A Fixed Tuned Low Noise SIS Receiver for the 600 GHz Frequency Band

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Abstract

A fixed tuned waveguide receiver has been designed and tested in the 600 GHz frequency band. This receiver is a scaled version of the 200 GHz fixed tuned receiver reported previously [1]. Equipped with a corrugated horn, the receiver operates at an IF of 5 GHz. The mixing element is an Nb/AlO_x/Nb SIS junction. Nominal junction size is about 1 μm^2. On-chip tuning is provided by a 2-section microstrip transformer in series with a short inductor section containing the device. Preliminary measurements show that this receiver has a low noise performance. Using a Martin-Puplett interferometer as the local oscillator diplexer, the DSB receiver noise temperature is about 275 K over most of the 600 GHz frequency band. Further work is under way to perfect the performance of the receiver.

I. Introduction

Fixed tuned waveguide receivers incorporating SIS junctions for the Smithsonian Astrophysical Observatory Sub-Millimeter Array (SMA) have been demonstrated to possess wide-band low-noise performance at frequencies up to 500 GHz [1,2]. Recently, we have scaled the original design for operation in the 600 GHz frequency band. In this report, we shall present the major features of this 600 GHz receiver as well as preliminary test results.

II. Mixer Block Design

Fig. 1 is a detailed drawing of the central portion of the 600 GHz mixer block. Its dimensions are essentially one third of the corresponding dimensions of the 200 GHz mixer block from which it is derived. As in the original design, the reduced height waveguide section (0.373×0.091 mm) is created by mechanical punching. This shorted waveguide section, which forms the fixed backshort tuner of the mixer, measures 0.124 mm in depth. This mechanical layout together with the low-pass IF filters produce a driving point impedance of about 35 Ω at the waveguide feed point over the required operating bandwidth.

The mixer block is fitted with an electro-formed corrugated feed horn section that includes a transition from reduced height guide to corrugated guide. The semi-flare angle of the horn is about 11°. The quartz mixer chip, measuring $0.165 \times 0.050 \times 2$ mm, is clamped between the horn section and the mixer block back piece, in a suspended microstrip line configuration parallel to the E-plane of the waveguide. The chip is contacted on both the IF connector side and the ground side by gold plated beryllium copper wire, 0.125 mm in diameter. Since the contact pads on the chip are overlaid with a thin gold layer, no indium is needed to maintain the mechanical contact.

Two grooves are milled on each side of the block along the H-plane of the waveguide. They allow a pair of magnetic pole pieces to come into close proximity of the junction.

III. Junction Design and Tuning

At the center of the mixer chip is the waveguide to thin film microstrip transition. A thin film microstrip coupling network has been designed to couple the junction to the driving point impedance of 35 Ω of the waveguide circuitry. As in the lower frequency receivers, the design employs a 2-section transformer plus a short inductive lead in front of the junction.

The insulator of the thin film microstrip line is the 200 nm layer of SiO used to define the size of the $Nb/AlO_x/Nb$ junction. Reproducibility and tolerance considerations dictate a minimum line width of about 2 μm, implying a maximum characteristic impedance of about 16 Ω. This sets a ceiling to the target source impedance of the junction. We have chosen a value of 13 Ω, consistent with previous designs. Since the frequency is around the gap frequency of niobium, we assume that the optimum source resistance for the junction is simply its normal state resistance R_N. Therefore, the target value of R_N is also 13 Ω.

The ωCR product of the junction is determined by the current density of the junction. A higher current density yields a lower ωCR product and therefore a potentially broader operating band width with the appropriate tunning. We have chosen a target current density of 12 kA/cm^2. This corresponds to an ωCR product of 4.25 at 650 GHz assuming a junction specific capacitance of 65 fF/μm^2. Considering that the atmospheric window in this frequency band runs from 600 to 720 GHz, corresponding to about 18% bandwidth, it is possible to design a tuning circuit to cover this entire window [3]. At the target current density, a junction size of $1.1 \times 1.1\,\mu$m is required to give an R_N of 13 Ω.

