A LOW NOISE 565-735 GHz SIS WAVEGUIDE RECEIVER

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Abstract

We report recent results on a 565-735 GHz SIS heterodyne receiver employing a $0.36\mu m^2$ Nb/AlO$_x$/Nb SIS tunnel junction with high quality circular non-contacting backshort and E-plane tuners in a full height waveguide mount. No resonant tuning structures have been incorporated in the junction design at this time, even though such structures are expected to help the performance of the receiver. The receiver operates to 735 GHz, well above the gap frequency of niobium, $\approx$ 680 GHz. Typical receiver noise temperatures from 565-690 GHz range from 160K to 230K with a best value of 185K DSB at 648 GHz. At 730 GHz the receiver noise temperature has gradually increased from 230K to 300K. The monotonic rise in noise temperature above 680 GHz is attributed to a combined effect of absorption loss in the niobium RF choke and antenna transmission lines and inability to tune out the large parasitic junction susceptance. With the mixer cooled from 4.3K to 2K the measured receiver noise temperatures decreased by approximately 15%, giving roughly 180K DSB from 660 to 680 GHz. The receiver has a full 1 GHz IF passband and has been successfully installed at the Caltech Submillimeter Observatory in Hawaii.

Introduction

A waveguide superconducting insulator superconducting (SIS) heterodyne receiver with a center frequency of 665 GHz has been designed to take advantage of 600 to 730 GHz atmospheric window. The results discussed here were achieved by using a $0.36\mu m^2$ Nb/AlO$_x$/Nb tunnel junction in a full height rectangular waveguide mixer [2] with two circular non- contacting tuning elements [3,4] and an integrated 1-2 GHz wide IF matching network.

It is clear that near quantum limited results [1] have been achieved by scaling SIS waveguide receivers to higher frequencies [5, 6]. Since a SIS junction is essentially a sandwich of two superconducting electrodes separated by a very thin insulating material, ($\approx 12\mathring{A}$), the geometric capacitance is appreciable, 75-85 fF/(μm^2). To achieve a good RF match to the embedding impedance it is important to tune out the geometric capacitance of the junction. This becomes increasingly difficult as the operating frequency of the mixer is raised. For this purpose waveguide receivers typically employ high 'Q' non-contacting backshort and E-plane tuners.

Recently advances in niobium thin film processing have permitted RF matching on the chip itself, by means of lithographically produced tuning structures, to tune out the parasitic capacitance. This technique has been very effectively used in both open structure devices [7,8] and waveguide mixers [9-16].

Above the gap frequency, ($2\Delta/h \approx 680$ GHz), the photon energy is large enough to break Cooper-pairs in the superconductor causing large absorption losses in the material. Dierichs *et al.* [17] have measured intensities for lossless resonant stubs and compared them against calculated intensities according to Mattis-Bardeen theory. These measurements did not indicate any resonances above the gap frequency of niobium. Calculations at 750 GHz show that the film losses of the niobium antenna mount and RF choke structure will increase fifteen fold compared to below the gap. The transmission line losses are therefore significant, ($\geq$ 40%/wavelength) [18], making it difficult to design a superconducting matching network centered at 665 GHz with the required 20% bandwidth. To minimize the effect of the increased absorption losses near and above the gap frequency it was decided to improve the waveguide tuners and use untuned $Nb/AlO_x/Nb$ tunnel junctions. This approach would ensure a broadband 600-730 GHz SIS receiver provided of course that high quality non-contacting backshorts were found that would meet our design objectives. The theory and performance of these waveguide tuners will be elaborated on by Walker *et al.* [4] in a separate paper. However the results of preliminary scale model testing will be presented in this paper.

$Nb/AlO_x/Nb Junction Fabrication$

The $Nb/AlO_x/Nb$ tunnel junctions were fabricated using a standard self-aligned lift-off trilayer process. The $Nb/AlO_x/Nb$ trilayer was deposited in-situ in a high vacuum deposition system with a base pressure of $4*10^{-9}$ Torr, through a photoresist lift-off stencil (AZ5214) onto 50 μm thick quartz substrates. The trilayer remaining after lift-off formed the first half of the antenna/filter structure. The junction mesa was patterned using electron beam direct writing on a 120 nm thick PMMA followed by evaporation of $\approx$ 50 nm chromium metal and subsequent lift-off. Contact regions of the trilayer are then protected with a photoresist stencil and the combined chromium/photoresist mask was used to etch the junction in a parallel plate reactive ion etcher (RIE). The etch parameters were $62\%CCl_2F_2$ + $31\%CF_4$ + $7\%O_2$, 30 mTorr pressure, and .18 Watts/cm^2. The electrical isolation of the base electrode and subsequent wire layer are provided by thermal evaporation of 150 nm of SiO. The substrates were tilted and rotated during this operation. The chrome was lifted off using a commercial wet etch. The second half of the antenna was formed by a whole wafer deposition of Nb in the same vacuum system used for trilayer deposition and was patterned using RIE. Tunnel junctions with areas down to $0.25\mu m^2$ were fabricated using this technique.

