

National Radio Astronomy Observatory
Charlottesville, Virginia

MMA MEMORANDUM # 87
(also distributed as EDIR No. 291)

Progress on Tunerless SIS Mixers for the 200-300 GHz Band

A. R. Kerr, S.-K. Pan, A. W. Lichtenberger¹ and D. M. Lea¹

23 July 1992

INTRODUCTION

In the last few years, designers of SIS mixers have begun to exploit the potential of superconducting integrated circuits for achieving full waveguide bandwidths without mechanical tuning. Coplanar and microstrip mixer designs have given promising results at 100 GHz [1, 2], but have not yet approached the performance of the best mechanically tuned SIS mixers [3, 4].

This report describes recent progress on an integrated SIS mixer for the 200-300 GHz band, similar in concept to the coplanar mixer described in [1]. A coplanar circuit allows a much thicker substrate than is possible with a microstrip circuit if higher modes and troublesome parasitic reactances are to be avoided. (A thick substrate greatly simplifies mixer fabrication and assembly.)

The failure of the mixers reported in [1] to match the performance of the best tunable SIS mixers was unexplained at the time of writing of [1]. Since then, we have found strong indications that the upper Nb layer in the tested mixers was very lossy. The evidence is as follows: (i) The conversion loss of the mixers was about 10 dB greater than expected. (ii) The IF output impedance was much lower than expected. (iii) Other (non-integrated) mixers, from the same wafer and with similar tuning circuits, had much higher conversion loss than subsequent mixers of similar design. (iv) Analysis by Mears, *et al.*, [5, 6], of our I-V curves, measured with LO power applied, indicated a substantially capacitive embedding admittance, which suggests that the inductive tuning circuit was not operating properly. Furthermore, the Nb interconnection layer (M3) was an unusual brown-orange color, and had poor adhesion to the wafer.

¹ Department of Electrical Engineering, University of Virginia.

MIXER DESIGN

Figs. 1 and 2 show the configuration of the mixer. For operation in the band 200-300 GHz, of interest to radio astronomers, the critical dimensions of the mixer block are scaled by a factor of 0.37 from the WR-10 design of [1]. The resulting non-standard waveguide has inside dimensions 0.0370 x 0.0185 inches, and falls between WR-3 and WR-4. (In the spirit of the EIA waveguide numbering scheme², we refer to the new size as WR-3.7.) Energy from the waveguide is coupled to a 50-ohm suspended-stripline via a broadband transducer. A transition is then made to a 50-ohm coplanar line which leads to a series array of six SIS junctions, each with its own tuning circuit [7, 3] as shown in Fig. 2. The inductance of the array of junctions in the hole in the ground plane is tuned out by capacitor C_H in Fig. 2. A four-element low-pass filter consisting of $-\lambda/4$ coplanar lines and capacitors acts as an RF choke, while passing DC and IF to a bonding pad at the end of the substrate. This filter was designed [8] to present a relatively low impedance to the SIS junctions from DC to 90 GHz, thereby reducing the likelihood of instability and premature saturation due to high embedding impedances between the IF and RF bands [9].

The mixer was designed according to the procedure described in [3]. The RF source impedance, R_S , and IF load impedance were chosen, for convenience, as 50 ohms. For junctions with a given J-V curve (J is the current per unit area), it is then possible to predict a desirable normal resistance R_N for which the mixer noise temperature is near its minimum, the conversion loss is close to unity, and the input VSWR ≤ 2 . In the light of further analysis since writing [3], we have found that for typical Nb/Al-Al₂O₃/Nb SIS mixers, this optimum value $R_N = 2.4 R_S (100/f(\text{GHz}))^{0.72}$. Accordingly, in the present design, $R_N = 62$ ohms. At 250 GHz, a critical current density $J_C = 4500$ A/cm² and a specific capacitance $C_S = 45$ fF/ μm^2 [10] gives $\omega R_N C \approx 3$ (the exact value depends on the amount of stray capacitance), and requires an effective (single) junction area of $0.64 \mu\text{m}^2$ to give the desired value of R_N . The choice of $\omega R_N C \approx 3$ is larger than the value of 1.6 suggested in [3] partly to avoid junctions too small to be reliably fabricated using the present process, but also to prevent the inductive junction tuners becoming too long, thus increasing the size of the hole required in the ground plane and its associated inductance which appears in series with the junctions. In this design we used six junctions in series, each with an area of $3.9 \mu\text{m}^2$ (diameter $2.2 \mu\text{m}$).