There has been some doubt concerning the losses of niobium thin film microstrip transformer at frequencies approaching the gap frequency. In our case, the total length of the tuning circuit is only about $\lambda_g/2$. The coupling loss is estimated to be less than 0.5 dB.

At the IF frequency, the low impedance section of the transformer behaves as a lumped capacitor and tends to reduce the IF coupling efficiency. The IF of the SMA is 5 GHz, which is considerably higher than the more popular 1.5 GHz IF of most SIS receivers. Consequently, it is important to minimize the IF output capacitance. Instead of having a quarter-wave low impedance section, we have used a low impedance section with an electrical length of 70°. Even in this configuration the wider section still makes up about half of the total IF output capacitance, which is about 0.3 pF. This is equivalent to a reactance of 100 Ω at 5 GHz.

In the lower frequency SMA receivers, the junction is located on a $5 \times 5\,\mu$m wiring pad. This is neccessary for aligning the final wiring layer to the junction in the fabrication process. In the 600 GHz frequency band, this pad corresponds to an additional line of about 10° in electrical length. This length is comparable to the length of the inductive lead in front of the junction. Furthermore, the microstrip width discontinuity between the inductive lead and the wiring pad also adds non-negligeable reactance to the tuning circuitry. Therefore, instead of a 2 μm wide lead, we have employed a 4 μm wide lead, wide enough to align the junction directly on it. The 4 μm wide lead is lower in characteristic impedance and is better suited to tune out high capacitive junctions in the 650 GHz frequency range. The predicted return loss of the coupling network is given in Fig. 2.

III. Receiver Noise Measurement

The mixer block is installed in a liquid helium dewar for laboratory noise temperature measurements. The atmospheric window is a 0.5 mm thick Teflon sheet. This is followed by a thin Zitex sheet on the radiation shield as an infrared block. A 90-degree offset parabolic mirror mounted on the cold plate focuses the beam emerging from the corrugated feed onto the local oscillator diplexer. Two additional layers of Zitex infrared filters are inserted in front of the aperture of the corrugated feed horn to ensure that the mixer chip is not heated by infrared radiation focused by the optical grade parabolic mirror.

Local oscillator power is provided by solid state multipliers pumped by a Gunn oscillator. A cascaded doubler-tripler covers most of our frequency band, from 620 to 710 GHz, with a peak available power of about 100 μW at some frequencies. A Martin-Puplett diplexer provides LO/signal diplexing. At frequencies where there is abundant local oscillator power, a wire grid polarizer has also been used for LO injection purposes.

Double-side-band noise temperatures are measured using the standard hot (295 K) and cold (77 K) load method. Linear noise temperatures are computed from the experimental Y-factor with correction for Planck's radiation law. No corrections has been made for losses in the optics. The IF amplifier has a noise temperature of about 8 K. Measurements are made with a 1 GHz IF bandwidth.

IV. Results and Discussion

The junctions used in the laboratory tests have current densities of around 8 kA/cm^{-2}, lower than the design value. Their normal resistances are in the 20 Ω range. At 4.2 K, the gap voltage is typically 2.85 mV, corresponding to a gap frequency of 690 GHz. The subgap to normal state resistance ratio (R_{sg}/R_N) is typically 12.

The lowest noise comes from a junction that is 20% smaller than the nominal size. The measured noise temperature is plotted in Fig. 3. The receiver performs best at around 580 GHz. Noise temperature is generally around 275 K from 625 GHz to 680 GHz. When the junction temperature is lowered to 2.5 K, the receiver noise temperature is reduced by about 30 K at around 600 GHz and by more than 50 K towards 700 GHz. This is clearly related to the proximity to the gap frequency. The use of a polarising grid as LO injector also improves the performance. The lowest noise temperatures measured at 4.2 K are 142 K at 580 GHz and 225 K at 675 GHz.

