

# A SINGLE-CHIP BALANCED SIS MIXER FOR 200-300 GHz

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## ABSTRACT

The balanced mixer is fabricated on a 2 x 1 mm quartz substrate which contains an RF quadrature hybrid and two SIS mixers. These components are realized in capacitively-loaded coplanar waveguide, which minimizes stray coupling between adjacent components and coupling to undesired modes in the thick quartz substrate. Signal and LO waveguides are coupled to separate ports of the main substrate via suspended striplines. The mixers were fabricated using the UVA Nb/Al-oxide/Nb process. Over the 225-300 GHz band, the mixer noise temperature was 37-48 K and the overall receiver noise temperature was 46-78 K DSB, both referred to outside the cryostat. The LO-to-RF isolation was >12 dB, which we hope to improve by reducing leakage of power under the substrate between the LO and signal ports.

## INTRODUCTION

At the 1996 THz Symposium we proposed designs for single-chip balanced and sideband separating SIS mixers [1]. Results for a 200-300 GHz sideband separating mixer were reported at the 1998 THz Symposium [2], and the present paper gives results for a balanced SIS mixer in the same band.

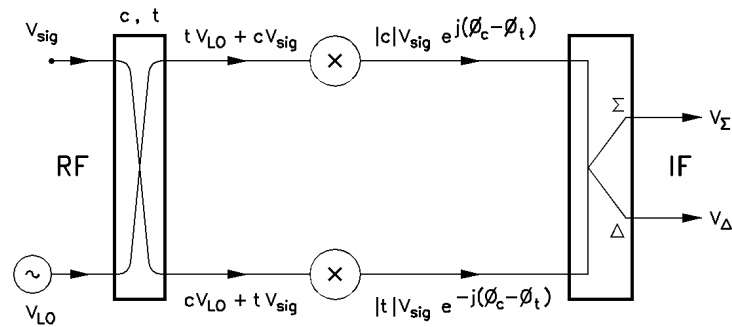
Balanced mixers have been used in commercial and military equipment since before WWII. They have three advantages over single ended mixers: (i) a LO coupler or diplexer is not required ahead of the mixer, (ii) the required LO power is substantially less than that of a single-ended mixer with an LO coupler, and (iii) sideband noise from the LO is

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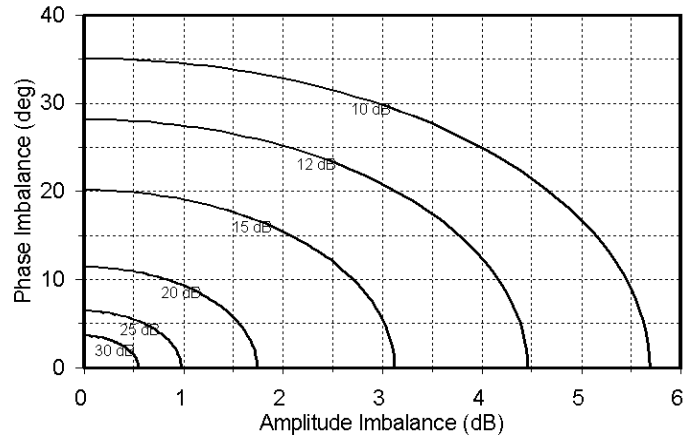
suppressed. LO power is usually coupled into a single ended mixer using a directional coupler or beam splitter. If the signal loss through the LO coupler is to be kept small, the LO loss must be substantial, typically 15-20 dB and most of the LO power is wasted. The balanced mixer has a separate LO port with efficient coupling so the required LO power is reduced by 12-17 dB relative to the simple single-ended mixer with LO coupler. In a single ended mixer, noise from the LO source in the signal and image bands is coupled into the mixer and converted to the IF. Depending on the nature of the LO source, its (sideband) noise temperature may be room temperature or higher. If the LO source has an effective noise temperature of 300 K at the sideband frequencies, then with a 15-20 dB beam splitter it will contribute 10-3 K in each sideband at the input of the mixer, which may be comparable with the intrinsic noise temperature of the receiver itself. With some LO sources we have observed a considerably higher excess sideband noise — as much as 50 K of sideband noise at the input of the mixer with some frequency multipliers in the 200-300 GHz range. In a balanced mixer, sideband noise is suppressed by an amount depending on the phase and amplitude balance through the mixer.