Receiver Description

Optics

Fig. 1 shows a block diagram of the 665 GHz receiver. The optics was designed to give a 14 dB edge taper on the secondary mirror of the telescope. A 13 μm mylar beam splitter is mounted at 45° to the signal and local oscillator beams. The local oscillator's electric field is perpendicular to the plane of incidence and about 5.7% of the radiation couples into the cryostat, the remainder is absorbed by a sheet of Eccosorb. The vacuum window is made out of 19μm

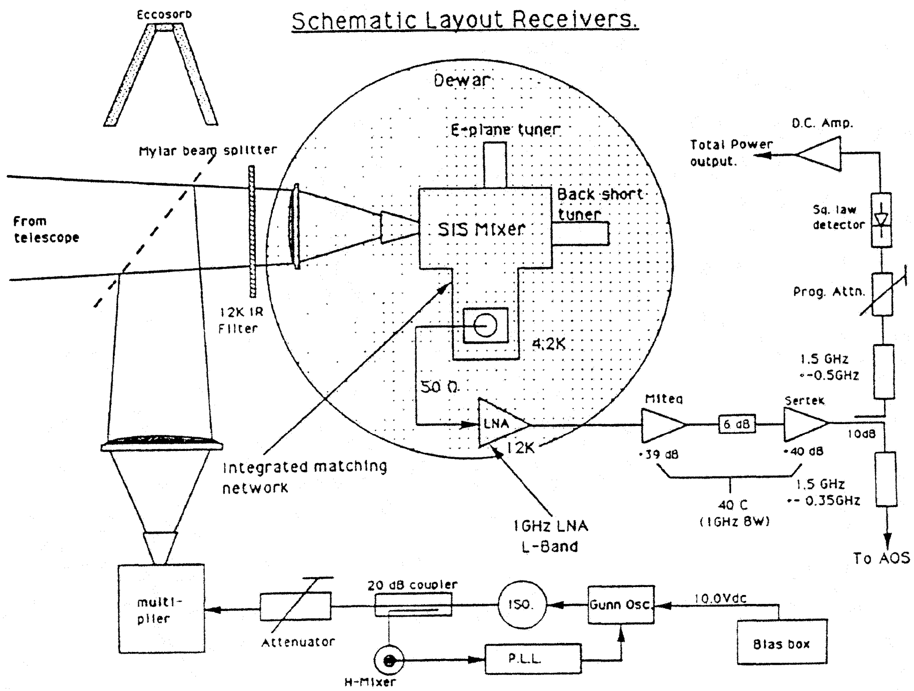

Fig. 1. Schematic layout of the receiver. Beam splitter, window reflection, and IR filter losses at 665 GHz contribute about 65 Kelvin to the receiver noise temperature. The matching network is mounted in the mixer block and is followed by a two stage balanced HEMT amplifier. The IF passband is 1.0 to 2.0 GHz.

HR500/2S material manufactured for food packaging by Hercules Inc. [19]. It has a dielectric constant of $\approx$ 2.6 and is a laminate of biaxially oriented polypropylene with 2.5 μm layers of polyvinlidene chloride on both sides. Laboratory experiments have shown that the material has adequate strength to function as a vacuum window for aperture diameters $\leq$ 25 mm. Experiments indicate that the Hercules material is considerably more opaque to He^4 then 25 μm mylar The material is also expected to have a low permeability to water and atmospheric gasses. The infrared blocking filter on the 12 Kelvin window consists of a one wavelength thick fluorogold disk. The mixer lens is made out of low density polyethelene, with an approximate dielectric constant of 2.41 at 4.2K ambient temperature. The optics are designed to give a frequency independent illumination of the secondary (Goldsmith 1982). The low loss polyethylene lens is placed in the near field of the scaler feedhorn. Antenna pattern measurements give reasonably close agreement to the theoretically expected response.

