A Low Noise 230 GHz Heterodyne Receiver Employing .25 μm^2 Area Nb/AlO$_x$/Nb Tunnel Junctions

Jacob W. Kooi, M. Chan, T. G. Phillips, B. Bumble, and H. G. LeDuc

***Abstract*—We report recent results for a full height rectangular waveguide mixer with an integrated IF matching network. Two .25 μm^2 Nb/AlO$_x$/Nb superconducting insulating superconducting (SIS) tunnel junctions with a current density of ≈8500 A/cm^2 and ωRC of ≈2.5 at 230 GHz have been tested. One of these quasiparticle tunnel junctions is currently being used at the Caltech Submillimeter Observatory in Hawaii. Detailed measurements of the receiver noise have been made from 200–290 GHz for both junctions at 4.2K. The lowest receiver noise temperatures were recorded at 239 GHz, measuring 48K DSB at 4.2K and 40K DSB at 2.1K. The 230 GHz receiver incorporates a one octave wide integrated low pass filter and matching network which transforms the pumped IF junction impedance to 50 Ω over a wide range of impedances.**

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 [1]. The recent results are achieved by employing a .25 μm^2 Nb/AlO$_x$/Nb tunnel junction in a full height rectangular waveguide mixer [2] with two tuning elements and an integrated IF matching network. It is believed that the receiver noise temperatures presented for these Nb tunnel junction mixers, along with recent results reported by NRAO [3], are the lowest yet reported for the 200–290 GHz band.

For waveguide mixers it is important to use relatively small ωRC junctions with a normal state resistance in the order of 50–100 Ω. This allows the junction to be efficiently coupled to both the IF and waveguide embedding impedance, minimizing the mixer conversion loss. Nb/AlO$_x$/Nb high current density junctions have been tested from 202 to 290 GHz at 4.2K. Typical receiver noise temperatures are 55K DSB from 200–250 GHz. At 267 GHz a sharp waveguide resonance [7]–[10] was evident which makes tuning the junction to the embedding impedance difficult, degrading the receiver noise temperature to 370K DSB. To minimize the added IF noise contribution to the receiver it is essential that the local oscillator pumped junction impedance is properly matched to the 50 Ω 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 circuit to any out of band signals to prevent the junction from saturating [6]. To meet all these criteria an integrated IF matching network was designed, resulting in IF coupling 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 120 nm thick PMMA followed by evaporation of ≈50 nm chromium metal and subsequent lift-off. Contact regions of the triayer 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 W/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 μm^2 were fabricated using this technique.

WIDEBAND IF MATCHING NETWORK

The receiver noise temperature is given by

$$T_r = T_m + \left(\frac{C_L * T_{if}}{\eta_{if}}\right).$$

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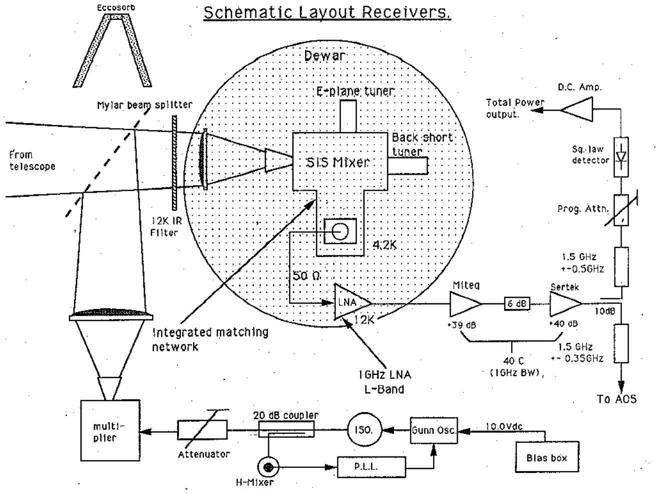

Fig. 1. Schematic layout of the receiver. Beam splitter and window reflection losses at 230 GHz contribute about 7.5K to the receiver noise temperature. The matching network is integrated in the mixer block and connected to the LNA [12] via a 3 inch stainless steel semi-rigid coaxial cable. The IF passband is from 1.0 to 2.0 GHz.

Where the mixer noise temperature (T_m) includes front end losses. The conversion loss (C_L) includes any RF loss and RF and IF mismatch and (η_{if}) includes IF reflection losses. Mixer noise and conversion loss have been calculated using the Shot noise method developed by Woody, Miller and Wengler [4].