Fig. 3 also shows a breakdown of the measured noise temperature into input noise (losses in the optics), mixer noise and multiplied IF noise at selected frequencies. It can be seen that input noise contribution is about 100 K or more. This explains why the use of a polarising grid injector considerably reduces the receiver temperature. The possible reasons for the relative high input losses are:

(a) The 0.5 mm Teflon vacuum window is $1.5\lambda_d$ thick at about 620 GHz. The bandwidth over which its transmission is close to unity is fairly narrow. In fact, at 690 GHz, the power transmission coefficient is only 90%.

(b) The off-axis parabolic mirror might generate a high level of cross-polarisation. A Martin-Puplett LO diplexer terminates this cross polarisation content at LO port, effectively introducing a room temperature loss.

(c) The polarising grids used in the LO diplexer may have losses of up to 3% per reflection at 700 GHz. In our setup, the signal beam undergoes 3 reflections in the diplexer.

(d) Misalignment of the diplexer also contributes to the input noise.

In general, the response curve of the receiver shifts in frequency with junction size. The fact that the performance is optimal with a smaller device and that the receiver performs best at the lower part of the band suggests that the value of the junction capacitance (65 fF/μm^2) used in the design process is too small. Another possibility is that the magnetic penetration depth used in the design may be different from that of the actual value. That is particularly important given that the operating frequency is close to the gap frequency.

In this receiver, a small resonance is always apparent at around 650 GHz. This feature is fairly independent of junction size. A possible explanation for this is the onset of a surface wave mode in the substrate carrying the junction. In the 200 GHz design, the substrate thickness was 0.125 mm. A strict scaling would require a thickness of 40 μm for operation in the 600 GHz frequency band. However, since the thinnest commercially available substrate is 50 μm, we have decided to forego a lapping step and to use the thicker substrate for simplicity. In practice, the substrate used was 54 μm thick. Therefore, the suspended microstrip line is probably not monomode over the entire frequency band. Nevertheless, the effect of the surface wave mode is not prohibitively damaging.

V. Conclusion

Preliminary tests have been made on a 600 GHz fixed tuned receiver employing a niobium SIS junction with a integrated tuner. The receiver has a double-sideband noise temperature of around 275 K over most of the 600 - 700 GHz frequency band. Input losses account for about 100 K of the total noise. We are currently making improvements to the receiver optics and we are also working on an improved tuner to reduce the noise temperature of the system.

