An 850 GHz WAVEGUIDE RECEIVER USING A TUNED Nb SIS TUNNEL JUNCTION FABRICATED ON A 1μm Si_3N_4 MEMBRANE

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ABSTRACT

We report on a 850 GHz SIS heterodyne receiver employing a tuned niobium tunnel junction with a current density of 14kA/cm^2, fabricated on a 1 μm Si_3N_4 supporting membrane.

Since the mixer is meant to be operated well above the superconducting gap frequency of niobium ($2\triangle/h \approx 690$ GHz) special care has been taken to minimize transmission line loss. We have therefore used junctions with an integrated radial stub RF matching network to tune out the large shunt susceptance of the junction and minimize the niobium film absorption loss. Scale model measurements of the waveguide embedding impedance have been made to aid in the design of the choke structure and RF matching network.

Detailed Fourier Transform Spectrometer measurements of tuned junctions show response up to 1000 GHz and indicate that the absorption loss in the niobium film is in the order of 4-7 dB at 850 GHz.

The latter has been confirmed with heterodyne measurements. From 800-840 GHz we report uncorrected receiver noise temperatures of 600K DSB with mixer temperatures of $\approx$ 513K. The calculated mixer conversion loss is about 12.4 dB, of which $\approx$ 7.2 dB

is due to the mixer and $\approx$ 5.2 dB to the absorption loss in the niobium. At 890 GHz the sensitivity has degraded to 1000K, which is primarily caused by the inability to achieve a good RF match. When cooled to 1.9K ambient temperature, the receiver noise temperature from 790-840 GHz dropped to about 450K DSB and increases to 2000K DSB at 982 GHz.

Both FTS and heterodyne measurements are in fairly good agreement with the theoretical loss calculated from the Mattis-Bardeen theory in the extreme anomalous limit. The Si_3N_4 membranes have successfully withstood repeated thermal shock cycles the LHe and appear to have a high enough thermal conductivity to cool the SIS tunnel junction to LHe temperatures.

INTRODUCTION

A waveguide superconducting insulator superconducting (SIS) heterodyne receiver with a center frequency of 850 GHz is being developed, for astronomy, to take advantage of the 780 to 950 GHz atmospheric window. The results discussed here were achieved by using a $0.22\mu m^2$ Nb/AlO$_x$/Nb tunnel junction fabricated on a $1\mu m$ Si_3N_4 membrane. The membrane is mounted on a pedestal which is centered over a full height rectangular waveguide. The mixer block is based on a design by Ellison *et al.*[1] and employs two circular non-contacting tuning elements [2, 3], magnetic field concentrators[6] and an integrated 1-2 GHz IF matching network[11].

Traditionally waveguide junctions have been constructed on quartz supporting substrates. To avoid RF leakage by means of surface modes down the quartz substrate, the cutoff frequency of these modes needs to be well above the operation frequency of the mixer. Unfortunately, dimensions of the substrate channel that hold the junction become unmanageably small for frequencies above 800 GHz. To avoid this problem we are exploring the idea of fabricating the junction on a 1μm Si_3N_4 membrane.

CONSTRUCTION

The first issue to be addressed is how to mount the membrane with its silicon support and RF choke structure (Fig. 1).