To improve the receiver noise temperature (T_r) it is important to minimize both RF and IF contributed noise. The front end losses include beam splitter, vacuum window, IF filter, focussing lens, antenna horn efficiency and waveguide reflection and transmission losses (Fig. 1). The beamsplitter and vacuum window use 12 and 25 μm thick Mylar, respectively. The $\lambda/2$ Fluorgold Infra Red filter was placed at the 12K stage. As compared with an earlier version [2] the IF noise contribution was reduced by improving the IF coupling efficiency (η_{if}), lowering the IF noise temperature (T_{if}) and reducing the conversion loss (C_L). The IF coupling efficiency was improved by obtaining a better match between the pumped junction impedance and the 50 Ω IF load so eliminating the need for an isolator between the cooled LNA and mixer block. The mixer conversion loss was reduced by improving the RF match between the waveguide embedding impedance and the junction. This was effectively achieved by employing a small area Nb/AlO$_x$/Nb tunnel junction. The normal state resistance of the .25 μm^2 Area Nb/AlO$_x$/Nb tunnel junctions with a current density of ≈ 8500 A/cm^2 is about 90 Ω.

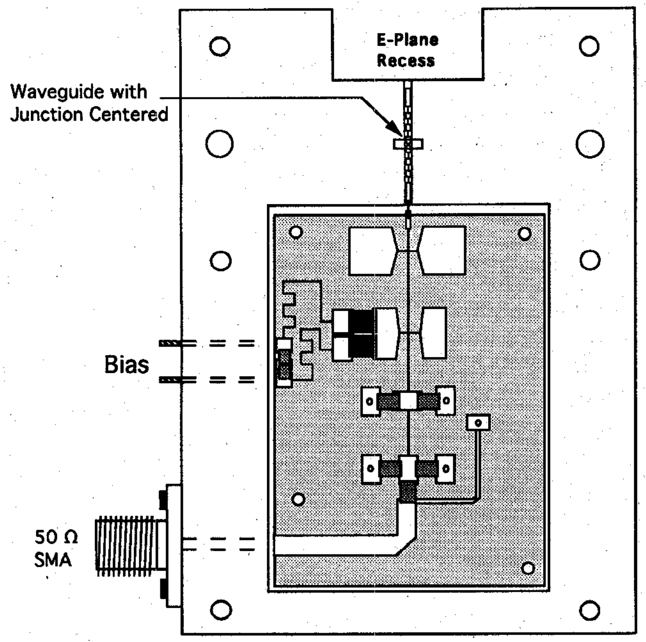

Fig. 2. Physical layout of the mixer block with IF integrated matching network. The distributed capacitances are 0.5 pF and 0.3 pF, respectively. The four lumped capacitors are 1.1 pF each.

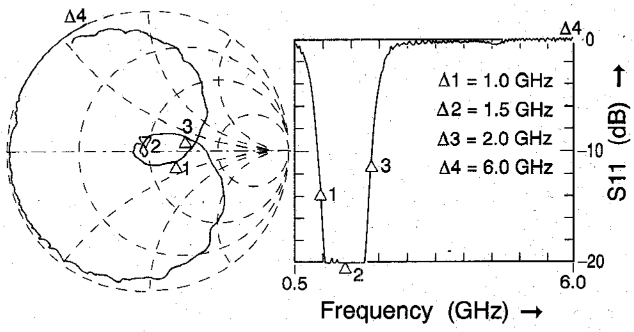

Fig. 3. Measured input impedance and return loss from 0.5–6.0 GHz into a 160 Ω load at 12K. Care must be taken when presenting a capacitive short circuit to out of band IF frequencies [6], too large a susceptance makes a wide band IF match virtually impossible.

There are several design criteria for integrating the matching network in the mixer block. The IF impedance typically should be two and a half times the value of the normal state resistance under normal operating conditions [11]. Also, it is important to present a short circuit to out of band signals to avoid saturating the high current density sub-micron tunnel junctions [6]. Unfortunately conventional chip capacitors have a parallel resonance (open) at approximately 10 GHz, making them impractical to use above this frequency. Instead we opted to use distributed capacitance on the microstrip board, which provides a high degree of rejection up to 22 GHz (Fig. 2). A further criterion was to minimize the physical size. This allows the matching network to be easily incorporated in the junction block. To avoid using large quarter/wave sections we decided on using a 5 pole Chebyshev lowpass filter and transformer. Fig. 3 shows S11(dB), the input reflection coefficient of the matching network as measured on a HP8510 network analyzer.