Balanced mixers require the relative phasing of the signal and LO at the two component mixers to differ by  $180^\circ$ . This can be achieved either using a  $180^\circ$  hybrid (transformer or magic-T) or a  $90^\circ$  hybrid (3-dB directional coupler). In the present work we use the latter, as shown in Fig. 1, because the quadrature hybrid is more easily realized as a planar circuit. One output of the IF ( $180^\circ$ ) hybrid contains the down-converted signal (upper and lower sidebands), and the other contains the down-converted LO sideband noise.



**Fig. 1. Schematic diagram of a balanced mixer of the type used in this work.**

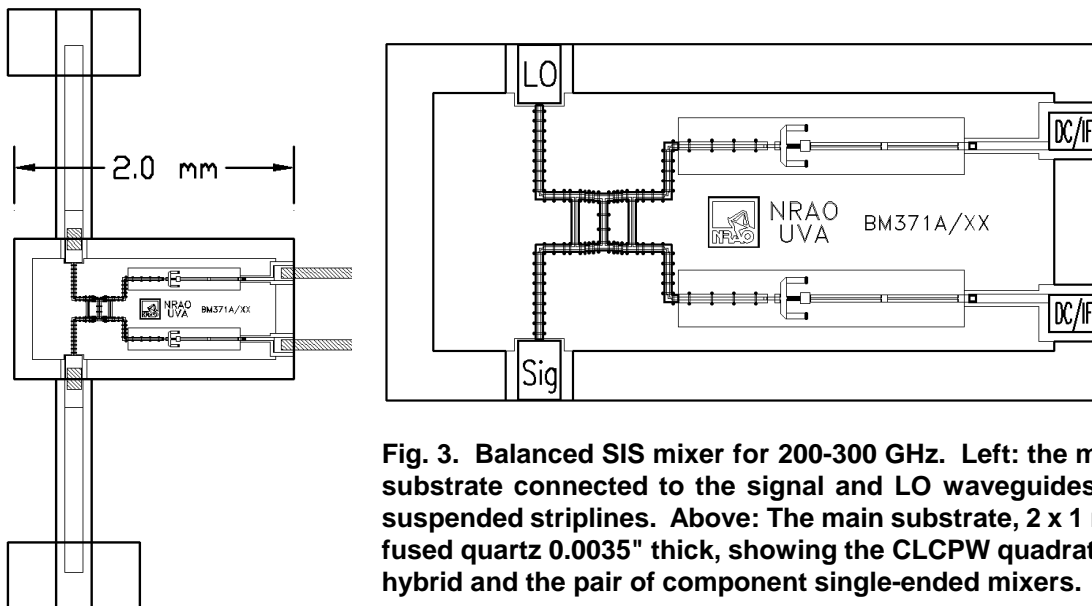
The LO noise rejection of a balanced mixer depends on accuracy of the amplitude and phase matching of the signal and LO through the two branches of the circuit. Fig. 2 shows the effects of amplitude and phase imbalance in a balanced mixer. It is seen that the rejection is quite insensitive to asymmetries in the mixer — even with 2 dB amplitude imbalance *and*  $15^\circ$  phase imbalance, the LO noise rejection is over 15 dB.



**Fig. 2. LO noise rejection of a balanced mixer as a function of amplitude and phase imbalance.**

## DESIGN

The layout of the balanced mixer is shown in Fig. 3. It is based on that described in [1] and uses the same capacitively loaded coplanar waveguide (CLCPW) and quadrature hybrid, as shown in Figs. 4 and 5. The component single-ended mixers are as described in [3]. They have four SIS junctions in series and are designed with low IF parasitic capacitance and inductance to allow operation with an IF as high as 12 GHz.