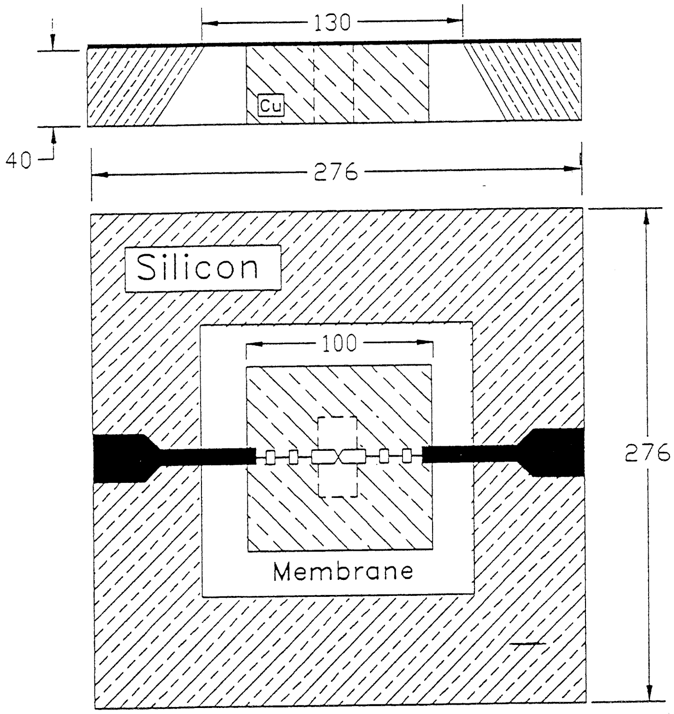

Fig. 1. ACAD Drawing of a RF choke and Silicon support structure that houses the junction. Dimensions are in μm

After some preliminary LN_2 thermal stress cycling the membrane was deemed strong enough to be placed on top of an optically polished flat copper pedestal which provides the ground plane for the RF choke (Fig. 2). A perhaps better design would incorporate a suspended RF stripline, which would free up the dimensional tolerance in the Z-direction. A 2-3 μm spacer is placed between the membrane and back short tuner drive block to prevent the membrane from breaking. I/V characteristics of both LHe dipped junctions and those cooled in a vacuum dewar designed for FTS testing are identical. This is a good indication that the thermal conductivity of the silicon nitride membrane is high enough to prevent heating of the junction by infrared radiation.

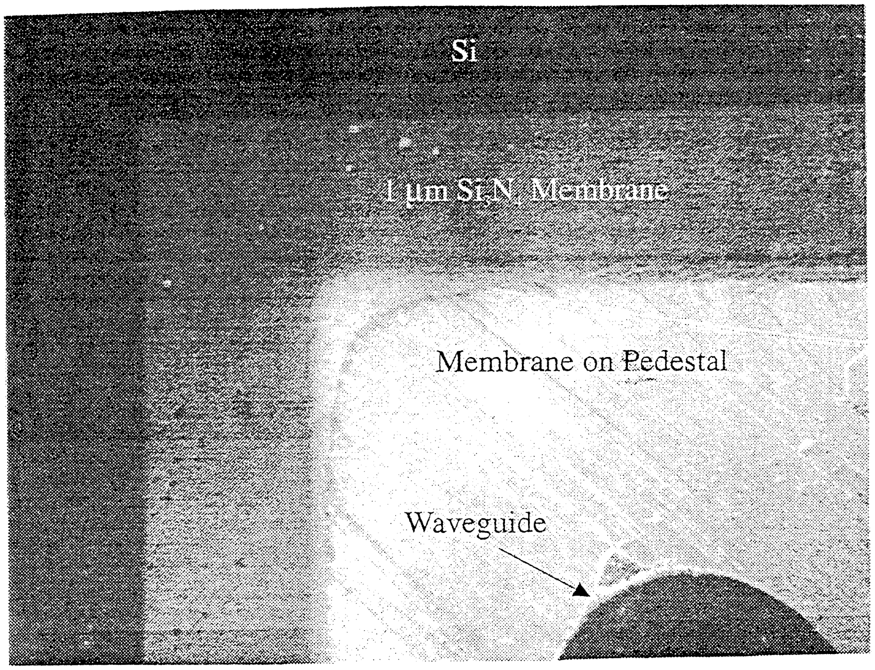

Fig. 2. Corner view of the silicon nitride membrane in contact with the pedestal. The silicon membrane extends 50 μm over the pedestal for stress relief. Of all the membrane junctions tested at LHe temperatures so far, none have been observed to fail.

To obtain a better understanding of the embedding impedance presented to a junction on a 1μm silicon nitride membrane mounted in a mixer, we performed a series of detailed scale model measurements. From it we determined an embedding impedance of 35 Ohm real, and have made the assumption in our computer simulations that this impedance is fixed (by adjusting both E-plane and backshort tuner accordingly).

