A LOW NOISE 230 GHz HETERODYNE RECEIVER EMPLOYING .25μm^2 Area Nb/AlO$_x$/Nb TUNNEL JUNCTIONS.

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Abstract

We report recent results for of a full height rectangular waveguide mixer with two tuning elements [1] and an integrated matching network. A .25μm^2 Nb/AlO$_x$/Nb superconducting insulating superconducting (SIS) tunnel junction was employed with $\omega RC \approx 1.7$ at 230 GHz. Detailed measurements of the receiver system noise have been made from 200-290 GHz with the junction at 4.2K. The lowest system noise temperature was recorded at 239 GHz, measuring 48 Kelvin DSB. Mixer noise and conversion loss have been calculated using the Shot noise method developed by Wengler and Woody [3]. System noise at 230 GHz has been evaluated both at 4.2K and 2.11K as a function of bias voltage, measuring 56K (DSB) and 47K (DSB) respectively. The 230 GHz receiver incorporates a one octave wide integrated low pass filter and matching network which transforms the pumped IF junction impedance to 50Ω over a wide range of impedances. It is believed that the receiver noise temperatures presented are the lowest yet reported for a 230 GHz receiver.

Introduction

The superconducting insulator superconducting (SIS) quasiparticle tunnel junction mixer has been shown to have great potential for producing heterodyne receivers approaching the quantum limit [2]. Feldman, [4] has shown that for slightly non ideal junctions using finite LO power the minimum noise temperature is controlled by the leakage current of the device. It will be seen that for the Nb/AlO_x/Nb high density tunnel junctions tested the noise level is in theory raised by a mere 3.6 K above that given by the quantum noise limit. For waveguide mixers it is important to use small ωRC junctions with a normal state resistance in the order of 50-100 Ohm. This allows the junction to be efficiently coupled to the embedding circuit. Nb/AlO_x/Nb high current density junctions with ωRC of $\approx$ 1.7 have been tested from 202 to 290 GHz at 4.2 Kelvin. Typical system noise temperatures are 55K DSB from 200-250 GHz. At 265 GHz a waveguide resonance was evident which makes tuning the junction to the embedding impedance virtually impossible, degrading the receiver noise temperature to 278K DSB. To minimize the added IF noise contribution to the system it is essential that the local oscillator pumped junction impedance is properly matched to the 50 Ohm IF load.

For astronomical purposes it is highly desirable to have as wide an IF bandwidth as possible. This is especially true for extragalactic molecular line observations. In addition, it is desirable to provide a short to any out of band signals to prevent the junction from saturating [5]. To meet all these all criteria an integrated matching network was designed, resulting in IF efficiencies of 96% or better from 1.0 to 2.0 GHz making the use of IF isolators unnecessary.

$Nb/AlO_x/Nb$ 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 0.004 inch 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 1200$\mathring{A}$ thick PMMA followed by evaporation of $\approx$ 500$\mathring{A}$ 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 1500Å 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.

Wideband Matching Network

The system noise temperature is given by:

$$T_{sys} = T_{mix} + \left(\frac{T_{if}}{C_{loss} * \eta_{if}}\right)$$

To improve system noise temperature it is important to lower the IF contributed noise by improving the IF coupling efficiency (η_{if}) and lowering the IF noise temperature (T_{if}) and/or conversion loss (C_{loss}). IF coupling efficiency is improved by achieving a better match between the pumped junction impedance and the 50 Ohm IF load. Reducing losses before the cooled low noise amplifier lowers the IF noise temperature as can be seen from:

$$T_{if} = T_{e1} + \left(\frac{T_{e2}}{G_1}\right) + \left(\frac{T_{e3}}{G_1 * G_2}\right),$$

where Te1 is the added noise contribution before the first amplifier.

Lastly, mixer conversion loss is improved by reducing RF losses and achieving a better match between waveguide and junction impedance. For practical reasons the IF bandwidth was set to be one octave wide, from 1.0 to 2.0 GHz. As was observed earlier it is especially important to provide a short for out of band signals when using high current density junctions [4]. This prevents possible saturation problems.

The criteria for the integrated matching network are summed up below:

-To integrate a 5 pole Chebyshev low pass filter and match to a 50 Ohm IF load impedance in one design.

-To allow for junctions with normal state resistances of 50-100 Ohm, with a preferred value of 70-90 Ohm. The IF impedance is usually two and a half times the value of the normal state resistance under typical operating, so the matching network is centered at 160 Ohm, real.

-To achieve a flat in band response: 1.0 - 2.0 GHz

S11<-10dB for Rp 100-300 Ω

S11<-20dB for Rp 160 Ω

This eliminates the need for a cooled isolator and excess semi-rigid coaxial cabling, reducing losses.