**Fig. 3. Balanced SIS mixer for 200-300 GHz. Left: the main substrate connected to the signal and LO waveguides by suspended striplines. Above: The main substrate, 2 x 1 mm fused quartz 0.0035" thick, showing the CLCPW quadrature hybrid and the pair of component single-ended mixers.**

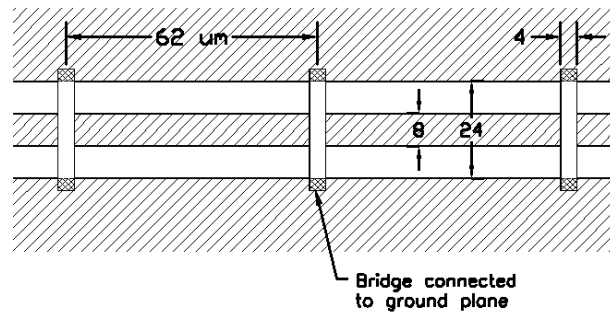


Fig. 4. A length of capacitively loaded coplanar waveguide (CLCPW) on a thick fused quartz substrate [1].  $Z_0 = 50$  . Dimensions in microns.

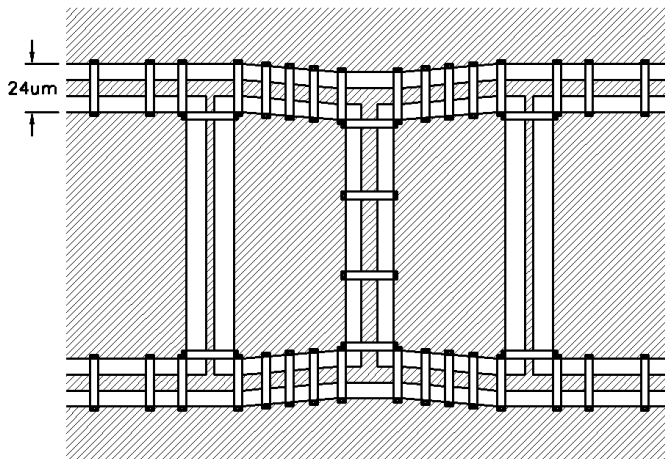


Fig. 5. Quadrature hybrid for 200-300 GHz [1].

## FABRICATION & ASSEMBLY

The mixers were fabricated on chemically polished fused quartz wafers 30 mm diameter and 0.25 mm thick. The SIS junctions are formed on small islands of Nb/Al-oxide/Nb trilayer. An SiO layer 200 nm thick is deposited around the junctions, and an additional 370 nm in the CLCPW sections. Vias connect the ends of the tuning stubs and the bridges in the CLCPW section to the base electrode. JPL's gold overlayer technique [4] was adapted to our process; since gold does not naturally oxidize, an in-situ physical cleaning of the surface of the junction counter electrode is avoided prior to depositing the Nb interconnection layer. Omitting the physical cleaning step has two advantageous: any native Nb and Al oxides which have grown after deposition of the junction SiO insulation will remain, and the SiO insulation layer will not be disturbed. Both these factors tend to prevent micro-shorts between the wiring and base electrodes, and we have been able to fabricate junctions with 200 nm insulation layers without resorting to anodization techniques.

In the gold overlayer process we used a separate DC magnetron sputtering system to deposit layers of Au(1-2 nm)/[Cr(4% wt.)-Au](28 nm) on top of the trilayer wafer after an ion gun clean. The Cr-Au mixture was used to increase the physical durability of the over-layer. Prior to the trilayer etch, the Cr-Au layer is etched in a solution of 10 g I, 40 g  $\text{INH}_4$ , 400 ml DI water, and 600 ml ethanol, which we have found etches Cr-Au films containing as little as 0.4% (wt.) Cr more repeatably and uniformly than pure Au films.

A new quadlevel resist, composed of NFR 200nm/polyimide 200nm/Nb 40nm/NFR (imaging resist) [5] was used as the etch mask in the junction step. The Au/Cr-Au layer is wet etched and the Nb junction defined with an  $\text{SF}_6+\text{CHF}_3+\text{N}_2$  RIE. It was found that the presence of Au in the plasma and in contact with the Nb layer reduces the anisotropy of the Nb etch. The bottom NFR layer was included as it was found to enhance the anisotropy of this Nb etch. The polyimide is included in the quadlevel structure because a trilevel resist of NFR/Nb/NFR will not liftoff satisfactorily due to the lack of a suitable chemical stripper for the NFR. After the junction etch and  $\text{SiO}_2$  deposition, a liftoff of the self-aligned quadlevel resist is performed with NMP [6]. Since the NFR is not fully removed with this stripper, the liftoff is followed by an oxygen plasma etch.