In designing the integrated tuning circuits for the individual junctions (Fig. 2), it was found that the (nominally) quarter-wave open circuit stub could be shortened considerably with only a small effect on the embedding impedance, provided the length l_L of the higher impedance line (the inductor) was slightly increased to compensate [8].

² In the EIA WR-# scheme, # is the waveguide inside width in hundredths of an inch, rounded to a whole number.

MIXER FABRICATION

Nb/Al-Al₂O₃/Nb tri-layers were deposited on z-axis crystal quartz wafers 0.010 inches thick using a process similar to that described in [10]. However, during Nb deposition, the DC magnetron power was held constant while the Ar pressure was adjusted to maintain constant current. This results in a constant deposition rate and uniform film stress from wafer to wafer over the life of the sputtering target.

Following deposition of the tri-layer, the main lithographic steps were as follows:

- (i) The Nb/Al-Al₂O₃/Nb trilayer was etched by RIE to define the final pattern of the lower Nb layer (M1).
- (ii) The upper Nb layer (M2) was removed by RIE in the vicinity of the $\sim\lambda/4$ stubs, and the lower Nb anodized to produce a 100 nm layer of Nb₂O₅.
- (iii) The junctions were defined, and 450 nm of SiO deposited, using the tri-level resist and RIE process described in [11]. M2 now remains only on the junctions.
- (iv) The Nb interconnection layer (M3) was deposited and patterned by lift-off.
- (v) A layer of Au for bonding and contact pads was deposited by sputtering and patterned by etching.

After dicing the wafer into individual mixers, each mixer was waxed facedown and ground to 0.0035" thick using a dicing saw as a surface grinder.

EXPERIMENTAL RESULTS

The mixers were tested in a liquid helium cooled vacuum cryostat [12] containing 4.2 K IF calibration components, similar to that described in [13]. The incoming RF signal enters the cryostat through a mylar film vacuum window supported by polystyrene foam [14]. It passes through a PTFE infrared filter at 77 K, and enters a scalar feed horn at 4.2 K. LO power is injected through a 20 dB branch-line coupler, also at 4.2 K. A 1.39 GHz IF was used, and all measurements were made with a 50 MHz bandwidth. The IF noise temperature, including a coaxial switch, two isolators, and a directional coupler, was 6.4 K. No IF impedance transformer was used, and no external magnetic field was applied to the mixers.

Using a chopper wheel to switch the input beam between room temperature and 77 K loads, and a Y-factor meter synchronized to the chopper wheel, the LO power and mixer bias voltage were adjusted for minimum receiver noise temperature. Fig. 3 shows the DSB receiver noise temperature as a function of frequency for three mixers from two different wafers, and, for comparison, the corresponding results for an NRAO type 401 (WR-4) mixer with two mechanical tuners [3]. At the higher end of the frequency band it was found that, for normal LO power levels, structure appeared on the pumped I-V curve and the receiver output became unstable, indicating interference from Josephson currents. This Josephson interference could be reduced either by biasing

closer to the gap voltage or by reducing the LO power. The points (Δ) and (\square) in Fig. 3 (but not the two isolated points (\square) at 230 GHz) were obtained with the LO level reduced sufficiently to eliminate Josephson effects. The points (+), were obtained at normal LO level but with increased bias voltage. The pair of isolated points (\square) at 230 GHz, were obtained at normal LO power and with the mixer biased as usual near the middle of the first photon step. Despite the apparently better receiver noise temperature at the two isolated points (\square), we believe operation in the presence of Josephson interference is undesirable because of the likelihood of nonlinear response and non-heterodyne detection. Furthermore, when sharp features are present on the photon steps of the pumped I-V curve, the mixer gain also shows sharp variations with bias. The dynamic range of the receiver is likely to be reduced as the IF voltage excursions become comparable with the width of the gain peak [15, 16].

