A Fixed-Tuned SIS Mixer with Ultra-Wide-Band IF and Quantum-Limited Sensitivity for ALMA Band 3 (84-116 GHz) Receivers

S.-K. Pan[1], A. R. Kerr[1], M. W. Pospieszalski[1], E. F. Lauria[1],
W. K. Crady[1], N. Horner, Jr.[1], S. Srikanth[1], E. Bryerton[1], K. Saini[1],
S. M. X. Claude[2], C. C. Chin[2], P. Dindo[2], G. Rodrigues[2], D. Derdall[2]
J. Z. Zhang[3] and A. W. Lichtenberger[3]

[1]National Radio Astronomy Observatory[*], Charlottesville, VA 22903
[2]Herzberg Institute of Astrophysics, National Research Council of Canada
[3]Department of Electrical Engineering, University of Virginia, Charlottesville, VA 22904

Abstract - This paper describes an 84-116 GHz Nb/Al-oxide/Nb SIS mixer with multi-octave IF bandwidth and quantum-limited sensitivity. The mixer can be integrated with a three-stage 4-12 GHz HFET preamplifier or fitted with a coaxial connector for operation with an external isolator and IF amplifier. An 84-116 GHz receiver using the mixer with an integrated 4-12 GHz HFET preamplifier has a double sideband noise temperature of 16-20 K (3 to 4 $h\nu/k_B$) over most of the IF band. Analysis of the mixer-preamp using Tucker's theory shows good agreement with measurements. The mixer is easy to build and is being used as a building block for the Band 3 sideband-separating receivers for the Atacama Large Millimeter Array (ALMA)[**]. With minor modifications, this mixer design can be scaled to other ALMA bands.

I INTRODUCTION

Fixed-tuned SIS heterodyne receivers have been successfully used for radio astronomy in the millimeter and submillimeter-wave bands. These receivers offer near quantum-limited sensitivity but in most cases have an IF bandwidth of only 1 to 2 GHz. Recently, SIS receivers with wider IF bandwidths have been built by integrating an IF preamplifier with the SIS mixer [1,2] or by using a wideband cryogenic isolator and IF amplifier [3]. The mixer-isolator-amplifier scheme may give less variation of receiver noise temperature across the IF band, but the loss of the isolator increases the effective IF noise temperature, and the thermal noise from the internal termination of the isolator is reflected at the output of the mixer and increases the overall receiver noise. In addition, the achievable IF bandwidth of the receiver is limited by the bandwidth of the cryogenic isolator. On the other hand, direct connection of the mixer and preamplifier requires a more detailed knowledge of the mixer and preamplifier in order to design the coupling network. Recent reports [1,2] have demonstrated that this approach is practical for higher frequency mixers (above 200 GHz). It is more difficult to design wide IF bandwidth integrated mixer-preamplifiers for lower frequencies. This is because the IF circuit parasitic capacitance and inductance are, in general, larger in the lower frequency mixer. Also, as pointed out in [4], when the intermediate frequency is a significant fraction of the LO frequency (*i.e.*, low frequency mixers with high IF), quantization of the IF becomes significant and the conversion loss, sideband ratio, noise temperature, and output impedance of the mixer all become IF dependent.

In this paper, we describe the design of an 84-116 GHz Nb/Al-oxide/Nb SIS mixer with multi-octave IF bandwidth and quantum-limited sensitivity. The mixer can either be connected to the IF amplifier through a cold (4.2 K) isolator or integrated directly with an IF preamplifier. Mixer simulations are carried out using a quasi five-frequency approximation [5] to Tucker's theory, and includes the excess shot noise due to Multiple Andreev Reflections (MAR) [6]. Experimental data agree well with simulated results. The mixer is being used as a building block for the ALMA Band 3 receiver cartridges.

II MIXER DESIGN

To fulfill the ALMA science requirements and take full advantage of the exceptionally good site conditions, the Band 3 mixer must meet the following specifications:

(i)   RF band at least 86-116 GHz; 84-116 GHz if possible.
(ii)   Intermediate frequency: 4-12 GHz.
(iii)   Double-sideband (DSB) noise temperature < 17 K, or single-sideband (SSB) noise temperature < 34 K, across 80% of the RF band.
(iv)   High saturation power. The large signal gain compression caused by the exchange of RF load temperatures of 77 and 300 K must be less than 5 %.
(vi)   A moderately well-matched RF input is desirable to avoid excessive baseline ripples due to vertex reflections from the subreflector.

The SIS mixer design procedure is as follows: A 4-junction series array is chosen to ensure that the mixer has sufficient dynamic range for solar observations [7]. A series array of junctions also allows the use of larger junctions, which gives greater uniformity and improved yield. To achieve wide bandwidth, a value of $\omega R_N C_J \sim 3$ (at 100 GHz) is chosen; this requires a critical current density $J_C = 2{,}500$ A/cm^2. A junction diameter of 2.2 µm is chosen, for which the array normal resistance is 70 ohms and the optimum source impedance is 35 ohms at 100 GHz [8]. Table I gives the junction and circuit parameters for this mixer when using the UVA niobium trilayer process.