The vias, which connect the ends of the tuning stubs and the bridges in the CLCPW section to the base electrode, can be accomplished in two ways. The first is to use large area junctions, and the second uses a direct contact from wiring layer to base electrode. We have chosen the second approach to avoid possible internal resonances in large-area junctions used as vias. Since an in-situ cleaning step is not used in our Nb wiring process, a second Au overlayer was defined on top of the base electrode after removing the Au/Cr-Au and Nb counter electrode from the via sites.

After dicing, the individual mixers were thinned to 0.0035" using a dicing saw as a surface grinder. (More recently, we have been using a lapping machine to thin the whole wafer with an accuracy of  $\pm 0.0002$ " [7].) The mixer chip was connected to its suspended striplines with 0.0001" gold ribbons using Indalloy #2 solder [8] and Supersafe #334 flux [9]. Soldering to the mixer chip is done using a parallel gap welder [10] with a 0.005" x 0.010" soldering tip and a 900 ms heating pulse. Gold ribbon connections were also soldered to the IF/DC pads. The assembly was placed, circuit side down, in the lower half of the mixer block and the IF/DC connections made. Gold crush wires, 0.0007" diameter, between the edges of the main substrate and the block ensure a good ground contact when the upper half of the block is bolted in place.

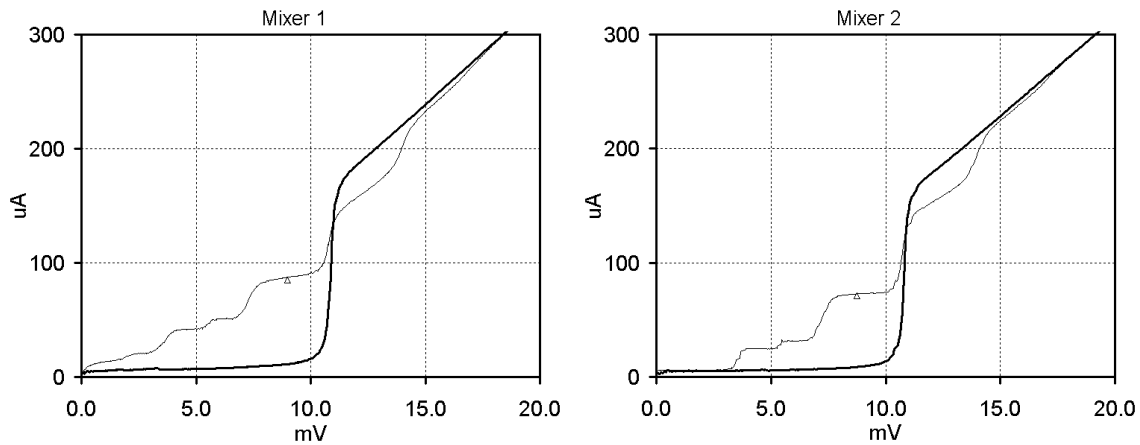
## MEASUREMENTS

The mixer was tested in a vacuum cryostat cooled to  $\sim 4$  K by a Joule-Thompson refrigerator. The incoming RF signal enters the cryostat through a plastic film vacuum window [11] supported by a 0.125" sheet of expanded PTFE [12]. It passes through a 50-K infrared filter, also made of 0.125" expanded PTFE, a PTFE lens at 4 K, and into a scalar

feed horn. The LO is connected to the mixer through an (overmoded) stainless steel waveguide. A 4 K IF plate containing a coaxial switch and 50-ohm IF calibration components, similar to that described in [13], enables the noise temperature at either port of the balanced mixer to be measured. The IF noise temperature, including the coaxial switch, two isolators, and a directional coupler, was 3.6 K at 1.4 GHz.