Acknowledgement

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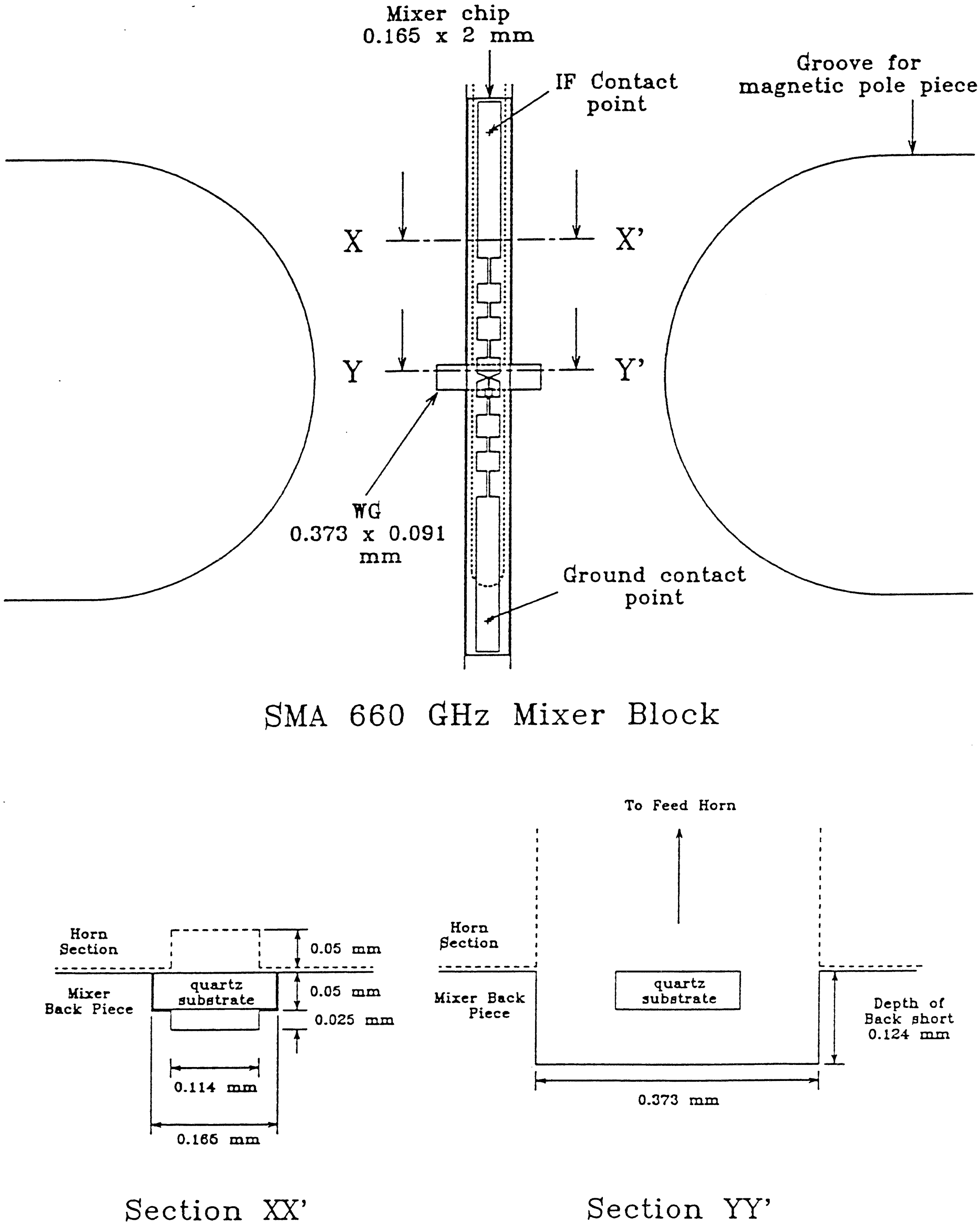


Fig. 1 Details of the central portion of mixer block showing mixer chip

Reference

[1] R. Blundell *et al*, A wideband fixed-tuned SIS receiver for 200 GHz operation, *Proc. 5th Intl. Symp. Space THz Tech.*, pp. 27-37.

[2] R. Blundell *et al*, A fixed tuned SIS receiver for the 400 GHz operation, *these proceedings*.

[3] A.R. Kerr, Some fundamental and practical limits on broadband matching to capacitive devices and the implications for SIS mixer design, *IEEE Trans. Microwave Theory & Tech.*, vol. 43, pp. 2-13, 1995.

