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A 200-300 GHz SIS Mixer-Preamplifier with 8 GHz IF Bandwidth

E. F. Lauria[1], A. R. Kerr[1], M. W. Pospieszalski[1,2], S.-K. Pan[1], J. E. Effland[1], A. W. Lichtenberger[3]

[1] National Radio Astronomy Observatory, Charlottesville, VA 22903
[2] Inphi Corporation, Westlake Village, CA 91361
[3] Department of Electrical Engineering, University of Virginia, Charlottesville, VA 22904

Abstract **Initial results are presented for a 200-300 GHz SIS mixer/preamplifier with an IF bandwidth of 8 GHz. The mixer uses Nb/Al-oxide/Nb tunnel junctions in a circuit with low IF capacitance and inductance. The mixer block mounts directly on the body of a three-stage 4-12 GHz preamplifier which uses discrete InP HFET devices. Mixer bias is provided through the input circuit of the preamplifier. At a LO frequency of 230 GHz, the measured mixer-preamp gain is 30-35 dB, and the DSB receiver noise temperature is 45-57 K across the whole IF band. The preamp alone has 40 dB of gain, and dissipates 7.7 mW. With four amplifiers required in each ALMA cartridge, there is concern that the cooling capacity currently planned for ALMA receivers will be marginal. This mixer/preamplifier has demonstrated that an IF bandwidth of 8 GHz is indeed achievable for ALMA Band 6.**

I. INTRODUCTION

Superconductor-Insulator-Superconductor (SIS) mixers are used in the most sensitive heterodyne receivers at frequencies between about 100 GHz and 1 THz. Usually, the SIS mixer is connected to an IF amplifier through a length of 50-ohm cable, and an IF isolator is often included to minimize the effect of mismatch at the IF port of the mixer. In classical mixer receivers (*e.g.*, those using semiconductor diode mixers), it is common to design a coupling network to give a conjugate match between mixer and amplifier. In receivers using SIS mixers, matching the IF port of the mixer can result in negative RF input resistance and reduced dynamic range, which are undesirable in most applications. Low-noise operation with a modest conversion loss and low RF input SWR is achieved when the SIS mixer sees a relatively low IF load impedance, *i.e.*, not with a matched IF load. In that case, the electrical distance between the mixer and IF amplifier can strongly affect the overall noise performance. An IF isolator [1] can minimize variation of the receiver noise temperature across the IF band, but thermal noise added by the termination of the isolator can add substantially to the overall noise temperature, and the IF bandwidth is limited to that of the isolator. A balanced amplifier has noise characteristics [2] similar to those of an amplifier with an isolator and can operate over a larger fractional bandwidth, but has the disadvantage of greater power dissipation and complexity. The limitations of the amplifier with isolator and the balanced amplifier can be overcome if the IF amplifier is located electrically close to the mixer with an appropriately designed coupling network between the mixer and the amplifier, as proposed in 1987 by Weinreb [3]. In 1996, Padin *et al.* [4] reported an integrated SIS mixer-preamplifier with an IF bandwidth of 4 GHz (0.4–4.5 GHz) using a single GaAs transistor.

After considering the IF amplifier configurations described above, the most promising option appeared to be to integrate an IF preamplifier closely with the SIS mixer without an isolator, as in the Padin scheme, but using InP transistors which have recently been used to advantage in a low-noise 3-13 GHz cryogenic amplifier [5]. The high gain and low power dissipation of InP devices allow a three-stage preamplifier with sufficient gain not to require a further cryogenic IF amplifier. The alternative approach, using an isolator, would incur additional noise from the termination of the isolator, and, because cryogenic isolators are not available with more than an octave bandwidth, would require an IF of 8-16 GHz or higher with a somewhat higher amplifier noise temperature.

The noise temperature of a receiver consisting of a mixer followed by an IF amplifier to which it is not matched is given by:

$$T_R = T_M + \frac{1}{G_M^{Av}} T_A^{Z_M}, \qquad (1)$$

where T_M is the equivalent input noise temperature of the mixer, G_M^{Av} is the available gain of the mixer, and $T_A^{Z_M}$ is the noise temperature of the amplifier with source impedance equal to the IF output impedance Z_M of the mixer. If an ideal isolator is used between the mixer and amplifier, the receiver noise temperature is:

$$T_R = T_M + \frac{1}{G_M^{Z_0}}\left(T_A^{Z_0} + \left|\Gamma_M^{Z_0}\right|^2 T_I \right) , \qquad (2)$$

where $G_M^{Z_0}$ is the (transducer) gain of the mixer operating into the characteristic impedance Z_0 of the isolator, $T_A^{Z_0}$ is the noise temperature of the amplifier with source impedance equal to Z_0, $\Gamma_M^{Z_0}$ is the reflection coefficient of the mixer output relative to Z_0, and T_I is the noise temperature of the internal termination in the isolator.