The balanced mixer has separate SMA DC/IF connectors for each component mixer. These were connected through cables of equal length to the 4 K 180° IF hybrid [14]. Bias-T's [15] on the other side of the hybrid were connected through isolators to the IF switch. No IF impedance transformer was used between the junctions and the 50-ohm IF plate. A DC magnetic field was applied to the mixer to suppress the Josephson currents in the junctions.

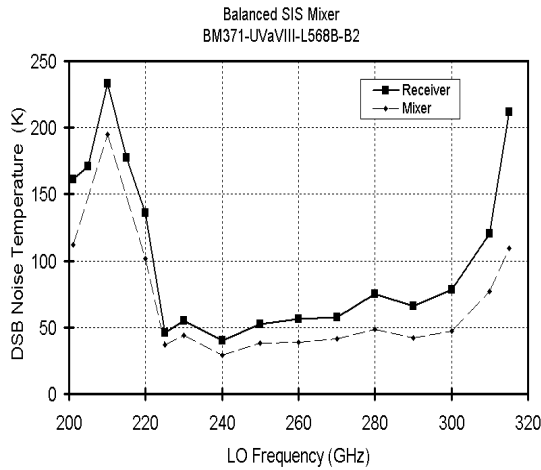
Fig. 6 shows the I-V characteristics of the two component mixers with and without LO power applied. The critical current,  $I_C = 118 \mu\text{A}$ , was determined from the measured quasiparticle current rise,  $I_{\text{gap}}$ , at the gap voltage using the relation  $I_C = (I_{\text{gap}} / 4)$ . An SEM was used to measure the junction diameter,  $1.5 \mu\text{m}$ , from which the critical current density  $J_C = 6700 \text{ A/cm}^2$  is deduced.



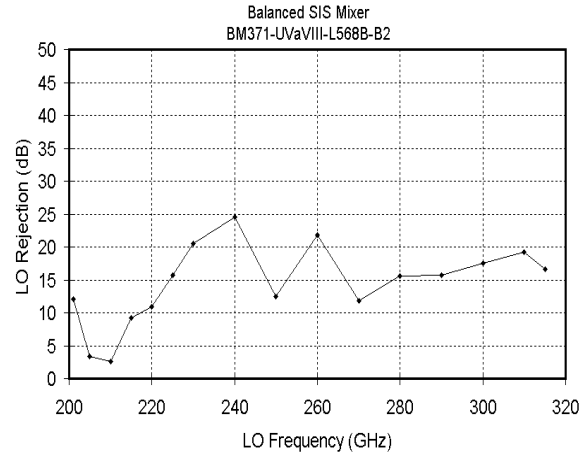
**Fig. 6. I-V characteristic of the two component mixers with LO power applied (light curve) and without LO power (heavy curve). Each mixer has four junctions in series. The bias point is indicated by the marker.  $F_{\text{LO}} = 225 \text{ GHz}$ .**

Measurements were made using RF hot and cold loads (room temperature and liquid nitrogen) in front of the receiver with the IF switch connected in turn to each output of the IF hybrid. The calibrated IF plate enables the mixer noise temperature and conversion loss in each channel to be deduced, and also the overall receiver noise temperature. The LO sideband rejection is simply the quotient of the conversion losses measured at the two IF ports. Fig. 7 shows the DSB mixer and receiver noise temperatures as functions of LO

frequency; note that both noise temperatures include the contributions from all the input components (vacuum window, IR filter, lens, horn). Fig. 8 shows the LO sideband rejection.



**Fig. 7. Mixer and receiver noise temperature (DSB).**



**Fig. 8. LO rejection.**

## DISCUSSION

The performance of the balanced mixer was very close to that of the single-ended mixer [3] on which it was based. It is clear that the loss of the CLCPW quadrature hybrid and transmission lines is not significant in this frequency band.

The variation of the LO rejection with frequency in Fig. 8 results from a small amount of leakage between the signal and LO ports of the balanced mixer chip, whereby some LO power enters the component mixers through the signal port and spoils the amplitude balance and phasing of the LO at the two mixers. Likewise, some signal power enters the LO port, with a similar effect. This leakage does not originate in the CLCPW circuit of the balanced mixer but at the transitions from the suspended striplines to the mixer chip. We suppressed this leakage to the present level using pieces of MF-112 absorber [16] above and below the mixer substrate. (The absorber does not affect propagation on the CLCPW lines as their fields are contained within a small region close to the line.) Further improvement should result from a wider substrate on which the RF and LO ports are further apart so the signal and LO leakage components will be more completely absorbed.