JUNCTION DESIGN

Above the gap frequency of niobium, ($2\Delta/h \approx 690$ GHz), the photon energy is large enough to break Cooper-pairs in the superconductor causing large absorption losses in the niobium film. To minimize the absorption loss (calculated to be 50-65% per wavelength at 850 GHz, depending on the SiO insulator thickness) in the RF tuning structure above the gap it is important to keep the RF matching network as simple and short as possible. To this effect we have opted for the radial stub [7-9] matching network. The 850 GHz lumped element model is shown in figure 3. To tune out the large junction susceptance at 850 GHz an inductance made out of a small section of niobium transmission line is placed in parallel with the junction.

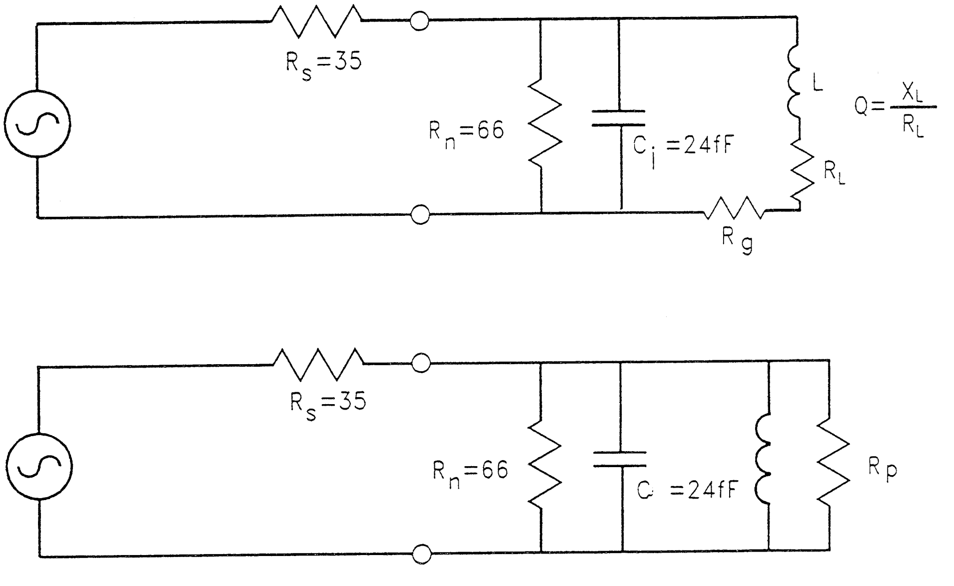

Fig. 3a, b. 850 GHz Radial stub model. R_p reduces the real part of the RF junction impedance at resonance. To obtain a low reflection (S11) coefficient and minimize the niobium absorption loss the junction normal state resistance R_n was chosen to be about 70 Ω.

If we define the Q as the reactive part over the dissipative part we see that

$$R_p = (1 + Q^2)(R_l + R_g) \tag{1}$$

R_p is in parallel with the RF resistance of the junction, $\approx R_n$. R_l presents the loss in the niobium transmission line and R_g the loss in the radial stub. Equation (1) can be simplified if we assume that $Q^2 \gg 1$ so that

$$R_p \approx \frac{X_l^2}{(R_l + R_g)} \tag{2}$$

Using this simple result we make several observations. Firstly, we can minimize the absorption loss in the niobium film by employing small area junctions which increases the transmission line reactance X_l. Secondly, the coupling efficiency is increased by decreasing Rn by means of employing high current density devices. And lastly, it can be shown (Zmuidzinas *et al.* [12]) that the niobium loss is minimized by maximizing the SiO insulating layer thickness to transmission line width ratio. In our case we have opted for an insulator thickness of 450 nm, which is a standard process in the JPL junction fabrication.

Given the discussed absorption loss we calculate that for an 35 Ohm embedding impedance optimum power transfer is obtained for a junction with a normal state resistance of ≈ 70 Ohm.