ReflectionandAbsorptionLosses

To better understand the noise contribution of the front-end optics of the receiver, losses of different slabs of selected materials were measured at 654 GHz. With the receiver tuned, the hot (293K) and cold (80K) IF power response was measured with or without a 'lossy' slab of material inserted in the beam. This procedure gave information on the effective 'cold' blackbody temperature from which the total insertion loss of the material was computed. L includes both the reflection and transmission losses of the sample.

$$T_{eff} = L(T_{hot}) + (1 - L)T_{cold} \tag{1}$$

Correcting for the reflection loss of the optically thick slab gives the transmission loss, α. Table 1 tabulates the dielectric constant and the loss tangent. The dielectric constant was obtained from the literature [20] and is assumed to be relatively constant with frequency.

$$tan(\delta) = \left(\frac{\lambda_o \alpha}{\pi\sqrt{\epsilon'}}\right) \tag{2}$$

α = transmission loss per unit wavelength.
ϵ' = the real part of the dielectric constant.

Table 1. 654 GHz Measured Absorption Losses

Material	Dielectric Constant (ϵ')	α (np/mm)	tan(δ)
Fluorogold	2.56-2.64	0.120	10.8 x 10^{-3}
Mylar	3.0	0.451	3.8 x 10^{-2}
Styrofoam packaging 1 lb/ft^3	1.1	8.6-17.2 x 10^{-4}	1.2-2.4 x 10^{-4}
Radvai Styrofoam 1.75lb/ft^3	1.1	0.0023	3.2 x 10^{-4}

MixerBlockConstruction

The basic waveguide mixer block is scaled from the 230 GHz design of Ellison *et al.* [2] and utilizes a double stub tuning structure. The block is composed of two sections and uses magnetic field concentrators as discussed by Walker *et al.* [12]. The front section constitutes the corrugated feedhorn, circular to rectangular waveguide transformer and E-plane tuner. The back section holds the junction and backshort tuner. The corrugated feedhorn beamwidth was measured by Walker *et al.* on a scaled version at 115 GHz. It measures 10.5° at the ε^{-2} power contour in both E and H planes. The three section circular to full height rectangular waveguide transformer and E-plane tuner were constructed on the same mandrel as the corrugated feedhorn. This reduces number of waveguide discontinuities and minimizes ohmic loss in the guide. The E-plane is situated $1/2\lambda_g$ in front of the junction. The junction is mounted in a 90 μm by 100μm groove which cuts across the face of the waveguide, parallel to the E-field. The junction is fabricated on a highly thermally conductive piece of single crystal quartz. The substrate dimension are 75 μm in width and 50 μm in height. The junction has been carefully centered in the waveguide [21] and is contacted with silver paint on both the ground and IF side. Fig. 2 shows the result of using Indium to try to contact the junction substrate on the ground side up to the waveguide wall. Using Indium on the ground side close to the waveguide wall introduces a shunt susceptance and loss. The danger of introducing a low Q resonant circuit by using indium so close to the waveguide wall far outweighs any thermal and mechanical benefits.

The thermal conductivity of the single crystal quartz is high enough to keep the junction cold with only silver paint on both IF and ground sides of the RF choke.

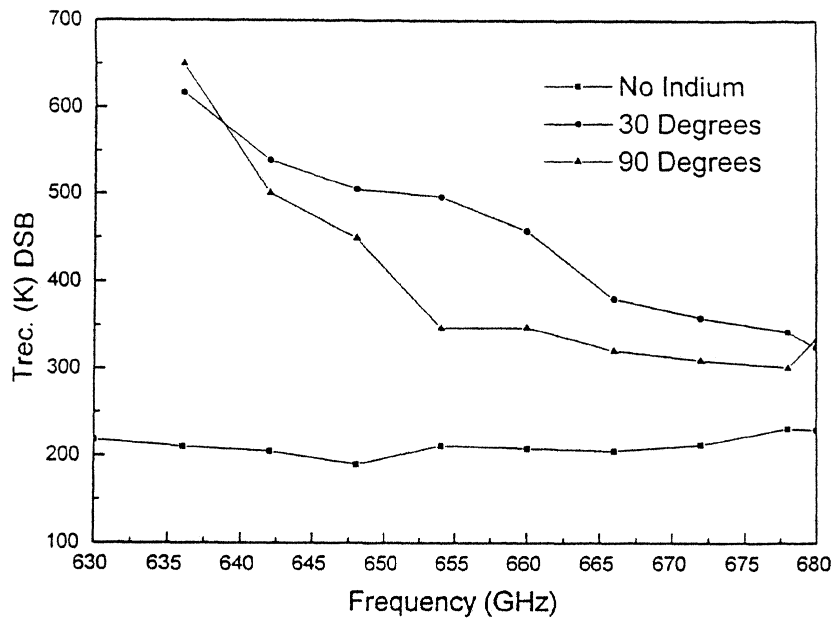

Fig. 2. Result of using indium close to the waveguide wall to provide both mechanical support and a thermal and electrical short circuit. Data is taken with the same junction.