-Out of band response: 2.0-22 GHz

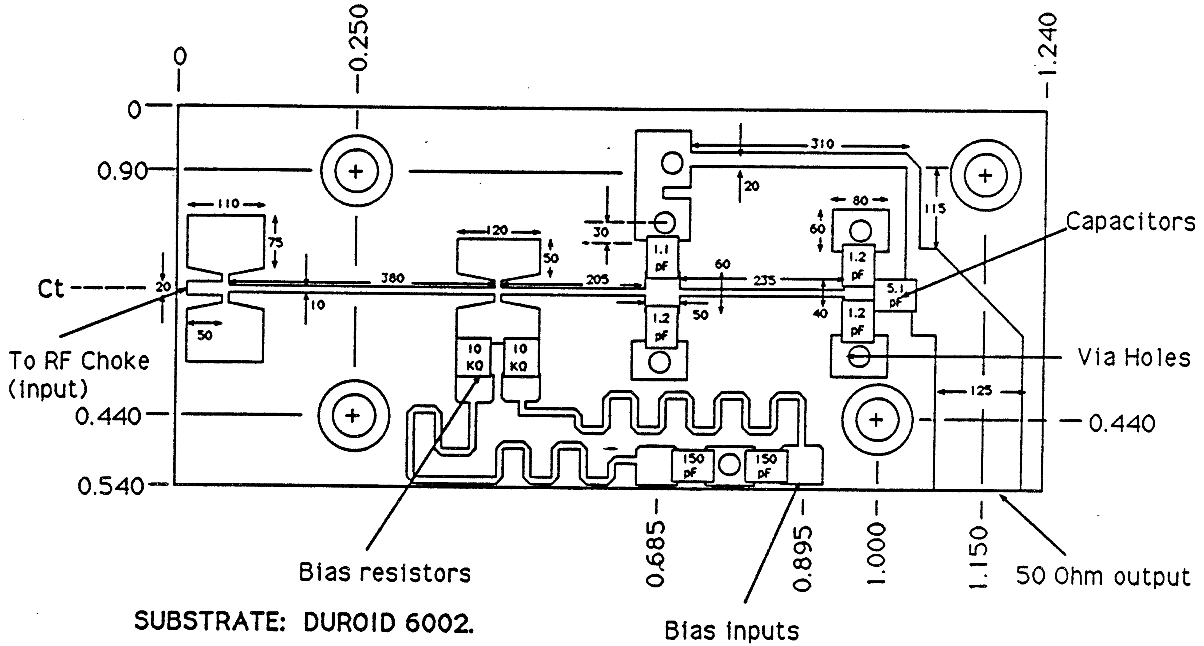
S11>-.005 dB (Short)

It is important to present a short to out of band signals to avoid saturating the high current density sub-micron tunnel junctions. Chip capacitors have a parallel resonance (open) at approximately 10 GHz, making them impractical to use above this frequency.

-Small physical size to reduce losses and allow the matching network to be easily incorporated in the junction block. Quarter wave sections are too large at 1.5 GHz center frequency to be used.

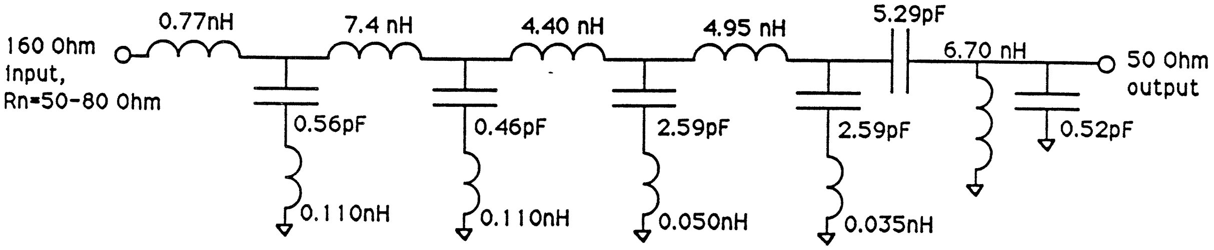
In designing a microstrip low pass filter a large ratio of high and low impedances sections is critical. With the physical line width limited to about 0.25 mm it became clear that a small dielectric constant (ϵ_r) board was to be used. Furthermore it is highly desirable to use a temperature stable PC board with matched coefficients of expansion to Copper since the operating temperature is 4.2 Kelvin. RT/Duroid 6002 softboard with an ϵ_r of 2.94 was used. To achieve a wide rejection bandwidth we opted not to use chip capacitors but rather to use distributed capacitance on the board, which provides a high degree of rejection up to 22 GHz. A five pole Chebyshev low pass filter and transformer was used to achieve the criteria listed above. To present a true 160 Ω real impedance to the junction we accurately modeled the

RF Choke and included it in our Touchstone (EESOF) models. Figure 1 shows the physical layout, Figure 2 the equivalent electrical circuit. Figures 3 shows S11, the input reflection coefficient of the matching network as measured on a HP8510 network analyzer.



SUBSTRATE: DUROID 6002.
Substrate thickness : 50
Scale : 5 to 1
Cover Height Above Substrate : 150
Note : All Dimensions are in Inches

Figure 1. Layout wideband matching network.



In band response (1.0 - 2.0 GHz) equivalent circuit:

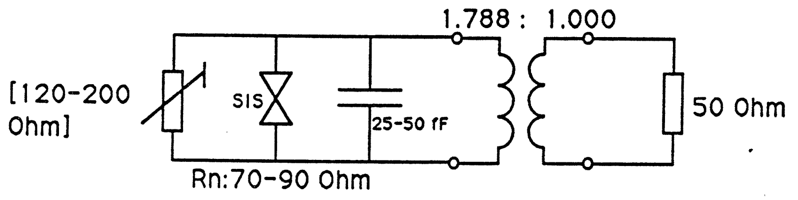


Figure 2. Equivalent electrical circuit.