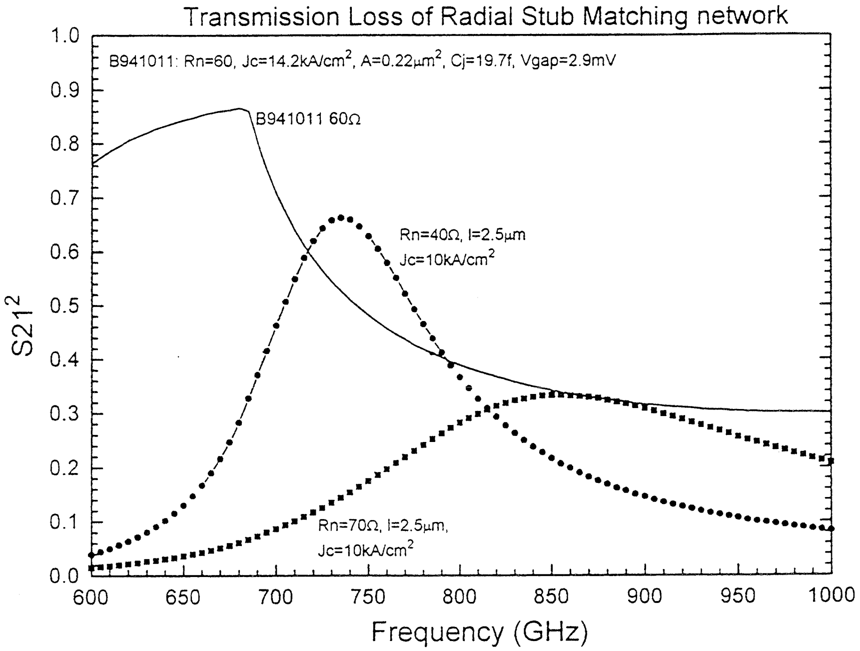

Fig. 4. Coupling efficiency calculations (based on the Mattis-Bardeen theory in the extreme anomalous limit) for both a conjugate input match (S11=0) and for two different area devices.

In our design we have opted for a $0.30\mu m^2$ area junction with a current density of 10,000 A/cm^2. The actual device has a current density of 14.2 kA/cm^2 and an area of $0.22\mu m^2$. The junction IV curves show a strong resonance from 1.4-1.8mV (670-867) GHz which is in good agreement with the video response measurements using a Fourier Transform Spectrometer (Fig. 6).

$Nb/AlO_x/Nb$ JUNCTION and CHIP FABRICATION

Our starting substrate is a (100) silicon wafer 254μm thick, 51mm diameter, and polished both sides with a 1μm coating of Si_3N_4 for subsequent membrane formation. Si_3N_4 is deposited under conditions for reduced compressive stress by low pressure chemical vapor deposition (LPCVD). Fabrication of the Nb/AlO$_x$/Nb tunnel junction is accomplished using a standard trilayer deposition technique [13, 14]. Here the trilayer is deposited by a lift-off process employing a multi- layer photolithographic technique using PMMA under AZ5214 photoresist. Magnetron sputter deposition and room temperature oxide growth are done in-situ in an ultra-high vacuum system with a base pressure of 2 x 10-9 Torr.

One side of the antenna/filter structure is formed by the trilayer with 160 nm Nb base, 6nm Al, and 90nm Nb counter-electrode . A junction mesa of 0.3 μm^2 area is defined by direct write electron beam lithography in a 100nm thick PMMA stencil. Chromium is deposited through the PMMA stencil and serves as an etch mask over 500nm of polyimide. Contact regions of the trilayer are then protected with a photoresist stencil. The combined chromium+photoresist/polyimide structure is etched using an oxygen reactive ion etch (RIE) process step. Polyimide remaining defines an isolation window and junction mesa for subsequent Nb RIE. To achieve Nb etch directionality we utilize a gas mixture of $62\%CCl_2F_2 + 31\%CF_4 + 7\%O_2$. Electrical isolation of the base electrode from the wire layer is provided by thermal evaporation of 200nm of SiO. Samples are rotated at a slight tilt angle during SiO deposition to assure both good isolation and self-aligned lift- off with the polyimide. After this lift-off step, another photoresist pattern is used to produce a total SiO thickness of 450nm under the tuning stub element.