RESULTS AND DISCUSSION

Nb/AlO$_x$/Nb tunnel junctions with areas of .49 μm^2, .33 μm^2 and .25 μm^2, $J_c \approx 8500$ A/cm^2, and ωRC products of ≈ 2.5 were mounted and tested in the receiver setup shown in Fig. 1. Measurements on the mixer performance indicate that the C_s for small area Nb junctions ≈ 75 fF/μm^2 rather than the 50 fF/μm^2 as measured for bulk material. The best noise performance was clearly obtained with the .25 μm^2 area junctions. This is expected as these junctions have the smallest shunt capacitance and the largest normal state resistance. This combination gives the best RF match while not significantly degrading the IF match (>96%). Measurements indicate that the mixer conversion loss with Nb junctions is typically 2-3 dB better than with similar ωRC product Pb junctions. This is thought to be primarily due to the sharper knee of the Nb I-V curves. 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. Fig. 4 shows the I/V curve of a .25 μm^2 area junction at 239 GHz at an operating temperature of 4.2K. Four curves are shown: The unpumped and pumped I-V curves and the hot load (295K) and cold load (77K) responses. The quasi-particle step width $(h\nu/e)$ at 239 GHz is .98 mV as observed from the pumped I-V curve. The typical bias voltage is Vgap minus half the photon step width, $\approx$2.30 mV. The sub-gap leakage or dark current at this bias point is seen to be 2.7 μA. Fig. 4 shows a Y-factor of about 2.70 at 239 GHz, corresponding to a receiver noise temperature of 48K DSB, which was the lowest value obtained at 4.2K. The IF noise contribution was calculated [4] to be 10K giving a mixer noise temperature of 38K DSB, of which 7.5K can be attributed to beamsplitter and dewar window reflection losses. The first quasi-particle step shows up at (Vgap-$h\nu/e$) or 1.8 mV and the fourth Josephson step at 2mV, $4^*(h\nu/2e)$. No magnetic field was applied to the junction in this receiver.

Feldman [5] 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 .25 μm^2 junction tested that the theoretical device noise temperature is $\approx$3.6K above the single sideband quantum noise limit, $(h\nu/2k)$. At 4.2K the best mixer noise temperature is about 38K DSB, 8 times the Feldman limit.

Cooling the junction to 2.1K shifted the gap voltage from 2.8 mV to 2.95 mV and decreased the sub-gap leakage current from 2.7 μA to 2.0 μA at 2.30 mV bias. Upon cooling the junction the receiver noise temperature at 239 GHz decreased by 8K, to 40K DSB. The calculated mixer noise temperature and conversion loss (DSB) were both reduced by 19%. This is probably due to the sharpening of the I/V curve and reduction in leakage current. Fig. 5 shows the receiver noise temperature at both 4.2 and 2.1K at 230 GHz. Fig. 6 shows the conversion loss as a function of bias voltage measured both at 4.2 and 2.1K. Note the sharp decrease in conversion loss at 2.30 mV bias as the curve shifts to the right due to a change in gap voltage. Measured data indicates that the typical operating condition to achieve maximum sensitivity is about $(.33\text{-}50)I_c$. The critical current (I_c) for the junctions tested is about 21 μA. the pumped I-V curve (Fig. 2) indicates that about 18nW (−47 dBm) of LO power is incident on the junction. The LO power on the junction under normal bias conditions was adjusted to register 9 μA at 2.30 mV bias.

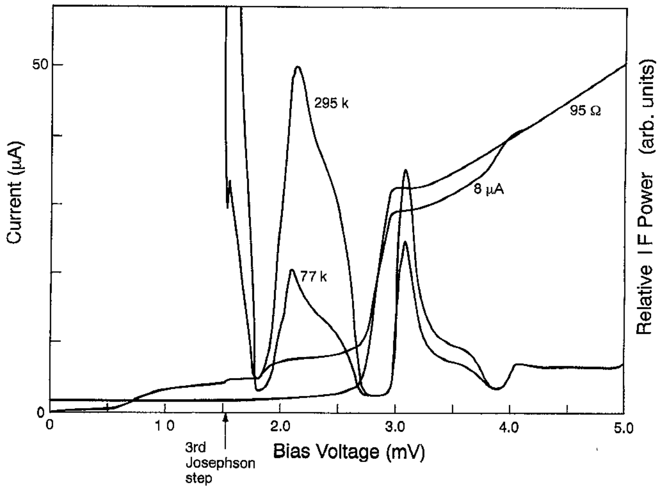

Fig. 4. Heterodyne response of the 230 GHz waveguide mixer at 239 GHz using a .25 μm^2 area Nb/AlO$_x$/Nb junction. Shown is the IF power as a function of bias voltage for hot (295K) and cold (77K) loads at the receiver input). Also shown is the pumped I-V curve. At 2.30 mV the receiver noise temperature measured 48K DSB with no magnetic field applied.