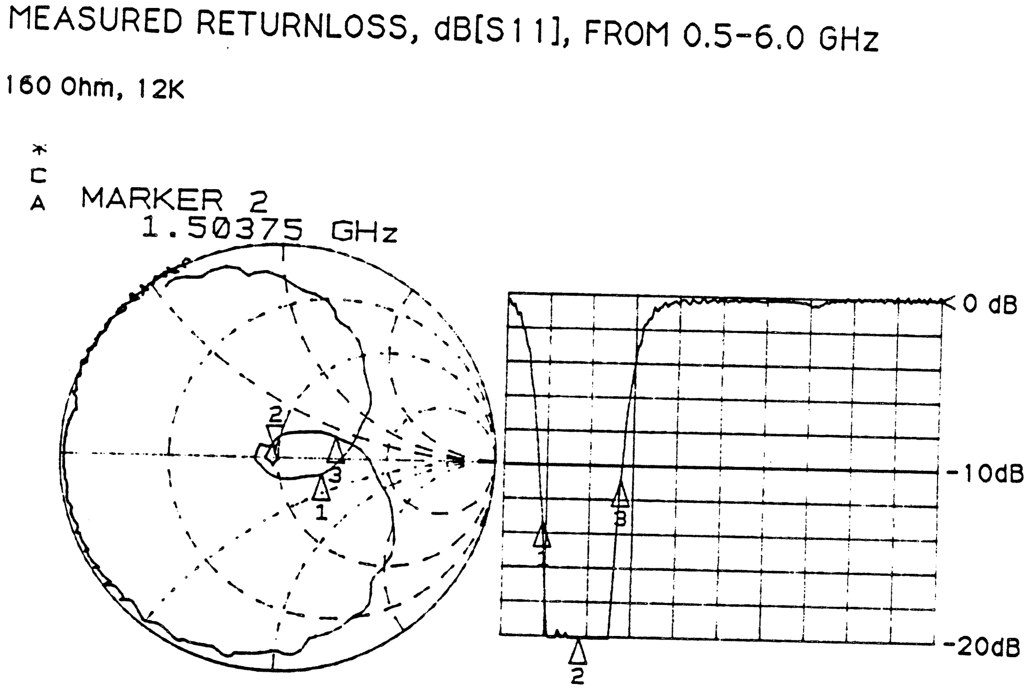


Figure 3. Input Reflection Coefficient (S11).

Measurements

Detailed measurements of receiver noise temperature (T_{sys}) were made from 202-290 GHz in 29 steps. The IF noise temperature (T_{if}), mixer noise temperature (T_{mix}) and conversion loss (C_{loss}) were all calculated using the 'Shot noise method' [2]. This method has to be modified to account for the different matching conditions in the normal state and pumped regions. One of the advantages of the integrated matching network is that the IF impedance presented to the junction is accurately known. The test setup is shown in Figure 4. The IF output of the 230 GHz mixer block was fed directly into the low noise amplifier. A 500 MHz LNA was used temporarily, to be replaced with a modified octave wide balanced HEMT amplifier centered at 1.5 GHz [6]. The IF spectral response for hot and cold loads was measured from 1.25-1.75 GHz, deviating less than 1 dB across the band. The LO is applied via a 0.5 mil Mylar beam splitter to the junction. During the tests the mixer was tuned for maximum noise output power, which is achieved when the junction is best matched to waveguide (low conversion loss).

