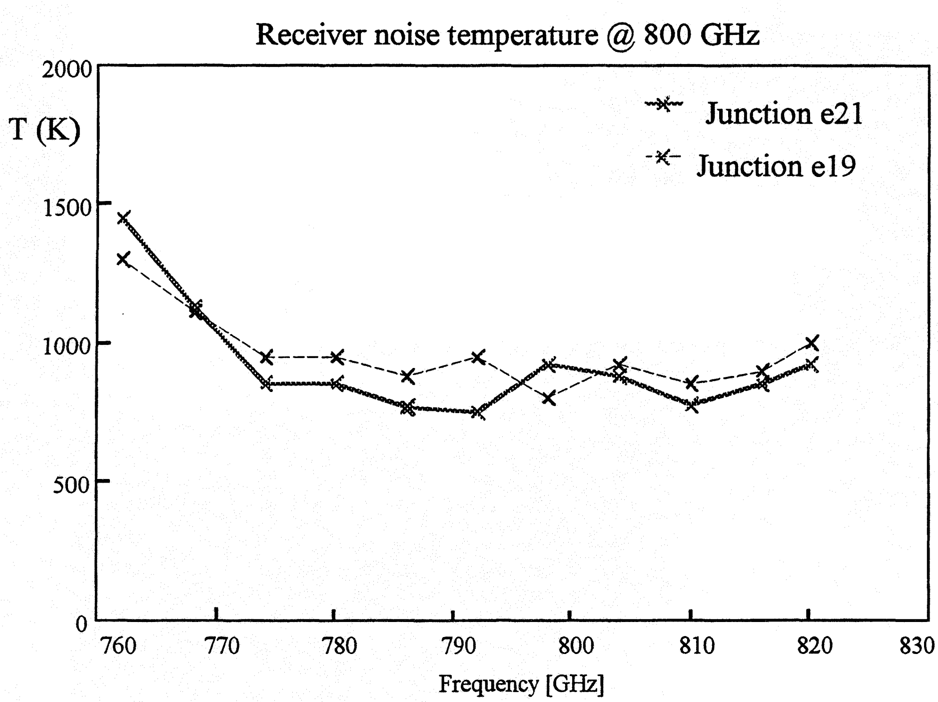

Fig. 6. Receiver noise temperatures for two nominally identical junctions in two nominally identical mixerblocks around 800 GHz

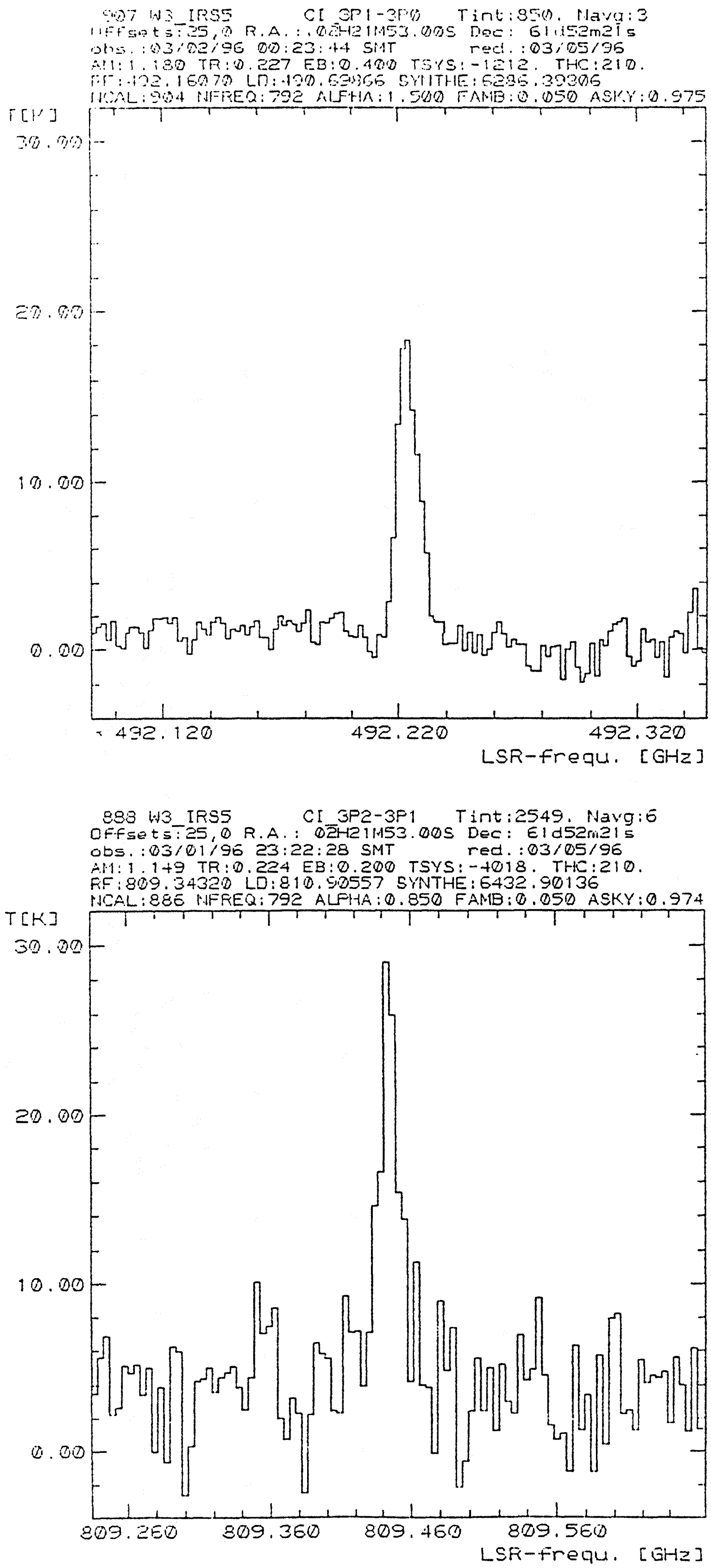

Fig. 7. $[CI]^3P_1 \rightarrow {}^3P_0$ and $[CI]^3P_2 \rightarrow {}^3P_1$ lines at 492 GHz and 809 GHz in W3 IRS5 simultaneously measured with the KOSMA dual channel receiver at the Submillimeter Telescope Observatory (SMTO) in Arizona