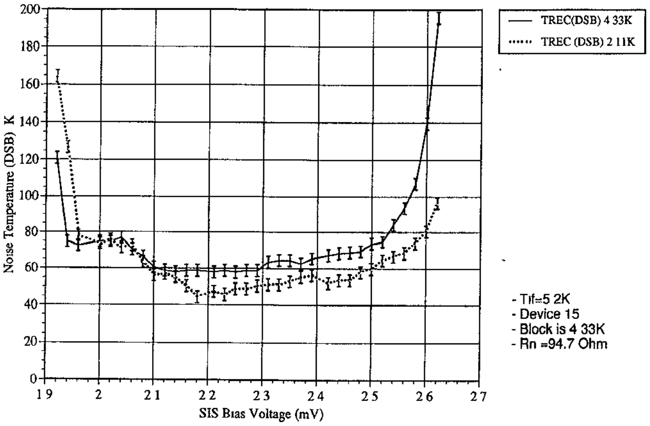

Fig. 5. Receiver noise temperature at 230 GHz as a function of bias voltage and temperature. The mixer is typically biased around 2.30 mV, half a photon step below the gap.

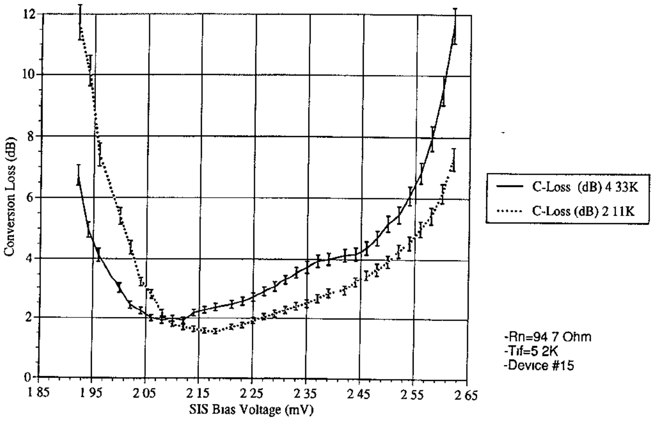

Fig. 6. Mixer conversion loss at 230 GHz as a function of bias voltage and temperature. Cooling the junction shifted the gap voltage from 2.8 mV to 2.95 mV. Sharpening of the I/V curve and reduction in leakage current reduced the conversion loss by about 19% at 2.30 mV bias.

Fig. 7 shows the frequency response from 205-285 GHz for the 230 GHz receiver in situ at the telescope. Note the sharp rise in noise temperature at 267 GHz. The reso-

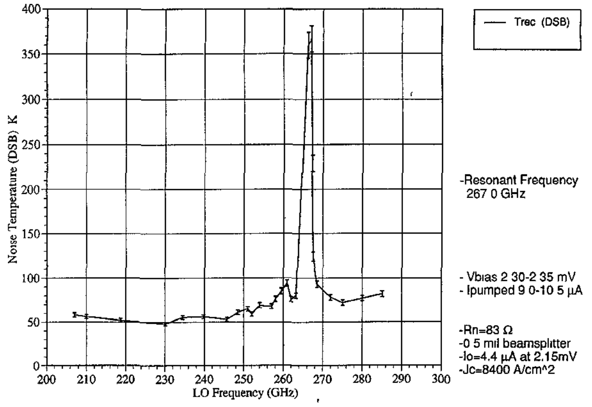

Fig. 7. Frequency response of the 230 GHz waveguide receiver *in situ* at the telescope. The resonance has been shown to be caused by the junction mount perturbing the waveguide, setting up undesirable modes [7].

nance was shown to be caused by the junction mount perturbing the waveguide, setting up undesirable modes [7]–[10]. This cross-mode coupling effectively shorts the embedding impedance making a good RF match to the junction nearly impossible, even though the junction was mounted in the center of the waveguide where computer models have shown the resonance to be the weakest. The conversion loss at resonance increased to 12 dB confirming the inability to achieve a proper match under resonant conditions. Theoretical and scaled model analysis [7] show that the resonance would be pushed out of band when the waveguide height is reduced by 20%.

CONCLUSION

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. The receiver has a typical double sideband noise temperature of 55K from 200 GHz to 250 GHz. At 267 GHz the receiver noise temperature degraded to 350K which is probably caused by cross-mode coupling due to the junction mount perturbing the waveguide. The lowest receiver noise temperature (48K DSB) and mixer noise temperature (38K DSB) were recorded at 239 GHz.

Both the conversion loss and mixer noise temperature decreased by 19% upon cooling the junction from 4.2 to 2.1K. Lastly, the importance of a proper IF match has been examined and experimentally verified.

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