On the IF side the junction is contacted with a 25 μm Au wire soldered to a 1-2 GHz wide IF matching network [22] which is mounted in the mixer block. The matching network is designed to transform a 160 Ohm IF impedance to 50 Ohm and to provide a short to out of band signals up to $\approx$ 22 GHz. The latter is needed to avoid saturating the junction with unwanted out of band signals. The output of the mixer block is directly connected to a 1-2 GHz balanced HEMT amplifier based on work by Padin *et al.* [23]. Any impedance mismatch between the matching network and low noise amplifier is absorbed by the amplifier's input Lange coupler. The RF choke structure is a 5 section Chebyshev bandpass filter designed to give maximum rejection (S11 $\leq$ -25 dB) at 665 GHz and presents a short circuit at the waveguide wall. Computer simulations of the RF choke at 750 GHz indicate that reflection (S11) and transmission (S21) characteristics are not severly effected above the gap frequency by the fifteen fold increase in niobium film loss (Fig. 7).

The 492 GHz receiver discussed by Walker *et al.* [12] has demonstrated 9 dB of conversion loss at 492 GHz with a receiver temperature of 178 K DSB using an untuned 0.16μm^2 Nb/AlO_x/Nb SIS tunnel junction. This block uses rectangular non-contacting tuners for both the backshort and E-plane as described by Brewer and Räisänen [24]. In order to ensure similar results at 665 GHz, tuners with a higher VSWR are needed to tune out the increased junction susceptance. Kerr *et al.* [3] have further investigated the use of tuners for the millimeter band. They found that tuners with multiple circular non-contacting sections have lower loss, and more smoothly varying reflection (S11) and phase characteristics than rectangular tuners. Fig. 3 shows the result of scaled model measurements on both the circular and rectangular non-contacting tuner designs. Both tuners have four low and high impedance sections. The input reflection (S11) of the circular tuner is approximately -0.06dB (VSWR $\approx$ 144). The VSWR of the rectangular non-contacting tuner with mylar tape is

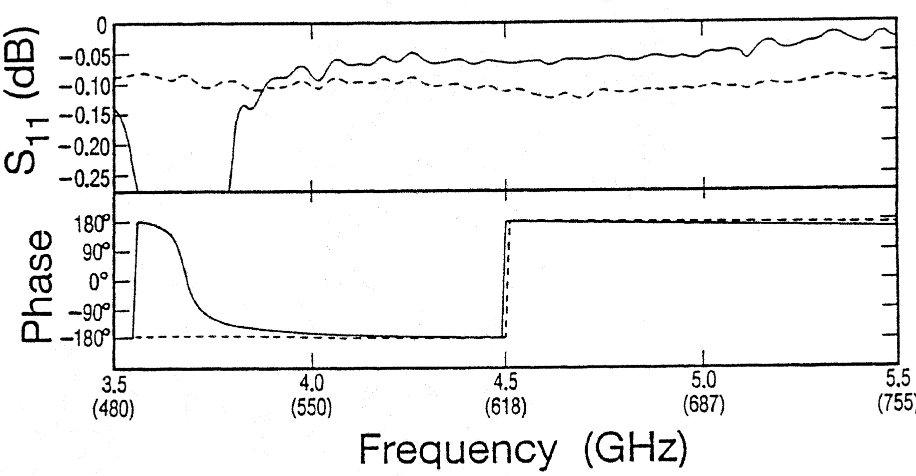

Fig. 3. Scale model tuner measurement on both the input reflection coefficient (S11) and phase response of the circular non-contacting tuner (solid line) and mylar covered rectangular tuner (dashed line). The resonance occurs when the combined length of one high-low impedance section approaches a quarter guide wavelength (Eq. 3). At 564 GHz this begins to show up in the frequency response of the receiver.

$\approx$ 78. At 665 GHz the VSWR of the rectangular tuner will degrade significantly because of increased dielectric losses in the mylar tape, resulting in higher mixer conversion loss. The poor phase characteristic of the reflection coefficient shows up as irregular receiver sensitivity across the frequency band. These problems, in theory, can be minimized by employing tuned SIS tunnel junctions although, as has been mentioned, the microstrip loss problem has to be avoided. Care has been taken in these model measurements to scale everything exactly to the dimensions in the actual mixer block. In the scale model the effective short circuit plane is located $\approx 10°$ behind the first dumbbell section. The tuner response degrades catastrophically when the first high-low section combined length (l_t) approaches a quarter guide wavelength. The resonant cutoff frequency can be approximated by

$$f_{res} = k\sqrt{\left(\frac{c}{4l_t}\right)^2 + f_c^2} \tag{3}$$

f_c is the cutoff frequency of the TE10 mode (431 GHz), k is (0.9-0.97) depending on the number of sections and c is the speed of light. Walker *et al.* will elaborate more on this in a separate paper [4].