The properties of the mixers were deduced from the measured IF output power from the receiver with hot and cold RF and IF loads [13]. For the three mixers (+, \square , and Δ) in Fig. 3, at 230 GHz, $L = 0.9$ dB, 2.5 dB and 2.6 dB DSB, $T_M = 17$ K, 12 K and 21 K DSB, and the IF output impedance $R_{IF} = 490$, 235, and 250 ohms, respectively.

DISCUSSION

Fig. 4 shows the theoretical mixer gain and receiver noise temperature at several LO power levels for the mixer represented by (+) in Fig. 3. It appears that the pronounced rise in the measured receiver noise temperature at higher frequencies is partly inherent in the present circuit design, and partly a result of the need to operate with lower LO levels at higher frequencies if the Josephson effects (mentioned above) are to be avoided. In the future, we plan to use a magnetic field to suppress the Josephson currents, which may eliminate the need to operate with reduced LO power.

At low frequencies, the mixers were limited by an apparent biasing instability. This is understood in terms of the RF embedding admittance (seen by the junction conductance), shown in Fig. 5, which becomes inductive at the low end of the band. Under this condition, a single SIS junction can exhibit negative DC (and IF) output conductance. For a series array of junctions, it is suspected that this can be an unstable situation in which the individual junctions become unequally biased, and ultimately reach one of a number of possible stable dynamic states in which the junctions remain unequally biased. As we have seldom seen this bias instability in tunable mixers using similar arrays of individually tuned SIS junctions, we surmise that it can be avoided by appropriate design of the embedding admittance as a function of frequency. We are now developing a new tunerless mixer designed to prevent this difficulty.

ACKNOWLEDGEMENTS

The authors thank N. Horner, F. Johnson, F. L. Lloyd, and G. Taylor for their invaluable work in fabricating and assembling the mixers.