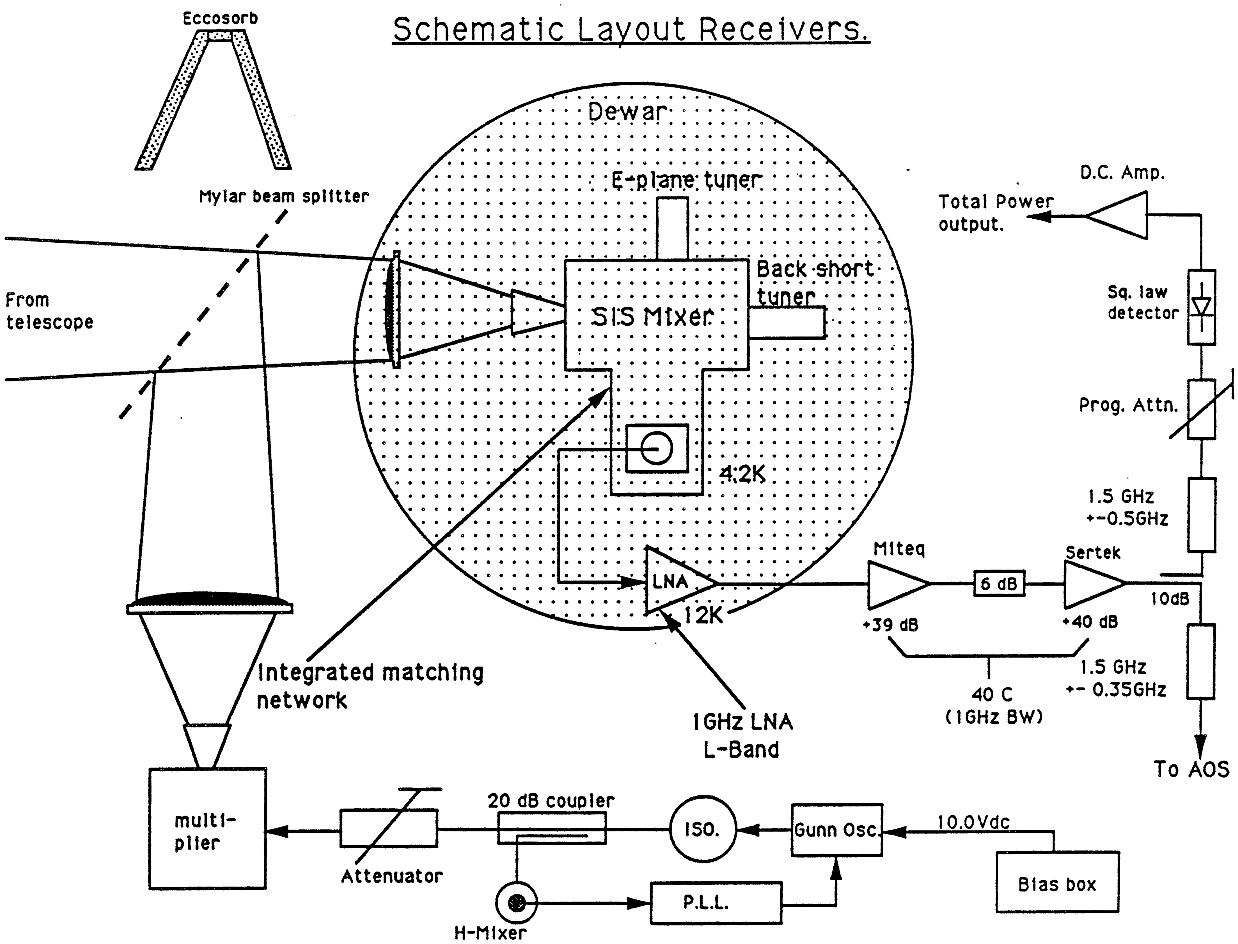


Figure 4. Schematic layout of the receiver.

The IF match generally remained good over a wide range of tuning conditions. The Y-factor measurement was independently verified using an HP 8562A Spectrum Analyzer, HP 436A Power meter and an HP 8472A Power detector. All measurements agreed within 5%. Data was also taken both at 4.2K and 2.11K with the same setup.

Results and discussion

Nb/AlO_x/Nb tunnel junctions with areas of .49μm^2, .33μm^2 and .25μm^2 and a ωRC product of 1.7 were mounted and tested in the receiver setup shown in figure 4. C_s for Niobium is taken to be 50fF/μm^2, however, there is reason to believe that it could be as large as 80fF/μm^2. If this is true the ωRC product can be as high as 2.7 at 230 GHz. The best noise performance was clearly obtained with the $.25\mu m^2$ area junctions. This is expected as these junctions have the smallest shunt capacitance (12.5fF-20fF) and the largest normal state resistance (95Ω). This combination gives the best RF match while not significantly degrading the IF match (>96%).

The real part of the LO pumped IF impedance can be obtained from the slope of the I-V curve and is observed to be about $(2.5\text{-}3.0)R_n$ under normal operating conditions.