The tuner itself consists of four beryllium copper concentric circular sections that extend from a rectangular shaft which is carefully fit in the waveguide. Scale model measurements have indicated that the position of the tuner in the waveguide is not critical as long as wall contact by the round sections is avoided. Fig. 4 shows a drawing of the backsort and E-plane tuners. The resonance occurs at $\approx$ 523 GHz which is starting to show up at 563 GHz (Fig. 7).

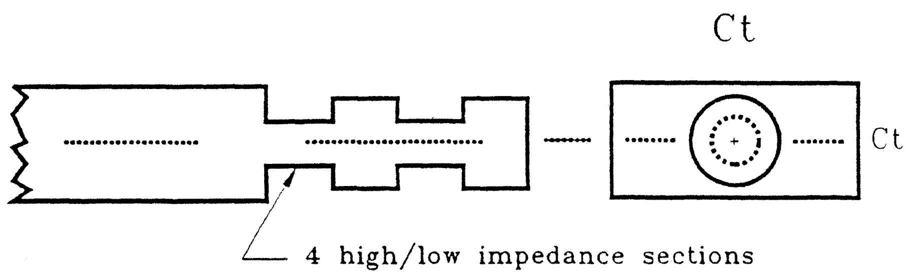

Fig. 4. Drawing of the 665 GHz circular non-contacting tuner. The tuner has 8 dumbbell sections, each being $\lambda_o/4$ long at the design frequency. The waveguide to tuner clearance is 4 μm. To avoid electrical contact with the waveguide walls it is important to coat the tuners with an insulator such as aluminum oxide.

ResultsandDiscussion

The mixer uses a high quality $0.36\mu m^2$ Nb/AlO_x/Nb tunnel junction with a current density of $\approx 10kA/cm^2$, a sub_gap leakage current of $2.6\mu A$ and a normal state resistance R_n of 50 Ohms. These characteristics allow the junction to be efficiently coupled to both the RF embedding impedance and IF impedance

(160Ω), for which the matching network was designed. The junction has a $\omega R_n C_j$ product of approximately 5.9. C_j is the geometric junction capacitance and is ≈ 28 fF for this junction. Different junctions with either higher current density (larger sub-gap leakage) or smaller areas (larger normal state resistance) have been tested but did not perform quite as well as the 50Ω 0.36μm^2 tunnel junction. The junction is fabricated on a 50μm thick single crystal quartz substrate.

Fig. 5 shows the pumped and unpumped I/V curves as well as the hot (295K) and cold (80K) total power response. The data was taken at 672 GHz with the mixer cooled to 4.2 K. At this particular frequency the DSB receiver noise temperature was 212 K. The mixer noise temperature is not sensitive to the magnetic field.

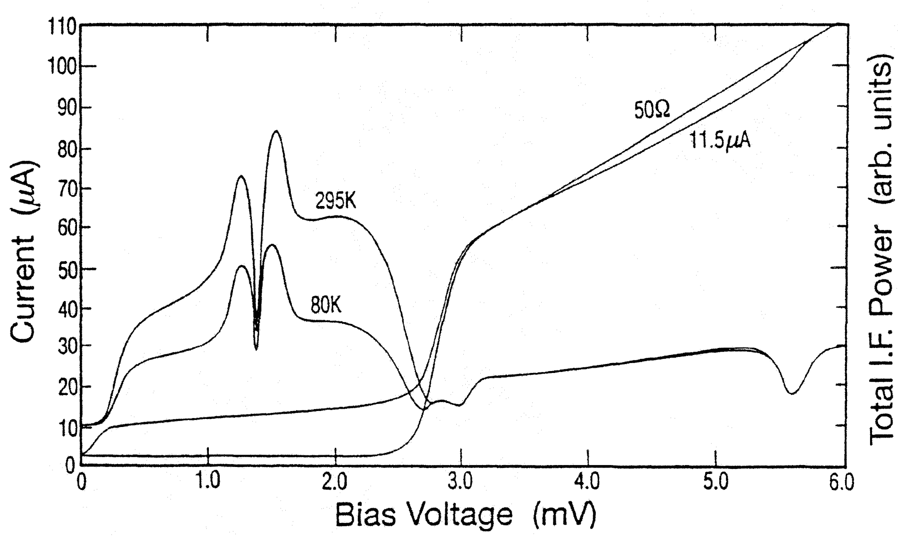

Fig. 5. Pumped and unpumped total power and I/V curves at 672 GHz. The uncorrected mixer noise temperature is 133K with 9.45 dB of mixer conversion loss. The best Y-factors were obtained at 2.1 mV and 11.5μA of pumped current ($I_c/3$). The second Shapiro step is visible at 1.39 mV and can be nulled by adjusting the magnetic field

Using the Shot Noise method [25] the IF amplifier noise temperature is calculated to be 6 Kelvin, which is in good agreement with the actual measured noise temperature of the amplifier. The resulting mixer conversion loss is 9.45 dB with an uncorrected double sideband mixer temperature of 133 K. This mixer noise temperature is approximately 8.3 times the theoretical SSB quantum limit.