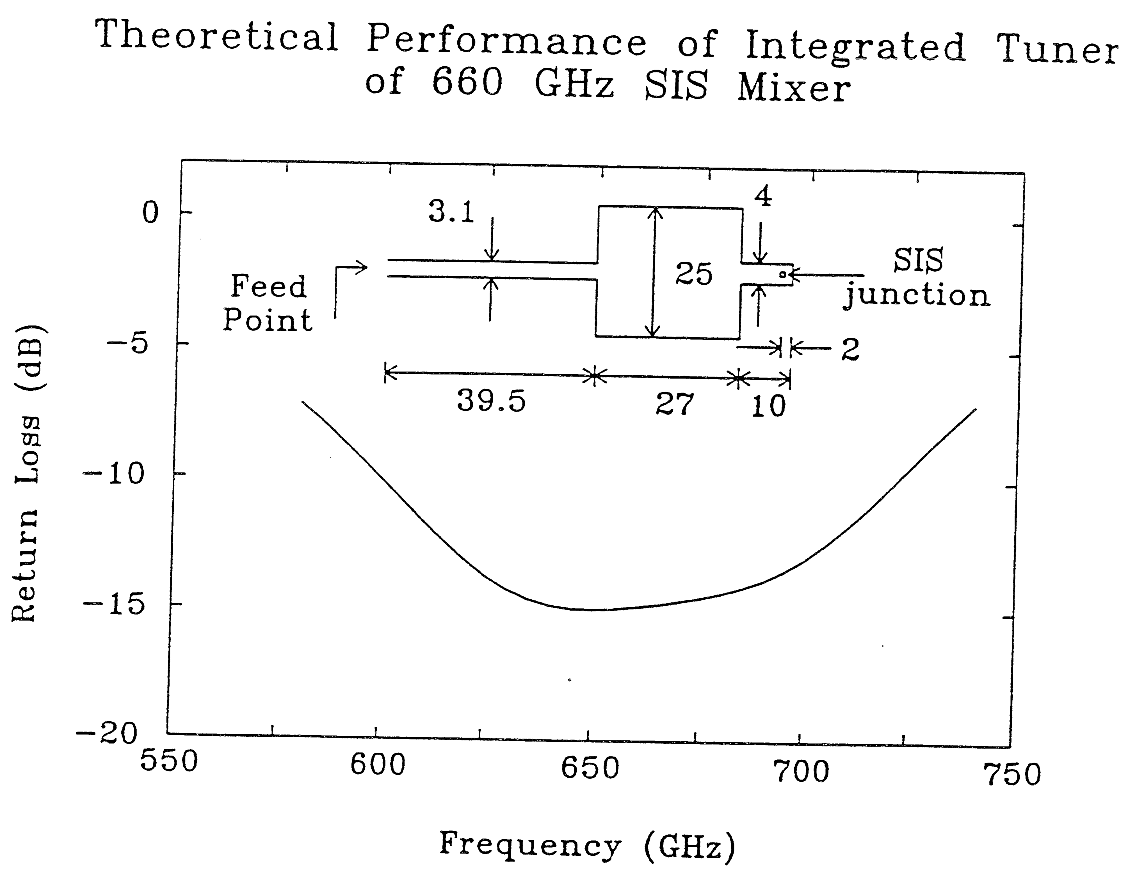
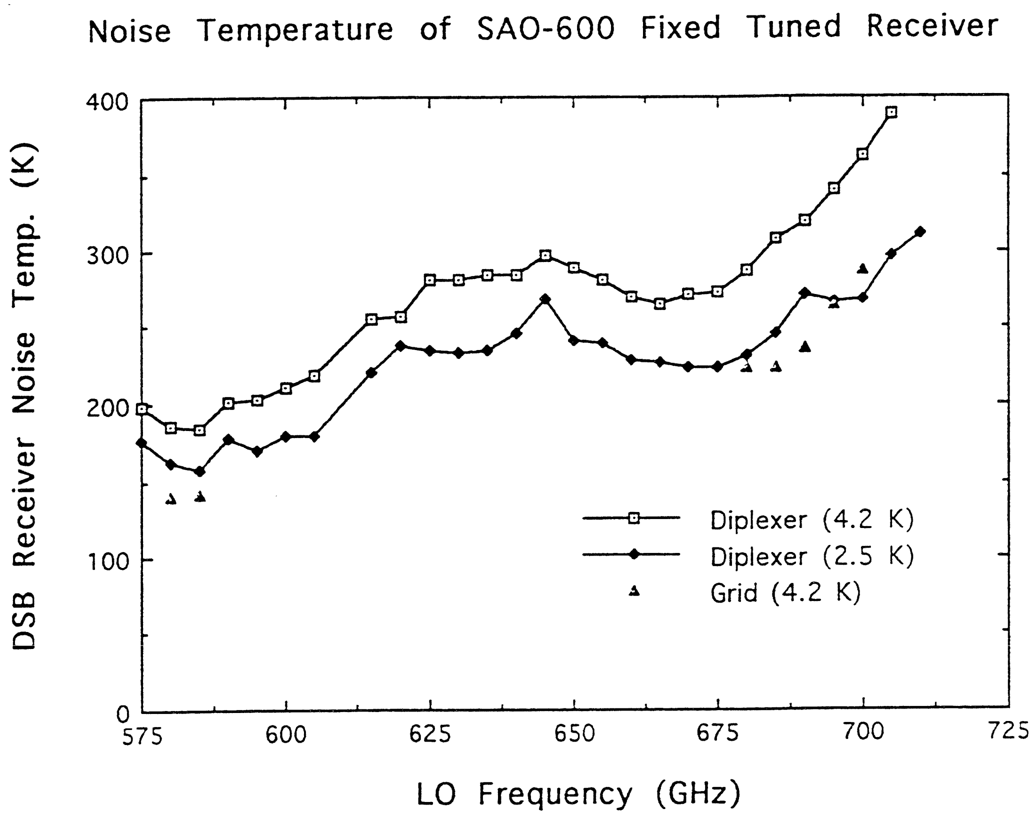