The second half of the antenna/filter is formed by a blanket deposition of 250nm Nb capped with 30nm gold for contacts. RIE etching with an AZ5206 photoresist stencil defines this final front side pattern. Window openings are patterned on the back side by infra-red alignment to the front. This step is masked with AZ5218 photoresist which enables CF_4 + 19% O_2 RIE etching through the back side Si_3N_4.

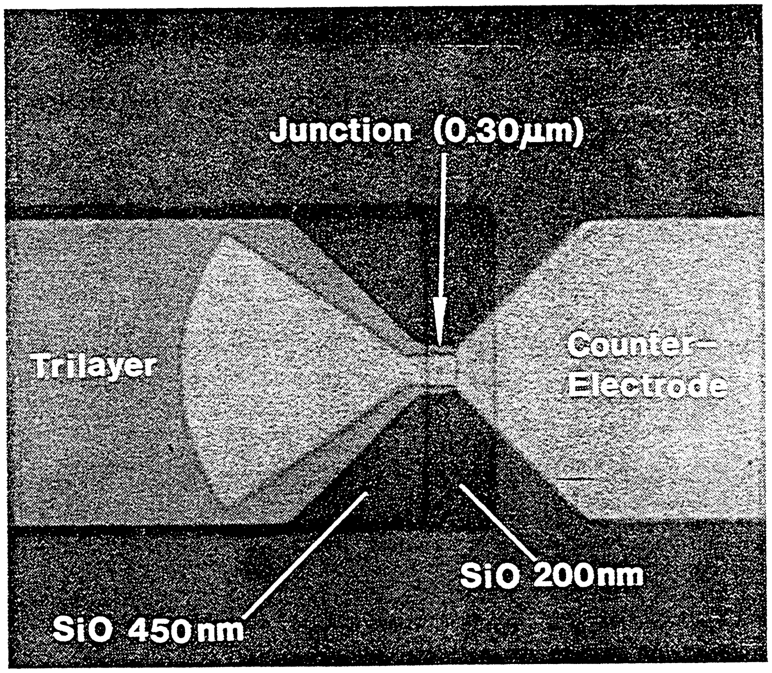

Fig. 5. 1000 X photograph of the junction on silicon membrane. The transmission line length is 2.5 μm on 450nm SiO which is terminated by a radial stub with a fan angle of 70 degrees. The junction size in the center of the bowtie antenna is 0.55 μm on a side.

Exposed silicon areas are anisotropically etched in a bath of 30% KOH solution at 70C. Etching stops after about eight hours when only the front side membrane and side (111) silicon planes are left exposed. The devices on the front are protected from the KOH solution by an 'O"-ring enclosure. Individual chips 1.78mm X 1.78mm are diced from the wafer using a diamond saw such that the wafer is mounted on the front side by wax to a backing substrate.

FTS MEASUREMENTS

To measure the response of the RF matching network we have tested junctions on 380μm SiO_2 and 1μm Si_3N_4 membranes as direct detectors on a Fourier Transform Spectrometer. These waveguide junctions have been mounted quasi-optically against a quartz hyperhemispherical lens as described by Büttgenbach *et al.* [4]. The advantage of this method is that there are no external tuning elements in the system as in the case with a waveguide mount, and as such the overall frequency response of the junction can be measured.

The disadvantage is that the junction's bowtie antenna and RF choke are mounted slightly out of focus on the back of an hyper-~~he~~mispherical lens. This presents an unknown and frequency dependent embedding impedance, which affects the magnitude of the video response. FTS measurements of a 345 tuned junction with known heterodyne response verify these arguments [5]

Figure 6 shows the measured video response for a 850 GHz junction on a 1μm Si_3N_4 membrane. A very similar frequency response was obtained with the junction mounted on SiO_2 (not shown) rather than on a silicon nitride membrane.

The difference being that the response of the SiO_2 mounted junction was a factor of two stronger than the junction mounted on the membrane.