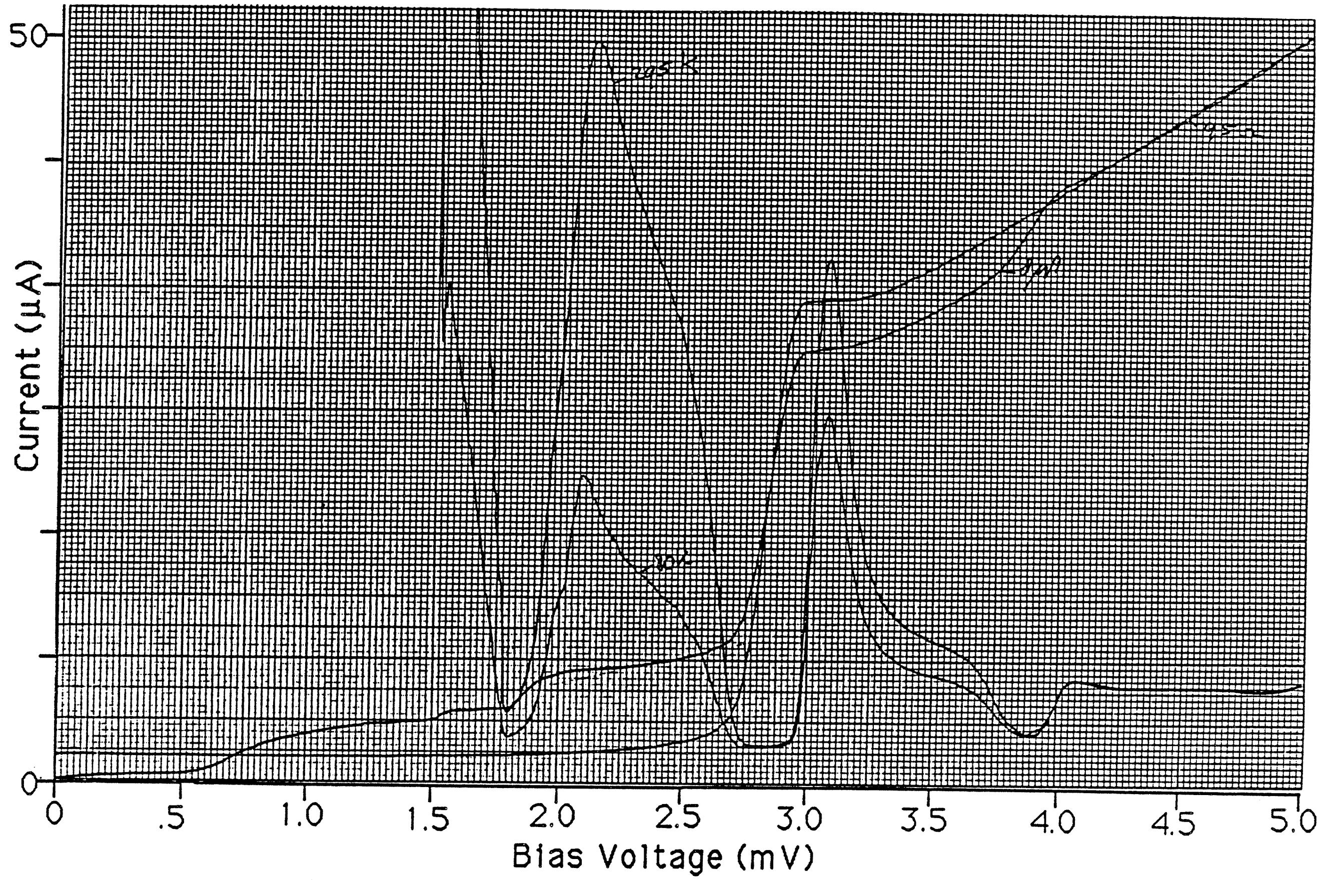


Figure 5. Nb/AlO$_x$/Nb I-V curve and IF response at 230 GHz.

Figure 5 shows the IV curve of a $.25\mu m^2$ area junction at 239 GHz and an operating temperature of 4.2 Kelvin. Four curves are shown: The unpumped and pumped I-V curves, and the hot load (295K) and cold load (80K) responses. The quasi-particle step (hν/e) at 239 GHz is .98 mV which can be easily verified from the pumped I-V curve. The typical bias voltage is Vgap minus half the photon step, ≈ 2.35 mV. The sub-gap leakage or dark current at this bias point is seen to be 2.7 µA. Figure (9) shows that the typical operating condition to achieve maximum sensitivity is about 3 times the sub-gap leakage current at the proper bias point. This has been observed for Pb junctions as well. In this case the LO power on the junction was adjusted to register 8μA at 2.35 mV bias.

Figure 5 shows a Y-factor of about 2.70 at 239 GHz, corresponding to a system noise temperature of 48K DSB, which was the lowest value obtained at 4.2 kelvin. The IF noise contribution was calculated to be 10K giving a mixer noise temperature of 38K DSB. The first quasi-particle step shows up at (Vgap-hν/e) or 1.8 mV and the fourth Josephson step at 2mV, 4*($h\nu/2e$).

Feldman [3] has shown that for slightly non ideal junctions using finite LO power the minimum noise temperature is controlled by the leakage current of the junction at the bias point. Using Feldman's result we find, for the .25μm^2 junction tested that the theoretical device noise temperature has a value of 9.1K SSB or about 3.6K above the quantum noise limit.

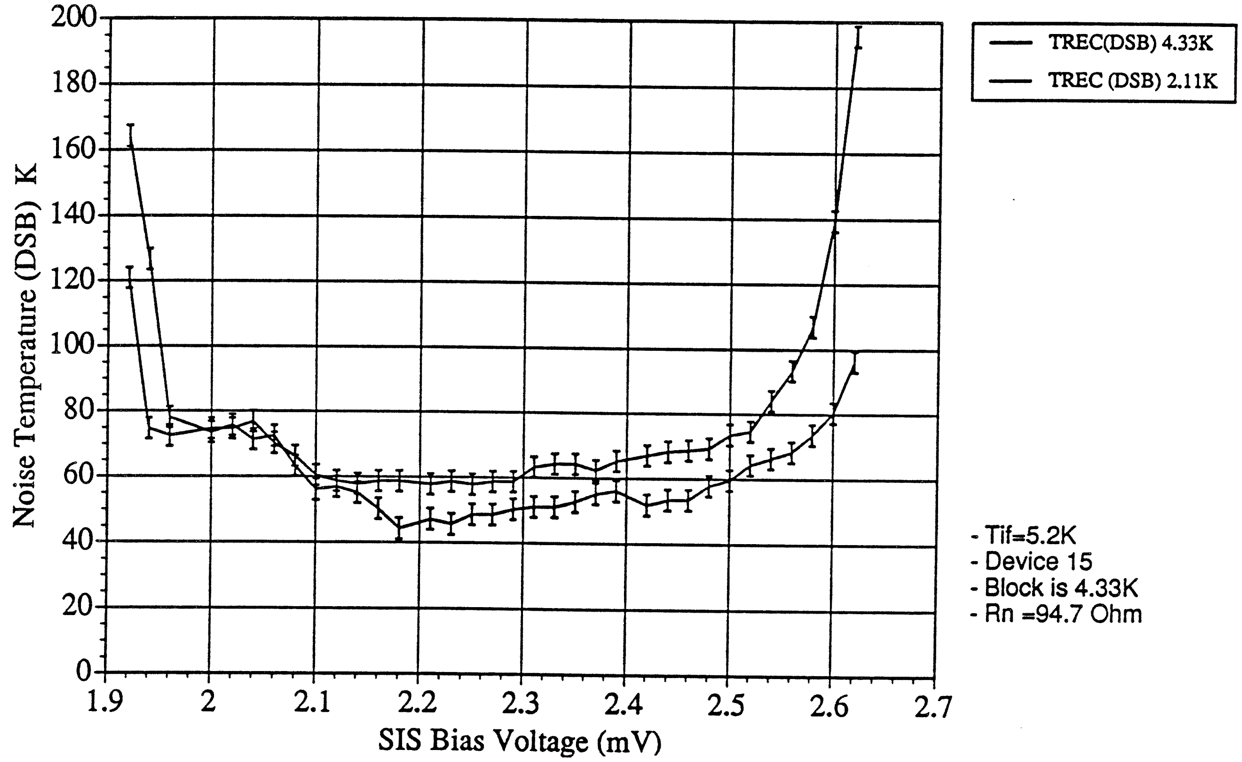


Figure 6. Receiver noise temperature at 230 GHz.