Fig. 2 Predicted return loss of tuning circuit for a junction with $R_N = 13\Omega$ and $C_J = 80$ fF.



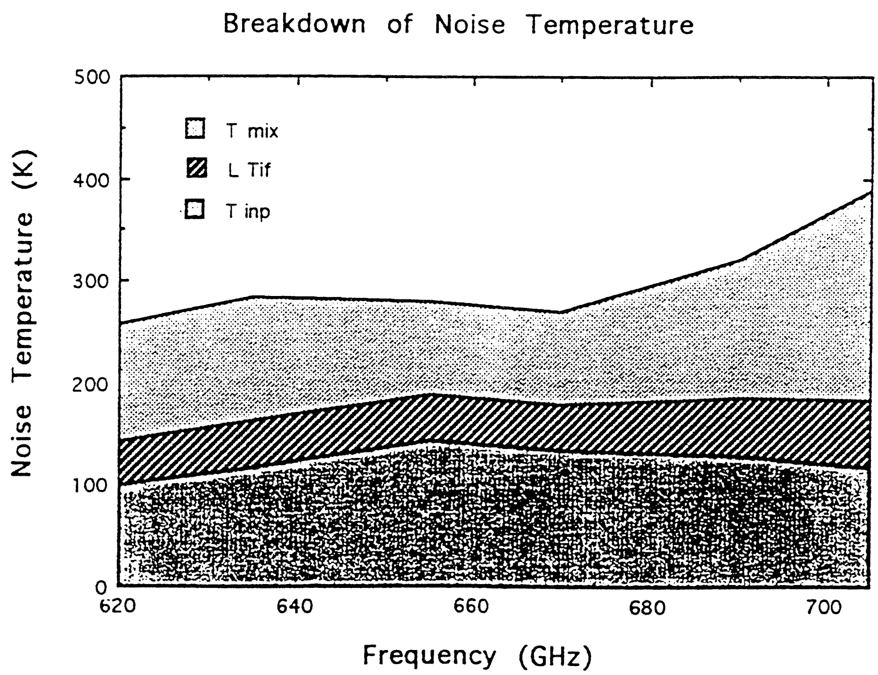


Fig. 3 DSB noise Temperature of the receiver as a function of LO frequency and its composition at selected frequencies. The breakdown is given for the case in which a Martin-Puplett LO diplexer is used, the device being at 4.2 K.

Fig. 4 Quasi-Particle Mixing with LO at 690 GHz