Cooling the mixer block to 2K improved the conversion loss by 1 dB and resulted in a receiver temperature of 180K and mixer noise temperature of 110K. The most likely cause of the improved mixer conversion loss and lower mixer noise temperature is the sharpening of the gap and reduction in the subgap leakage current. At 672 GHz the quasi-particle step width is 2.78 mV which is just below the band gap of niobium ($\approx$ 2.85 mV). Just above the gap frequency of niobium, 690 GHz, the receiver noise temperature was $\approx$ 230K and gradually increases to 300K at 730 GHz inspite of a factor of 16 higher absorbtion loss in the nioium film as compared to the loss below the gap frequency. The effect of dispersion loss in an untuned junction is relatively small because there are no high Q lossy niobium tuning structures with large current concetrations present. Another possible reason for the increase in mixer conversion loss above the gap is the inability to tune out the increasing parasitic junction susceptance. Adjusting the magnetic field on the junction had no significant effect on the receiver noise temperature.

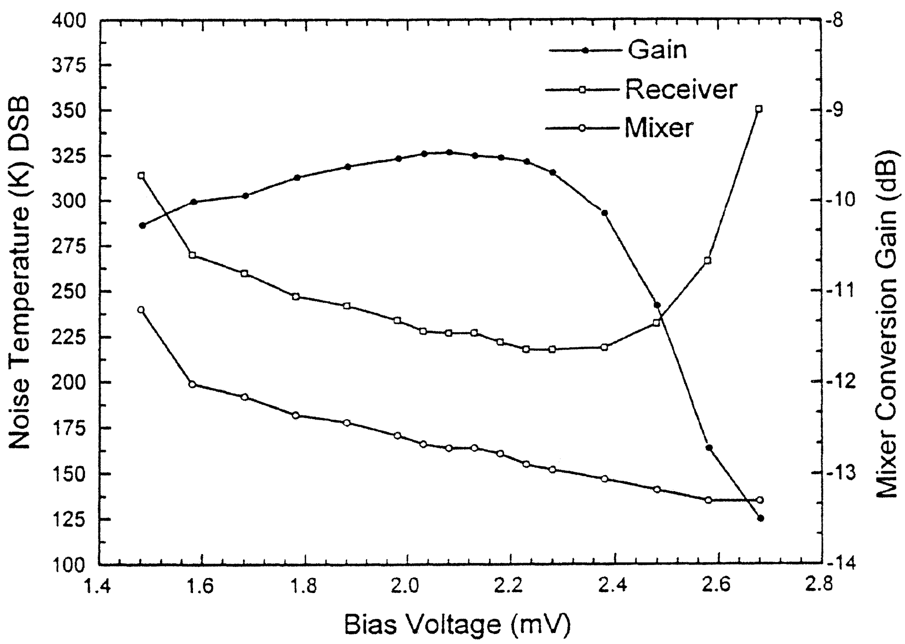

Fig. 6. Noise temperature and mixer conversion gain as a function of bias voltage at 654 GHz. The mixer temperature corrected for beamsplitter & window reflections is 89K.

Figure 6 shows the receiver noise temperature as a function of bias voltage. The best place to bias the mixer is between 2.1 and 2.25 mV. Similar results are observed with the 230-, 345-, and 492 Nb/AlO$_x$/Nb SIS quasi-particle mixers. The optimum LO drive is $I_c/3$, where I_c is the critical current of the junction, $\approx$ 35μA. Figure 7 shows the frequency response of the receiver from 560 to 738 GHz. The quality of the circular non-contacting tuners is apparent from the well behaved frequency response of the mixer.