Cooling the junction to 2.11K shifted the gap voltage from 2.8mV to 2.95mV and decreased the sub-gap leakage current from 2.7μA to 2.0μA at 2.35 mV bias. Upon cooling the junction the receiver noise temperature at 230 GHz decreased by 9K, to 47K DSB, and the conversion loss went down 26% from 3.5 dB to 2.6 dB. This is probably due to the reduction in leakage current and change in gap voltage. The shape of the I-V curve did not change significantly.

Figure 6 shows the receiver noise temperature at both 4.33 and 2.11 Kelvin. Note the change in gap voltage as the junction is cooled.

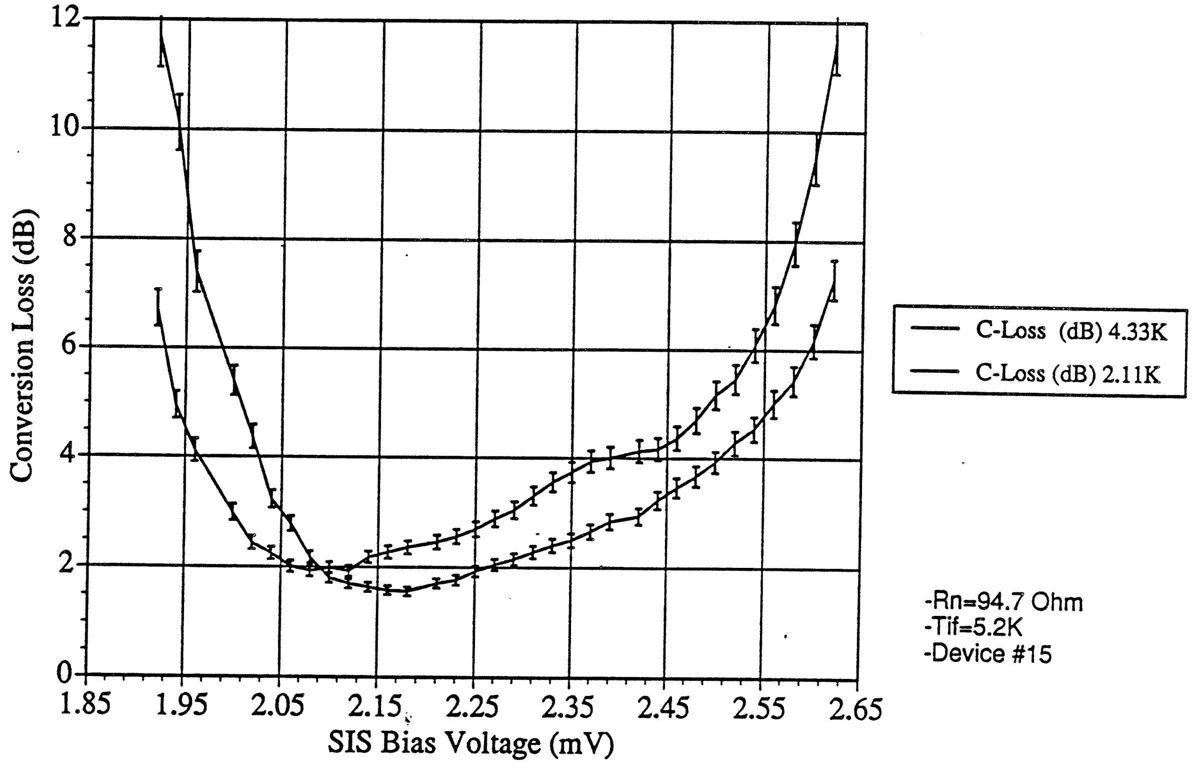


Figure 7. Mixer Conversion Loss at 230 GHz.

Figure 7 shows the conversion loss as a function of bias voltage measured both at 4.33 and 2.11 Kelvin. Note the sharp decrease in conversion loss at 2.35 mV bias as the curve shifts to the right due to a change in gap voltage. Figure 8 shows the receiver and mixer noise temperatures at 202 GHz. The difference in the curves is the IF noise contribution, about 10K. Figure 9 shows the receiver heterodyne response to LO power. Figure 10 shows the frequency response from 202 - 290 GHz for a .25μm^2 area junction, note the sharp rise in noise temperature at 265 GHz. The resonance was shown to be caused by the junction mount perturbing the waveguide, setting up undesirable modes [7]. This cross-mode coupling effectively changes the embedding impedance making a good RF match to the junction nearly impossible.