REFERENCES

- [1] A. R. Kerr, S.-K. Pan, S. Whiteley, M. Radparvar, and S. Faris, "A fully integrated SIS mixer for 75-110 GHz," *IEEE Int. Microwave Symp. Digest*, pp. 851-854, May 1990.
- [2] D. Winkler, N. G. Ugras, A. H. Worsham, D. E. Prober, N. R. Erickson, P. F. Goldsmith, "A full-band waveguide SIS receiver with integrated tuning for 75-110 GHz," *IEEE Trans. Magnetics*, vol. MAG-27, no. 2, pp. 2634-2637, March 1991.
- [3] A. R. Kerr and S.-K. Pan, "Some recent developments in the design of SIS mixers," *Int. J. Infrared Millimeter Waves*, vol. 11, no. 10, Oct. 1990. (Originally presented at the First International Symposium on Space Terahertz Technology, March 1990.)
- [4] H. Ogawa, A. Mizuno, H. Hoko, H. Ishikawa, and Y. Fukui, "A 110 GHz SIS receiver for radio astronomy," *Int. J. Infrared & Millimeter Waves*, vol. 11, no. 6, pp. 717-726, June 1990.
- [5] C. A. Mears and P. L. Richards, private communication, May-June 1990.
- [6] C. A. Mears, Qing Hu, and P. L. Richards, "Numerical simulation of experimental data from planar SIS mixers with integrated tuning elements," *IEEE Trans. Magnetics*, vol. MAG-25, no. 2, pp. 1050-1053, March 1989.
- [7] A. R. Kerr, S.-K. Pan, and M. J. Feldman, "Integrated tuning elements for SIS mixers," *Int. J. Infrared Millimeter Waves*, vol. 9, no. 2, pp. 203-212, Feb. 1988. This paper was presented at the International Superconductivity Electronics Conference, Tokyo, Japan, Aug. 1987.
- [8] The MMICAD microwave integrated circuit design program was used for circuit simulation and optimization. MMICAD is a product of Optotek, Ltd., Ontario, Canada K2K-2A9.
- [9] L. R. D'Addario, "Saturation of the SIS mixer by out-of-band signals," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, no. 6, June 1988.
- [10] A. W. Lichtenberger, C. P. McClay, R. J. Mattauch, M. J. Feldman, S.-K. Pan, and A. R. Kerr, "Fabrication of Nb/Al-Al₂O₃/Nb junctions with extremely low leakage currents," *IEEE Trans. on Magnetics*, vol. MAG-25, no. 2, pp. 1247-1250, March 1989.
- [11] A. W. Lichtenberger, D. M. Lea, R. J. Mattauch, and F. L. Lloyd, "Nb/Al-Al₂O₃/Nb junctions with inductive tuning elements for a very low noise 205-250 GHz heterodyne receiver," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-40, no. 5, pp. 816-819, May 1992.
- [12] Infrared Laboratories, Inc., Tucson, AZ, model HD-3(8) (modified).
- [13] S.-K. Pan, A. R. Kerr, M. J. Feldman, A. Kleinsasser, J. Stasiak, R. L. Sandstrom, and W. J. Gallagher, "A 85-116 GHz SIS receiver using inductively shunted edge-junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, no. 3, pp. 580-592, March 1989.
- [14] A. R. Kerr, in preparation.
- [15] A. D. Smith and P. L. Richards, "Analytic solutions to SIS quantum mixer theory," *J. Appl. Phys.*, vol. 53, no. 5, pp. 3806-3812, May 1982.
- [16] M. J. Feldman, S.-K. Pan, and A. R. Kerr, "Saturation of the SIS mixer," *International Superconductivity Electronics Conference, Tokyo, Digest of Technical Papers*, pp. 290-292, Aug. 1987.

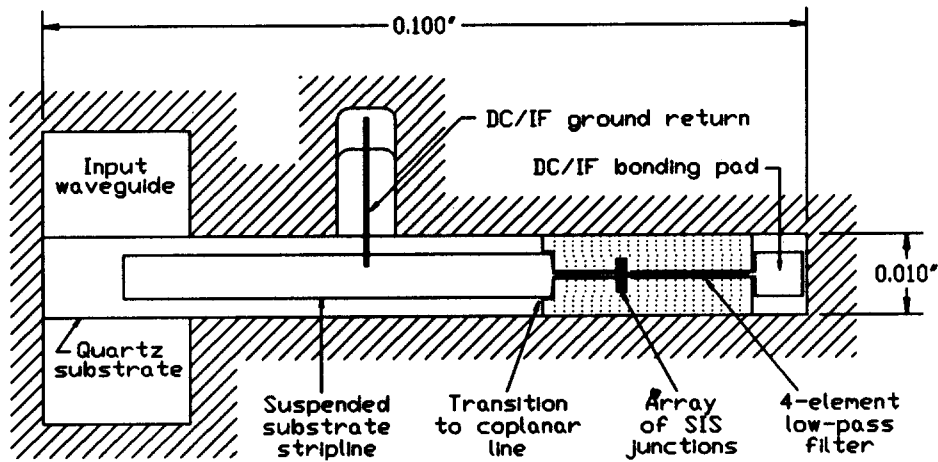


Fig. 1. The complete mixer, showing the waveguide to suspended stripline transducer, DC and IF ground return stub, and the coplanar mixer circuit. The quartz substrate is 0.100" x 0.010" x .0035" thick.