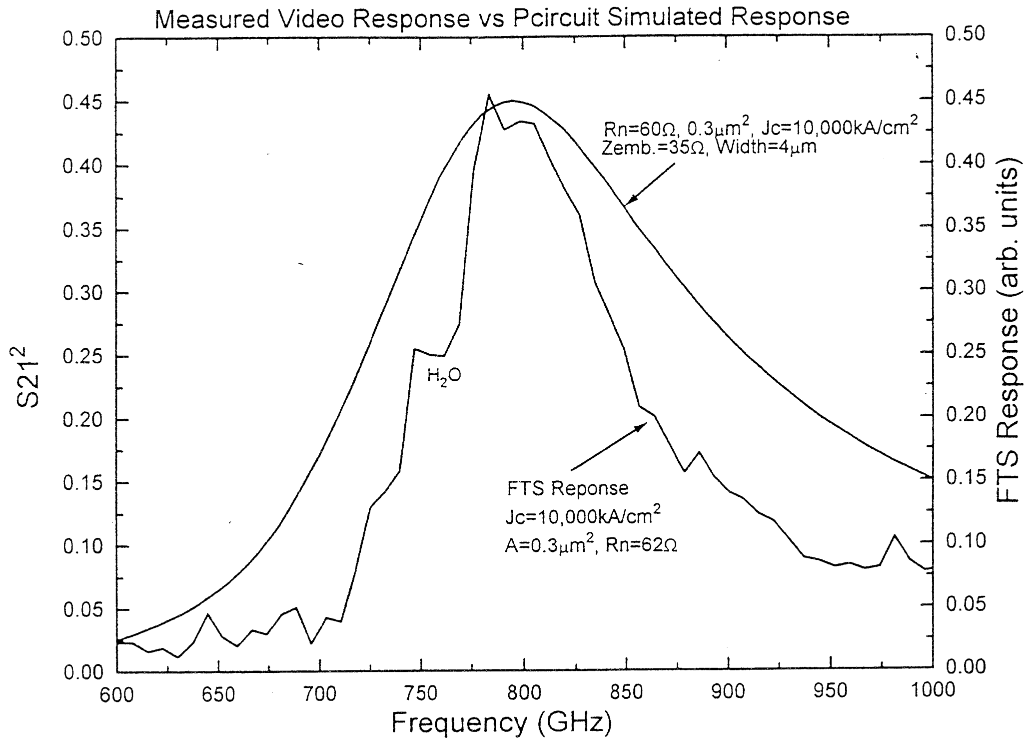

Fig. 6. Direct detection response of silicon membrane supported junctions from two different batches at 850 GHz. The inductive transmission line length used to tune out the junction capacitance is 2.5 μm.

This is probably caused by the high dielectric constant of Si (11.5) (mounted against the quartz lens) as compared to the membrane junction that had only a 25μm airgap. The measured video response of the junction shows reasonably good agreement with theory. We have superimposed the atmospheric window on top Mauna Kea in Hawaii to give some perspective to the broad response of the RF matching network.

Compared to FTS measurements on 665 GHz tuned junctions the response of the 850 GHz tuned junctions on silicon nitride membrane has degraded ≈ 4-7 dB. This is in fairly good agreement with the absorption loss predicted by the Mattis-Bardeen theory. Because of the many uncertainties in the optics of these quasi-optically mounted waveguide junctions and quality of the junctions, it is difficult to quote a more precise number.

The measured response is shifted down in frequency, compared to design, by about 50 GHz, 6%. Below the gap the radial stub has a rather narrow response due to the high Q, low loss, of the niobium transmission line. Above the gap however the response is smeared out a bit due to the loss of the niobium film. The magnitude of the measured response is not calibrated due to uncertainties in the optics of the system.

850 *GHz Results and Discussion*

The 822 GHz pumped/unpumped I-V curves and hot(285K)/cold(77K) total power response are shown in Figure 7. The Shapiro steps were carefully suppressed by adjusting the magnetic field. To further understand the breakdown of the measured 598K DSB receiver noise temperature shown in Figure 7, we employed a technique described by Blundell/Feldman *et al.* [15, 16]. By plotting the total IF power as a function of input load temperature for different values of LO drive level we obtained an equivalent front end receiver noise temperature of 160 ± 10 Kelvin, Shot noise calculated IF contribution of ≈ 5K and a mixer noise temperature of 513K.