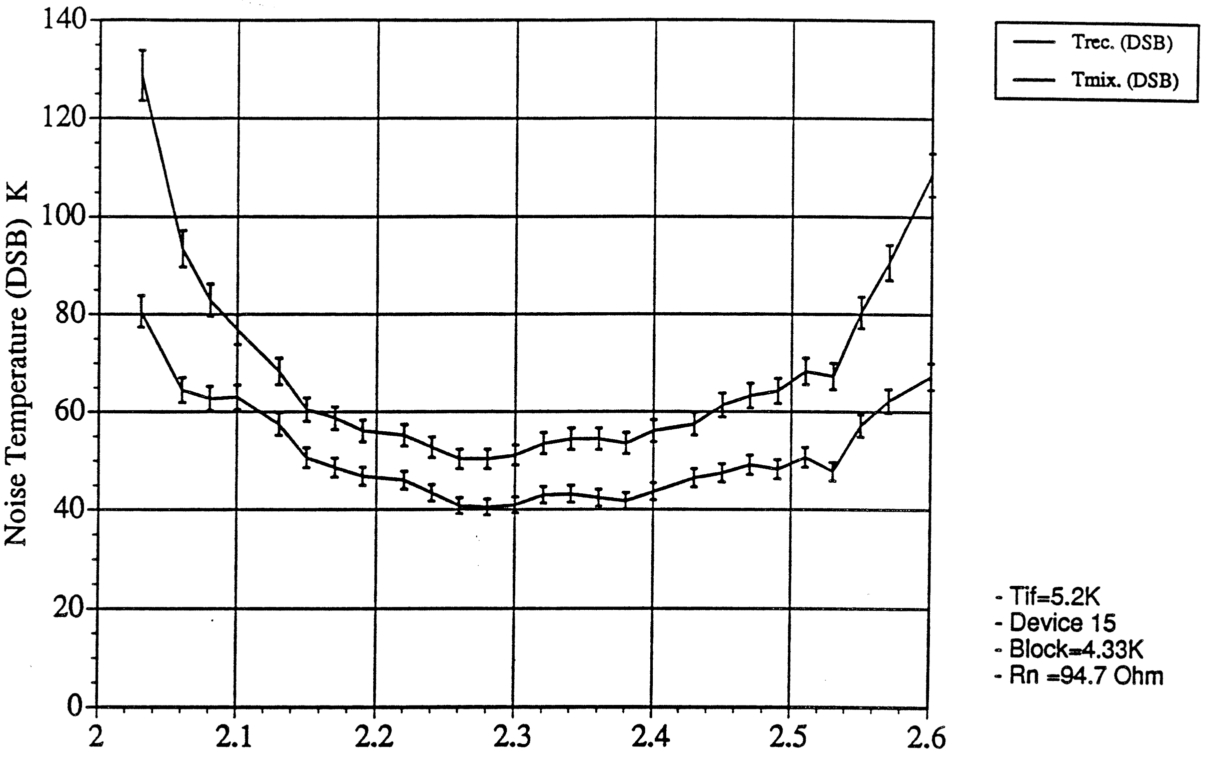


Figure 8. Receiver and Mixer noise temperature at 202 GHz.

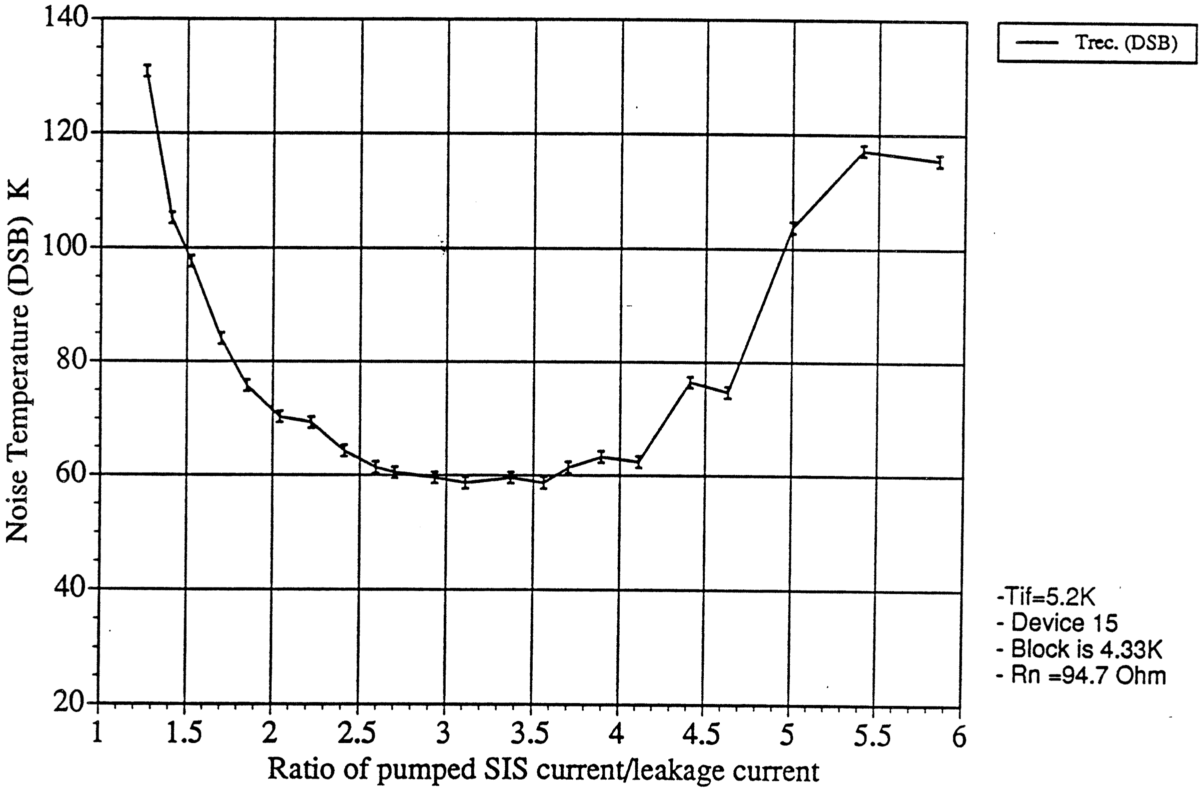


Figure 9. Receiver sensitivity as a function of LO power.