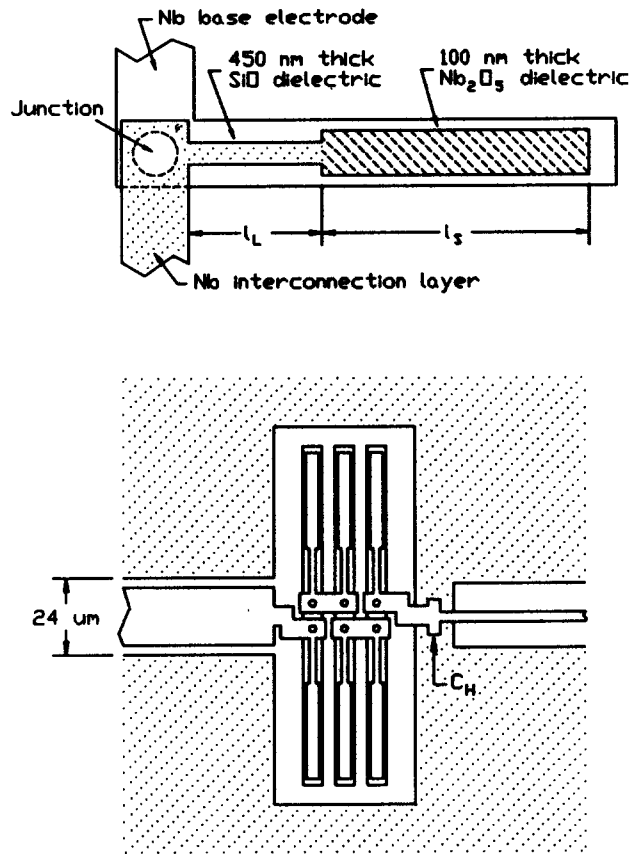


Fig. 2. (Upper) Details of an inductively tuned SIS junction. (Lower) Array of six inductively tuned junctions connected to the coplanar input line. The inductance of the hole in the ground plane in the vicinity of the array is tuned out by the capacitor C_H .

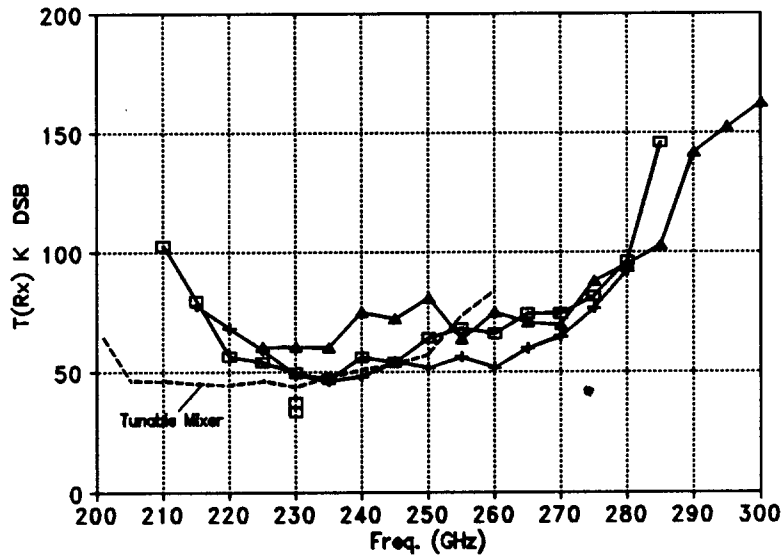


Fig. 3. DSB receiver noise temperature (measured outside the vacuum window) for three mixers from two different wafers. Also shown (dashed) for comparison is the noise temperature of a receiver using an NRAO 401 mixer with two mechanical tuners. Points (Δ) and (\square) in Fig. 3 (but not the two isolated points (\square) at 230 GHz) were obtained with the LO level reduced sufficiently to eliminate Josephson effects. Points (+) were obtained at normal LO level but with increased bias voltage. The pair of isolated points (\square) at 230 GHz were obtained at normal LO power and with the mixer biased near the middle of the first photon step. All measurements were made at 4.2 K.