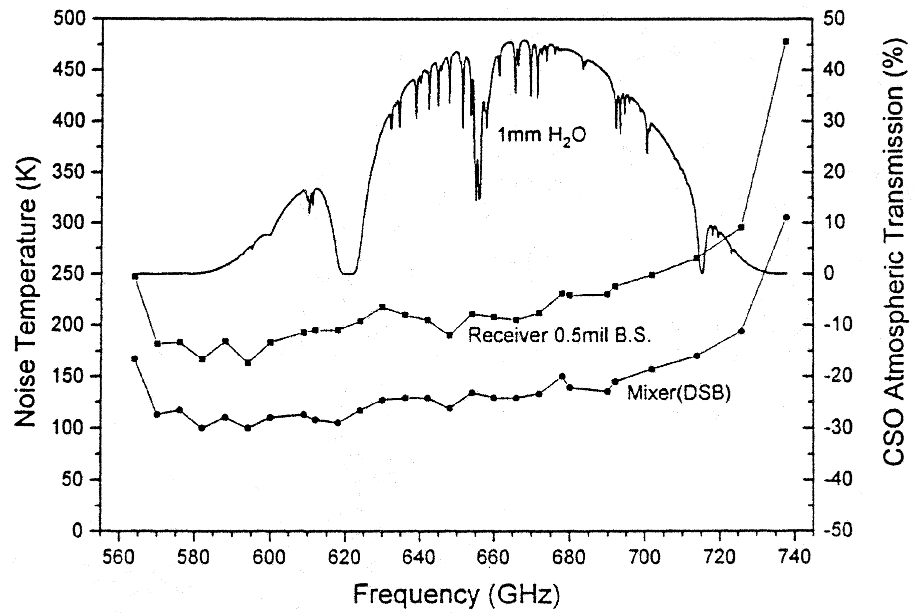

Fig. 7. Frequency response of the receiver from 560-738 GHz. The increase of noise temperature at 564 GHz is likely caused by the tuner resonance (Fig. 3). Cooling the mixer to 2K improved the receiver noise temperature by $\approx$ 15%

All measurements from 564-680 GHz were made with a 13μm beamsplitter. Data from 690-738 GHz were taken with a 20μm Hercules beamsplitter which has a reflection loss of $\approx$ 10.0% at 700 GHz. The quoted 690-738 GHz noise temperatures are referred to a 13μm beamsplitter.

In figure 8 and 9 we present double sideband spectrum taken with a 500 MHz acousto-optical spectrometer at the Caltech Submillimeter Observatory toward Orion A and IRC+10216 respectively.

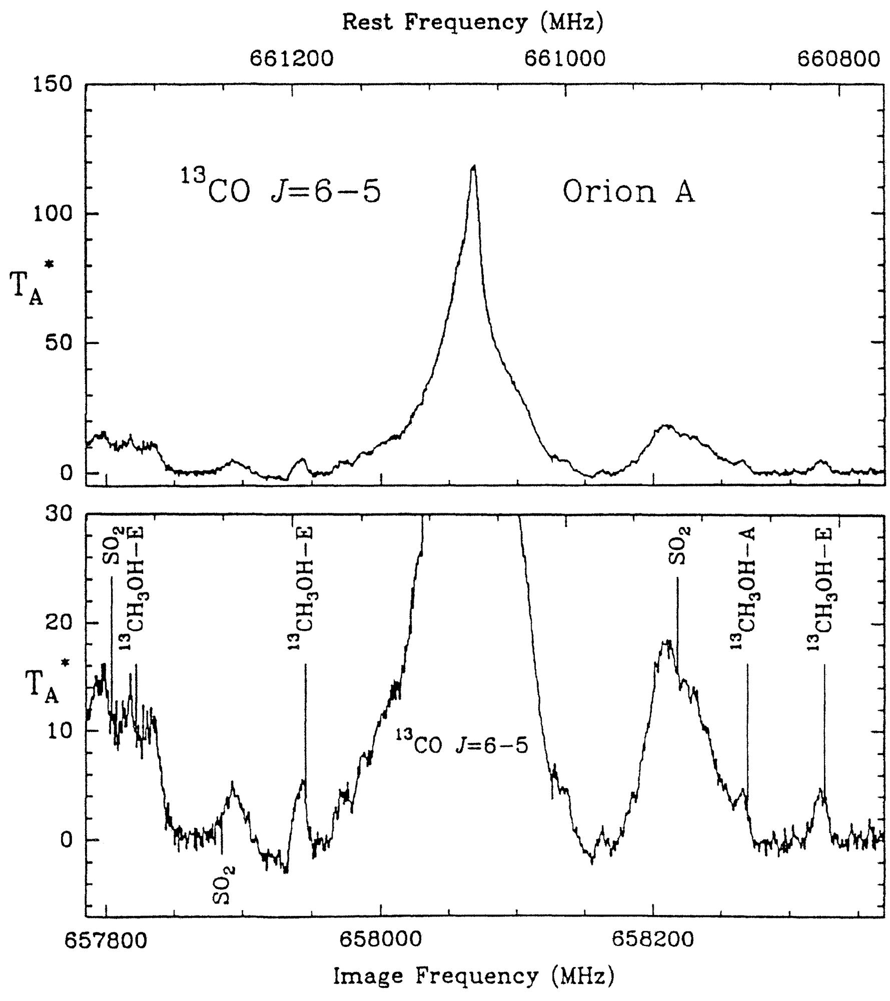

Fig. 8. ^{13}CO J=6-5. The system temperature was 3900K with a τ_{225GHz} = 0.040. Total integration time was 1.9 minutes at an airmass = 1.22