II. DESIGN

The IF signal from an SIS mixer passes through an RF choke and, in many designs, also through much of the RF tuning circuit, both of which may have significant series inductance and shunt capacitance which must be taken into account in designing the IF circuit of the mixer-preamplifier. It was noted in [4] that the IF bandwidth was limited by the capacitance in the IF circuit of the mixer. The SIS mixer used in the present work [6] was designed to minimize the inductance and capacitance in the IF circuit.

The IF preamplifier used here is based on the three-stage 3–13 GHz InP HFET amplifier described in [5], and has a noise temperature of ~4 K and 40 dB gain over the 4-12 GHz band when operated at 4 K with a 50-ohm source. The power dissipation of the preamplifier is 7.7 mW.

The microwave circuit simulator MMICAD was used to simulate the SIS mixer-preamplifier [7]. A circuit model of the SIS mixer was combined with a model of the preamplifier in the same circuit file to allow the effects of different coupling circuits to be evaluated. The goal was to minimize the overall receiver noise temperature across the IF band while maintaining acceptable RF input match (which depends on the IF load impedance) and gain variation. The mixer should work into a relatively low IF load impedance to avoid a high RF input reflection coefficient; for the mixers used in this work, a load of ~50 ohms or less is acceptable.

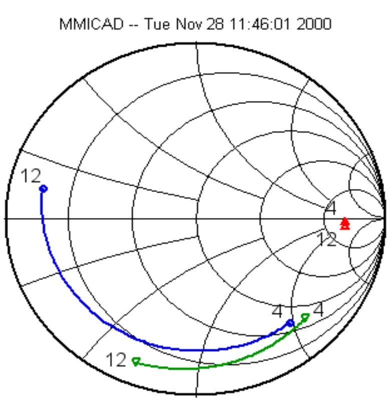

Fig. 1. IF output impedance of the SIS mixer at a LO frequency of 230 GHz. Points (△) indicate the intrinsic IF impedance (at the SIS junctions). Points (▽) are at the bonding pad on the mixer substrate and include the RF choke. Points (◇) include the bond wire between the bonding pad and the preamplifier input.

The IF output impedance of the mixer at three different reference planes is shown in Fig. 1 as a function of IF for a fixed LO frequency of 230 GHz. At the SIS junctions, the output impedance (△) is high and almost independent of frequency. The RF choke on the mixer substrate is primarily capacitive in the IF range and transforms the output impedance as indicated by the points (▽). The inductance of a bond wire between the bonding pad on the mixer substrate and the preamplifier input further transforms the impedance as indicated by the points (◇).

With this simple bond wire connection between the mixer and preamplifier, the simulated gain, noise temperature, and input return loss with the LO at 230 GHz are shown in Fig. 2. These are single-sideband quantities with the RF input in the upper sideband, but the corresponding lower-sideband quantities are virtually identical. The simulations used upper- and lower-sideband embedding impedances deduced from the mixer equivalent circuit, but the mixer's Y-matrix was computed assuming a zero IF. Also, a generic I(V) characteristic was used which differs from that of the test mixer. The simulated results are for the mixer-preamp alone and do not include the inevitable losses and noise contributions from the receiver's input components — vacuum window, LO diplexer, *etc.*

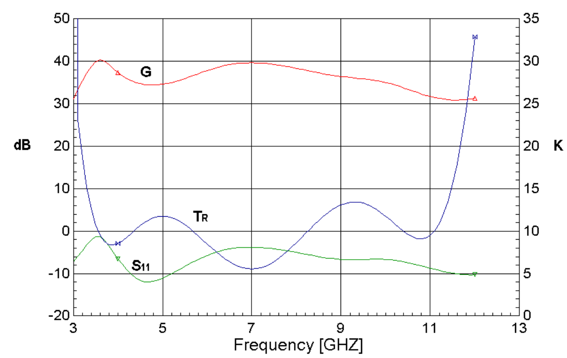

Fig. 2. Simulated single-sideband quantities for the mixer-preamplifier as a function of IF: gain (△) dB, receiver noise temperature (◇) K, and RF input return loss (▽) dB. The LO frequency is 230 GHz.