The down-converted signal appears at the port of the IF hybrid while the down-converted LO sideband noise appears at the port. By reversing the bias polarity on one of the component mixers, the outputs are reversed, with the signal appearing at the port [17]. In practice, one normally requires only the down-converted signal and not the LO noise, in

which case it is possible to replace the IF  $180^\circ$  hybrid in Fig. 1 with a simple T-connection and operate with opposite bias polarity on the two component mixers. It is important to note that replacing the  $180^\circ$  hybrid with a simple T-junction results in a change in the IF load impedance seen by the component mixers. The (desired) in-phase IF signals from the two mixers each see, at the T, an IF load impedance twice that of the actual load, while the out-of-phase IF signals from the two mixers see a virtual short circuit at the T.

An alternative way to obtain efficient LO coupling and rejection of LO sideband noise is to use a single-ended mixer preceded by a tuned diplexer — often a quasi-optical Martin-Puplett interferometer is used at millimeter and submillimeter wavelengths. This has the advantage of using a simpler mixer but requires a mechanically tunable diplexer if the receiver is to operate at different frequencies. Furthermore, with the Martin-Puplett type of diplexer, the bandwidth over which good LO noise rejection ( $> 10$  dB) and low signal loss ( $< 0.4$  dB) are obtained is restricted to  $\sim 40\%$  of the IF center frequency. By comparison, a balanced mixer based on a broadband RF quadrature hybrid requires no tuning and should be useable with a multi-octave IF, such as the 4-12 GHz IF currently planned for the ALMA radio telescope.

#### ACKNOWLEDGMENTS

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[4] H. G. LeDuc, B. Bumble, S. R. Cypher, A. J. Judas, and J. A. Stern, "Sub Micron Area Nb/AlO<sub>x</sub>/Nb Tunnel Junctions for Submm Mixer Applications," Third International Symposium on Space Terahertz Technology, 1992.

[5] NFR is a high resolution negative resist from JSR Microelectronics Inc, Sunnyvale, CA 94086.

[6] NMP: 1-Methyl-2-Pyrrolidinone.

[7] A. W. Lichtenberger, in preparation.

[8] Indium Corporation of America, Utica, NY 13502.

[9] Superior Flux & Mfg. Co., Cleveland, OH 44143.

[10] Hughes model VTA-90 parallel gap welder with power supply model MCW-550.

[11] Hercules HR500-2S film is 0.00075" thick. It consists of 0.0005" biaxially oriented polypropylene coated both sides with polyvinylidene chloride. The plastic film division of Hercules is now operated by Applied Extrusion Technology Inc., Covington, VA. HR500-2S is now obsolete and has been superceded by a similar material called UBS-2.

[12] Gore RA-7957 expanded PTFE has a submicroscopic open-cell structure. It has a density 25% of that of solid PTFE.

[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] M/A-Com model 2031-6331-00 1-2 GHz 180° hybrid.

[15] A. R. Kerr, "The NRAO Type-2B 1-2 GHz SIS Bias-T, " Electronics Division Technical Note No. 173, National Radio Astronomy Observatory, Charlottesville, VA, 15 Feb. 1996.

[16] Emerson & Cuming, Inc., Canton, MA. Type MF-112 absorber. See G.A. Ediss A.R. Kerr H. Moseley K.P. Stewart, "FTS Measurements of Eccosorb MF112 at Room Temperature and 5 K from 300 GHz to 2.4 THz," ALMA Memo #273, 8 Sep. 1999. Available at: <http://www.mma.nrao.edu/memos/html-memos/alma273/memo273.pdf>.

[17] The corresponding reversal of output ports in the case of a balanced mixer using conventional diodes also requires the orientation of one diode to be reversed. This is not necessary in the case of a balanced SIS mixer because of the antisymmetry of the I-V characteristics.