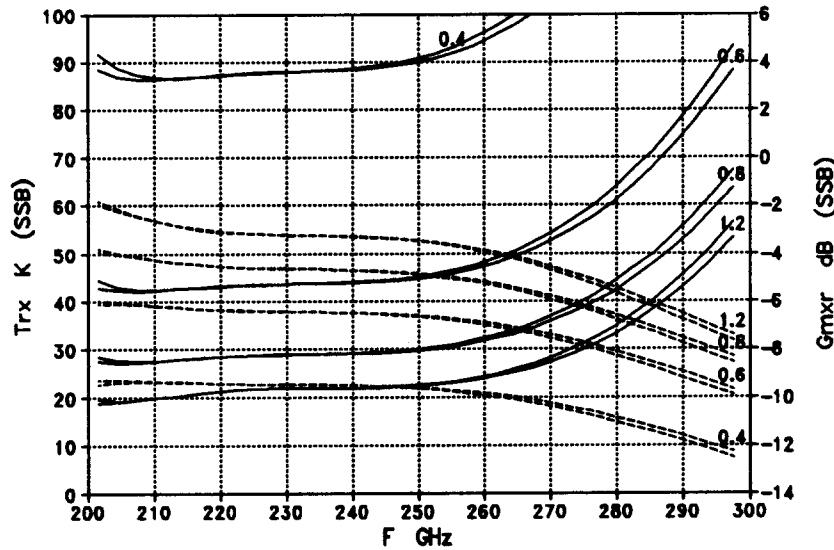


Fig. 4. Theoretical upper- and lower-sideband gain and receiver noise temperature (SSB) versus frequency for the mixer represented by (+) in Fig. 3. The parameter is the normalized LO amplitude $\alpha = eV_{LO}/hf$. The IF noise temperature is 6.4 K corresponding to the measured value for these experiments. No correction has been made for the loss of the vacuum window, infrared filter, feed horn, or LO coupler ahead of the mixer.

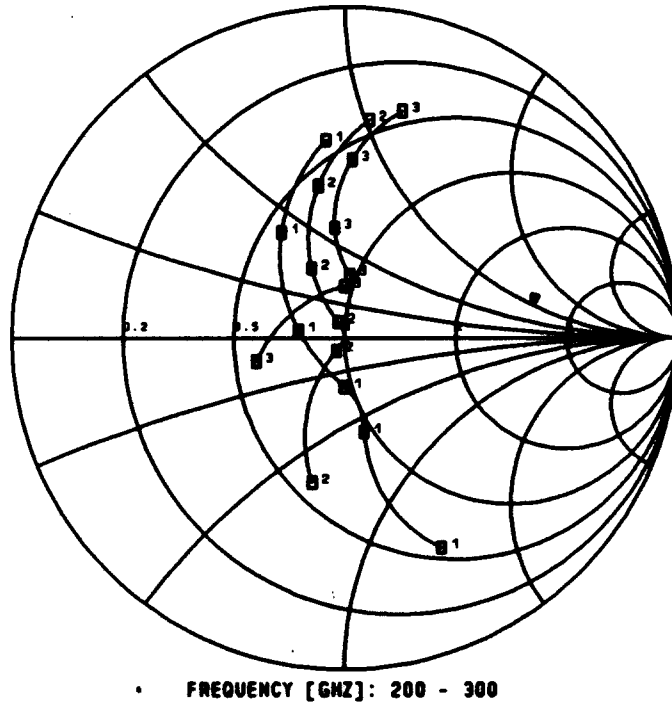


Fig. 5. The embedding admittance seen by the array of junctions, as a function of frequency, for inductor lengths $l_l = 10.6 \mu\text{m}$, $12.5 \mu\text{m}$, and $14.5 \mu\text{m}$, shown on a Smith (admittance) chart normalized to $(50 \text{ ohms})^{-1}$. Frequency markers are every 20 GHz.