For comparison, the same mixer connected to the same preamplifier through a hypothetical 4-12 GHz 50-ohm isolator at 4 K was also simulated, with the results shown in Fig. 3. It is clear that while the isolator smooths out the variation in T_R versus frequency, it adds substantially to T_R at all frequencies, and at 7.5 GHz it increases T_R from 6 K to 16 K.

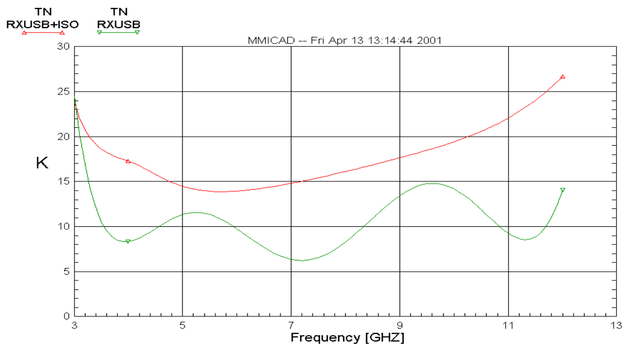

Fig. 3. Comparison of simulated single-sideband receiver noise temperatures for the mixer-preamp (▽), and the same mixer connected to the same IF amplifier through an ideal 50-ohm isolator (△). The LO frequency is 230 GHz.

III. Construction

The complete mixer-preamp assembly is shown in Fig. 4. In order to allow the mixer and preamplifier to be measured separately, they are made in separate housings which bolt together. The IF connection is made with a bond wire from the end of the mixer substrate to the amplifier input. To test the two components separately, a type-K coaxial connector can be mounted on each. The SIS mixer block was modified from the usual design to minimize the distance from the end of the mixer substrate to the preamplifier. At the input of the preamplifier is the inner bead of a K-connector followed by a 50-ohm microstrip line 0.14 in. long (substrate $\varepsilon_r = 2.1$) to the first transistor. To keep the mixer as simple and compact as possible, the mixer bias circuit is built into the preamplifier housing. Mixer bias is introduced through a high impedance low-pass circuit, similar to the gate bias circuits used in the amplifier, connected to the input microstrip line; this has negligible effect on the preamplifier characteristics.

IV. Measurements

The mixer-preamplifier was measured in a test receiver cooled to ~4 K by a Joule-Thompson refrigerator. The external RF signal from room temperature and cold (liquid nitrogen) loads enters the dewar through a plastic film and expanded PTFE vacuum window [8] and an expanded PTFE infrared filter attached to the 50-K radiation shield. A HDPE lens attached to the 4 K stage focuses the signal into a corrugated horn. LO power is injected into the signal waveguide through a 17 dB directional coupler between the mixer and horn. Fig. 5 shows the double-sideband receiver noise temperature and gain of the mixer-preamp, measured outside the dewar, as functions of intermediate frequency with the LO at 230 GHz. Fig. 6 shows the measured double-sideband receiver noise temperature as a function of IF with LO frequency as parameter. Fig. 7 shows the measured noise temperature as a function of LO frequency with the intermediate frequency as parameter. Also shown in Fig. 7 is the measured receiver noise temperature with the same mixer, but using a 1.5 GHz IF amplifier with an isolator.

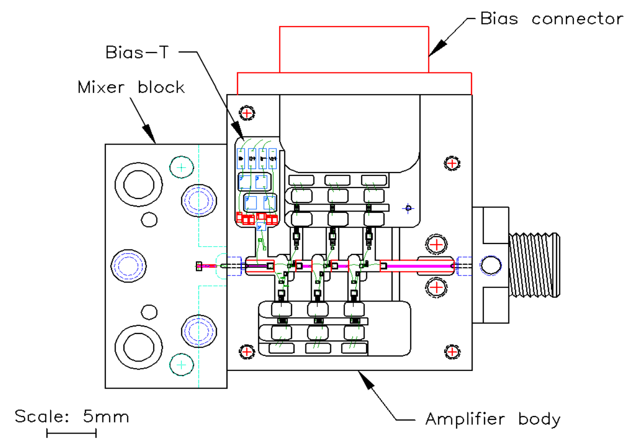

Fig. 4. The mixer-preamplifier assembly with the preamplifier cover removed.