The measured main beam efficiency at these frequencies is 30%, but due to the small beam size (11 arcsec) and the extended nature of the source these spectra are corrected for the 60% coupling efficiency to the Moon. Some of the molecular transitions have been identified in both upper and lower sidebands as indicated by the label.

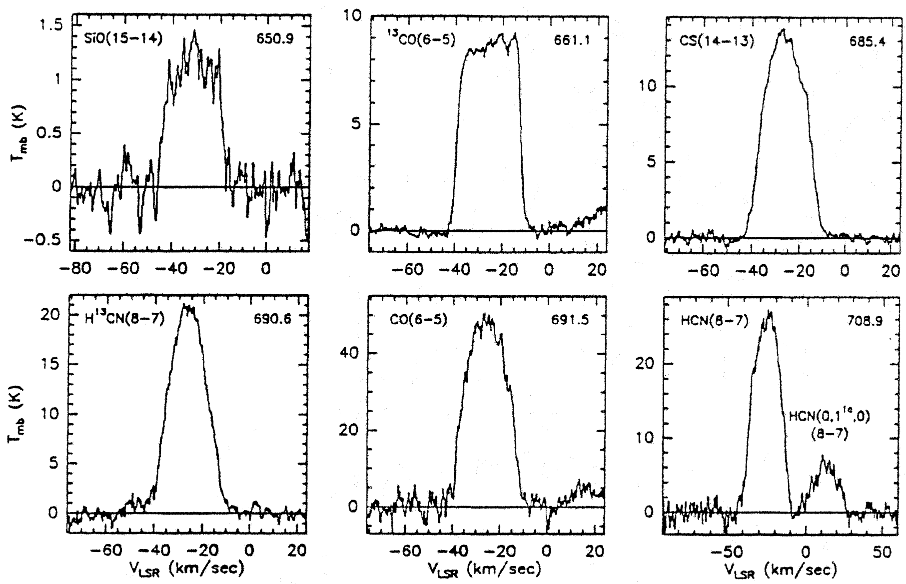

Figure 9. Spectral line survey of the most prominent molecular emission lines in IRC+10216 [26]. System noise temperatures varied from 5000-7000K with 1.0 - 1.5mm precipitable H_2O. Total integration time in all instances was less than 5 minutes.

Conclusion

A 665 GHz SIS heterodyne receiver has been developed to take advantage of the 600-730 GHz atmospheric window. The receiver has a full 1 GHz IF bandwidth and has been under test at the Caltech Submillimeter Observatory in Hawaii since August, 1993. The mixer employs an untuned $0.36\mu m^2$ Nb/AlO$_x$/Nb tunnel junction with a current density of $\approx$ 10 kA/cm^2. No adverse effect on the mixer conversion loss or noise temperature is seen up to the gap frequency of niobium (680 GHz). Above 680 GHz however the measured mixer conversion loss increases by $\approx$ 0.028dB/GHz. This increase is most likely caused by a combination of niobium loss and inability to tune out the large parasitic junction susceptance. To minimize the dispersion loss effect of the niobium film above the gap no tuning structures were incorporated on the junction. It is expected that tuned junctions will improve the performance below the gap frequency but will suffer from a much larger increase in conversion loss above the gap due to the high currents in the lossy tuning elements. The mixer block uses backshort and E-plane tuners with four circular non-contacting dumbbell sections. Scale model measurements of these tuners indicate an improved phase and VSWR over rectangular non-contacting tuners. Their superior performance is reflected in the flat frequency response of the mixer. Receiver noise temperatures are 205K $\pm$ 20K DSB dipping to 185K at 648 GHz. The mixer conversion loss varies from 9-11 dB and is comparable to the 492 GHz waveguide receiver installed at the CSO in September 1991 [12]. When the mixer was cooled to 2K the measured receiver noise temperatures decreased by approximately 15% which is similar to the result obtained on a 230 GHz waveguide receiver [22]. Pumping on the mixer resulted in a measured DSB receiver noise temperature of approximately 180 Kelvin from 660 to 680 GHz.

Acknowledgments

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