The shot noise calculated DSB conversion loss is ≈ 12.4 dB, of which about

5.2 dB is due to the absorption loss and 7.2 dB due to the mixer. The receiver heterodyne response was optimized for lowest noise temperature (i.e. largest Y-factor) by tuning for maximum total power. When the receiver was cooled to 1.9K ambient temperature the receiver uncorrected noise temperature dropped about 25% to 450 Kelvin. A 10μm beamplitter was used in all measurements. The multipliers were provided by RPG-Physics[10].

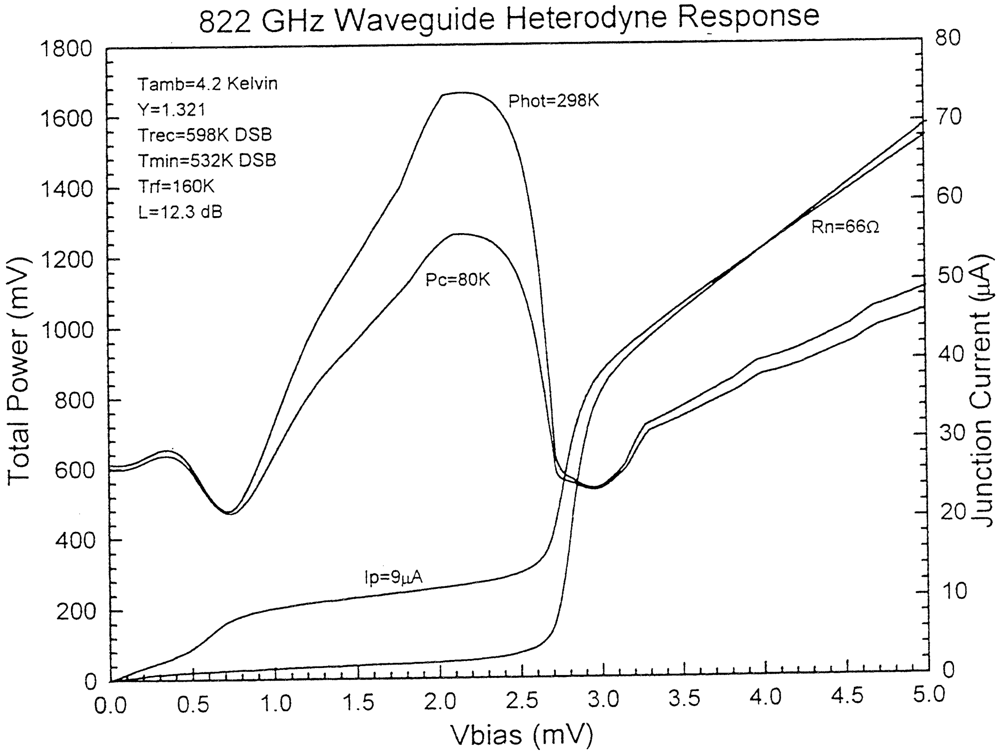

Fig. 7. I-V / Total power response. The optimum uncorrected receiver noise temperature at 822 GHz was 598 ± 5K, with 12.4 dB of mixer conversion loss. The junction has a resistive subgap to Rn ratio of ≈ 10. At 1.9 Kelvin ambient temperature this improved to 450K with a mixer loss of about 11.4 dB.

The measured frequency response of the 850 GHz receiver at both 4.2 and 1.9 Kelvin is shown in Figure 8. At 982 GHz the sensitivity has degraded to 2500K, DSB, which is due to both the loss in the niobium tuning circuit and inability to tune out the large junction capacitance.