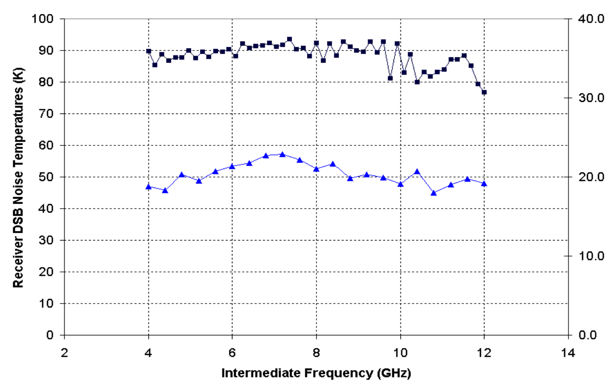

Fig. 5. Double-sideband receiver noise temperature (▲) and gain (■) of the mixer-preamp, measured outside the dewar, as functions of intermediate frequency, with a LO frequency of 230 GHz.

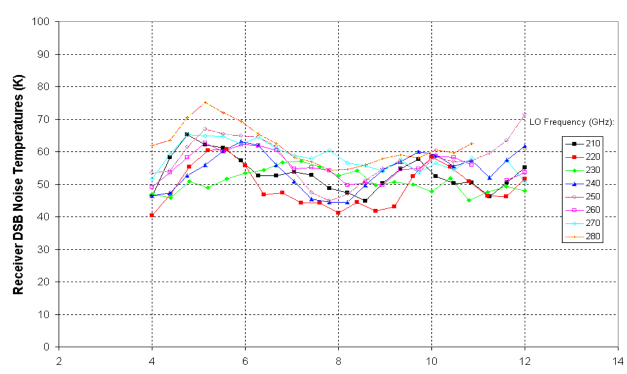

Fig. 6. Double-sideband receiver noise temperature, measured outside the Dewar, as a function of intermediate frequency, with LO frequency as parameter.

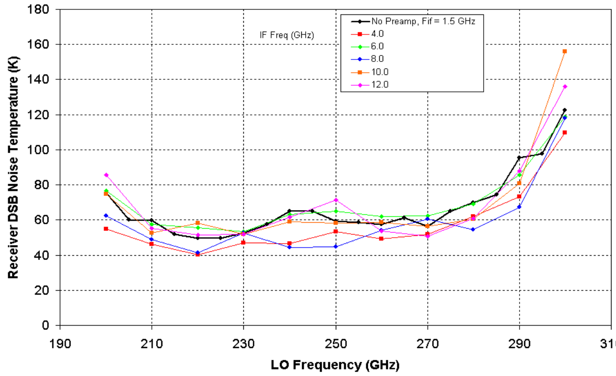

Fig. 7. Double-sideband receiver noise temperature, measured outside the Dewar, as a function of LO frequency, with intermediate frequency as parameter. Also shown is the receiver noise temperature measured with the same mixer but with a 1.5 GHz IF amplifier and an isolator.

V. Discussion

The simulated and measured results demonstrate the benefit of connecting the IF preamplifier directly to the SIS mixer without an isolator. The ripples in the T_R vs f_{IF} curves are a result of the small output conductance of the mixer and the electrical distance between the SIS junctions and the first transistor in the preamplifier.

The IF port of the intrinsic mixer is well described as a current source in parallel with a small conductance (positive or negative), but the accessible port is at the end of the substantially capacitive RF choke. Any attempt to design an optimum coupling circuit between mixer and preamplifier must take into account the mixer's RF choke and also the input microstrip line of the preamplifier which must be long enough to accommodate the connection to the mixer bias circuit.

In trying to optimize the mixer-to-preamplifier coupling circuit, it must be remembered that if the (intrinsic) mixer sees a high load impedance, even outside the intended IF band, that can result in reduced dynamic range and even instability given unfavorable out-of-band RF embedding impedances [9].

We have not yet investigated the possible benefits of changing the input impedance and/or (noise) optimum source impedance of the preamplifier to other than 50 ohms.

In designing the refrigeration system for the ALMA receivers, it is important to ensure that there is sufficient cooling capacity (at ~3.5 K) to support two polarization channels with sideband-separating mixers — a total of four preamps. This means that *at least* 32 mW of cooling capacity is required. Based on the specifications presented at the Preliminary Design Review in February 2001 in Tucson, we are concerned that the refrigeration capacity currently planned for ALMA may be marginal.

Acknowledgments

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