The junction was mounted in the center of the waveguide where computer models have shown the resonance to be the weakest. The resonance for Nb junctions appear stronger than their Pb counterparts perhaps in part due to a larger ωRC product than we expect. This would support the earlier argument that perhaps the C_s of Niobium is larger than the assumed $50fF/\mu m^2$. Data from a physically similar $.49\mu m^2$ area junction with twice the shunt capacitance (25fF) shows a waveguide resonance at 250 GHz. The model predicts that the frequency where other modes are excited is solely dependent on the geometry of the junction mount and not in any way on the junction shunt capacitance. If this is true it would indicate that the change in resonant frequency seen is more a result of change in geometry rather than junction capacitance. This is an area that clearly needs more investigation. The conversion loss at the resonance increased to 11dB, confirming the inability to achieve a proper RF match under resonant conditions. Theoretical analysis shows that the resonance is pushed out of band when the waveguide height is reduced by 20%.

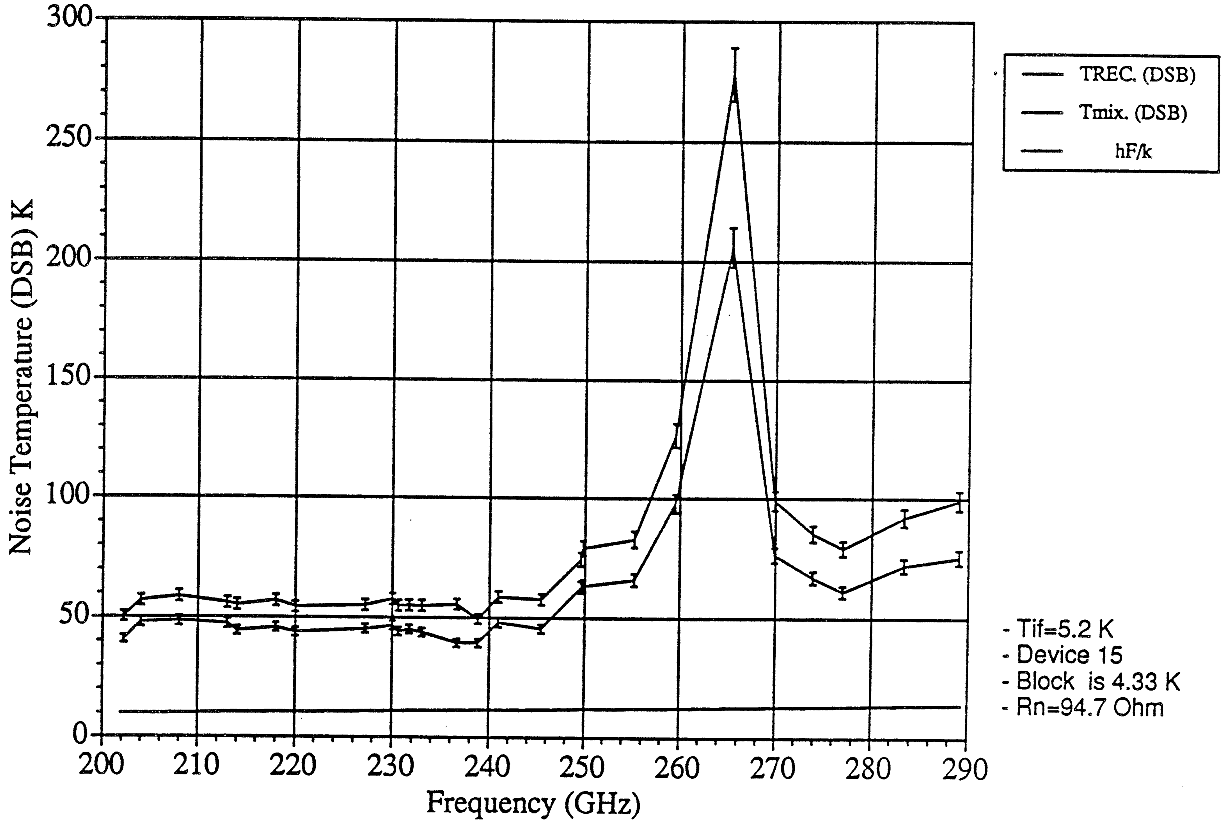


Figure 10. Frequency response of the 230 GHz waveguide Receiver.

Acknowledgments

We wish to thank Pat Schaffer for invaluable work on the receiver cryostat. Work at Caltech is supported in part by NASA *grant*# NAGW-107 and NSF *grant*# AST-9015755.

Summary

A 230 GHz SIS receiver with a wideband integrated matching network has been developed and tested using sub-micron Nb/AlO_x/Nb tunnel junctions. Detailed data has been taken from 202 to 290 GHz at 4.33 Kelvin. The receiver has a typical double sideband noise temperature of 56K from 200 GHz to 250 GHz. At 265 GHz the receiver noise temperature degraded to a 278K which is probably caused by cross-mode coupling due to the junction mount perturbing the waveguide. The lowest system noise temperature (48K DSB) and mixer noise temperature (38K DSB) were recorded at 239 GHz.

Data taken at 2.11 Kelvin and 230 GHz indicates that the mixer performance depends on the sub-gap leakage current of the junction. Conversion loss and mixer noise temperature decreased 26% and 16% respectively upon cooling the junction from 4.33 to 2.11 Kelvin.

Lastly, the importance of a proper IF match has been examined and experimentally verified.

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