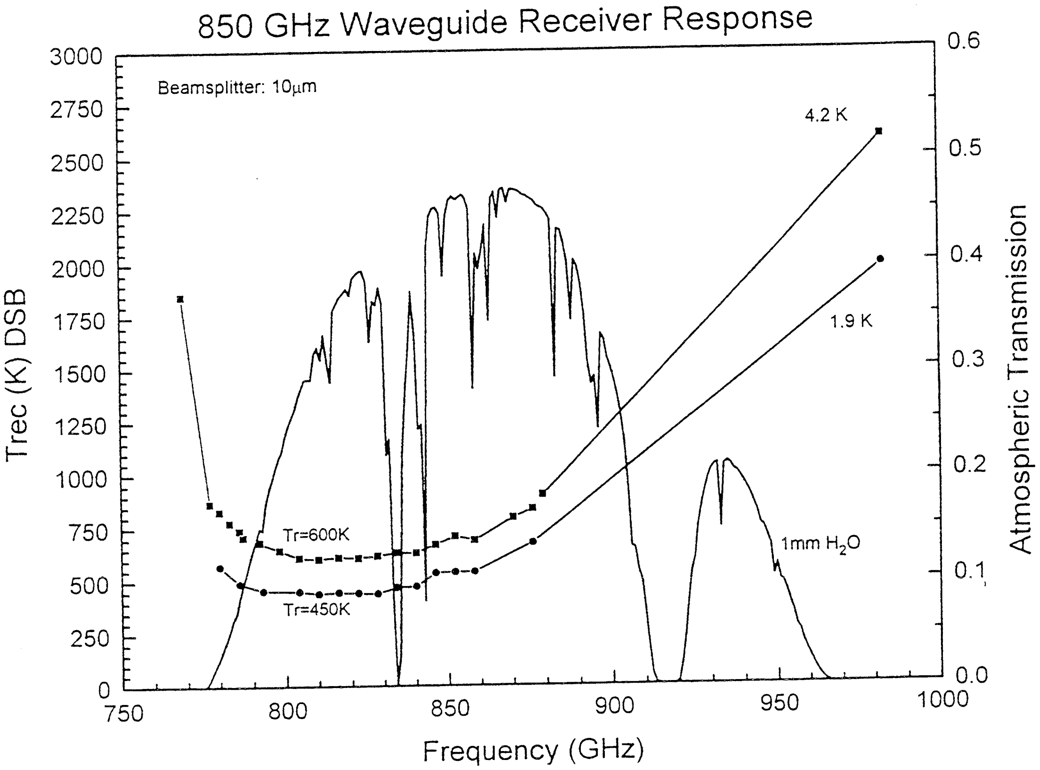

Fig. 8. Frequency response of the 850GHz waveguide receiver discussed. The receiver employs an Radial stub RF matching network and two mechanical circular tuners. Junction matching networks uses niobium wiring.

CONCLUSION

We have discussed the design and development of an 850 GHz waveguide heterodyne receiver employing a tuned $0.22\mu m^2$ Nb/AlO$_x$/Nb SIS tunnel junction on silicon nitride membranes. The junction membrane is mounted on a copper pedestal centered on the waveguide. Scale mixer model measurements show that the embedding impedance of the mixer block and RF choke/bowtie configuration is $\approx$ 35 Ω. A radial stub is used to tune out the large junction susceptance (ωRC $\approx$ 8.6 @ 850 GHz) and minimize the absorption loss of the niobium film.

Video response measurements with a Fourier Transform Spectrometer indicate response from 700-1100 GHz. This is confirmed by Josephson resonances in the I-V curve. From 800-840 GHz we report uncorrected receiver noise temperatures of 600K DSB with mixer temperatures of $\approx$ 513K. The calculated mixer conversion loss is about 12.4 dB, of which $\approx$ 7.2 dB is due to the mixer and $\approx$ 5.2 dB is due to the absorption loss in the niobium. At 890 GHz the sensitivity has degraded to 1000K, which is primarily due to the loss in the niobium tuning circuit. When cooled to 1.9K ambient temperature, the receiver noise temperature dropped to about 450K DSB from 790-840 GHz and increases to 2000K DSB at 982 GHz. Both FTS and heterodyne measurements are in fairly good agreement with the theoretical loss calculated from the Mattis-Bardeen theory in the extreme anomalous limit.

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