**Table 1. ALMA Band 3 Device Parameters
for UVA Niobium Trilayer Process**

J_C	2,500 A/cm^2
Junction size (diameter)	2.2 µm
Normal resistance of the array	70 Ω
Cs	65 fF/µm^2
SiO dielectric constant	4.2
I2 (SiO)	2,850 Å
M3	4,000 Å
Pd/Au	300 Å

The mixer circuit layout is similar to that described in [9], and minimizes the IF circuit parasitic capacitance and inductance. The junction capacitance is tuned out by a series CPW inductor to achieve an RF bandwidth approaching the fundamental limit for broadband matching to a capacitive device [10]. The complete mixer circuit, shown in Figs. 1 and 2, occupies a 4.3 x 0.6 x 0.2 mm quartz substrate. The waveguide is coupled to a 50-ohm suspended substrate stripline which makes a transition to a 50-ohm capacitively-loaded coplanar waveguide (CLCPW). Short sections of microstrip and CPW just to the left of the broadbanding stubs form a parallel-C — series-L impedance transformer. The CPW inductor immediately to the left of the junctions tunes out the junction capacitance. The RF circuit is completed by a capacitor to ground in parallel with the low impedance RF choke.
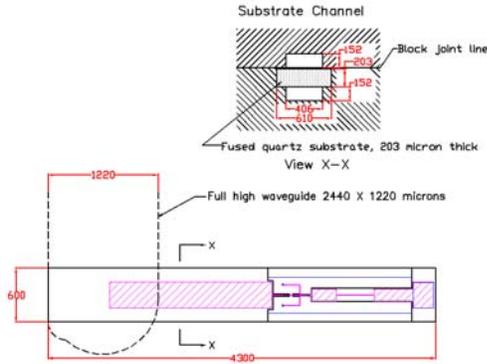
Fig. 1. Diagram of the mixer substrate. At the left is the waveguide probe. All dimensions are in microns.
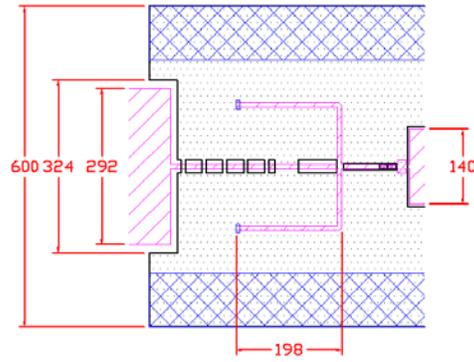

Fig. 2. Details of the RF matching circuit. From left to right: suspended microstrip to CPW transition, CLCPW, microstrip and CPW C-L transformer, the pair of microstrip short-circuit stubs, CPW inductor, four-junction series array, grounding capacitor, and RF choke.
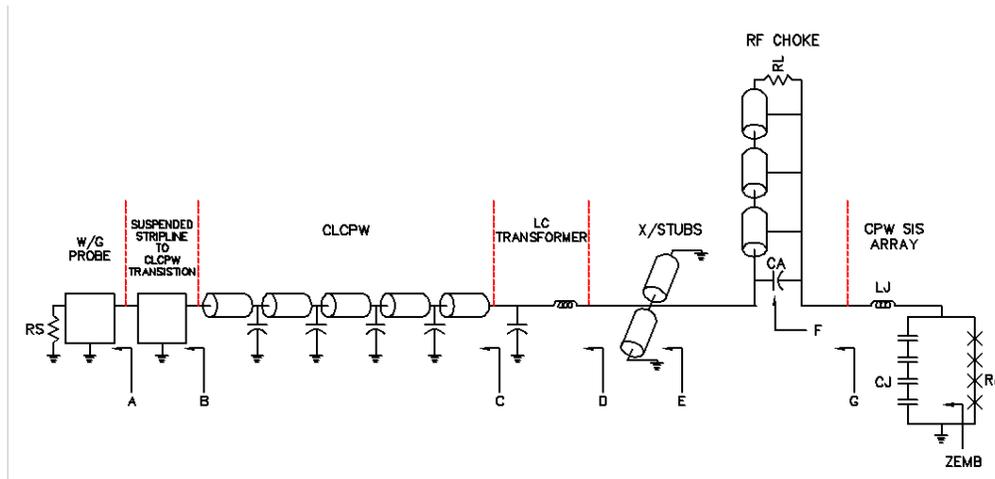

Fig. 3. Schematic circuit of the mixer. (The RF impedance transformation through the circuit is shown, section by section, in Fig. 4.)

The RF circuit of the mixer transforms the input waveguide impedance to the optimum embedding impedance for the array of junctions over the 84 to 116 GHz RF band. The waveguide to suspended stripline transducer was designed using QuickWave [11] FDTD EM simulator as described in [12]. The mixer tuning circuit and RF choke were designed and optimized using Sonnet *em* [13] and MMICAD v. 2 [14]. The RF impedance at successive stages of the circuit is shown on 50-ohm Smith charts in Figs. 4(A)-(G) — the letters A-G correspond to the labeled planes in Fig. 3. Figure 5 shows the embedding impedance seen by the SIS array (including the junction capacitance) on a Smith chart normalized to the 35-ohm optimum source impedance. Since the embedding impedance falls within the $|\rho| = 0.4$ circle over the entire 84-116 GHz band, good broadband mixer performance is expected [10].

Following [9] the mixer circuit is designed to exclude IF signals from most of the RF circuit, thereby reducing the parasitic capacitance and inductance in the IF circuit. One end of the SIS array is connected to DC/IF-ground through the CPW tuning inductor and the pair of short-circuit microstrip stubs, thus isolating the IF signals from the rest of the RF circuit. Figure 6 shows the simulated output impedance of the mixer at the output bonding pad on the mixer substrate for a LO frequency of 100 GHz. With an IF load impedance of 50 ohms, a 4-12 GHz IF band is practical with this design.
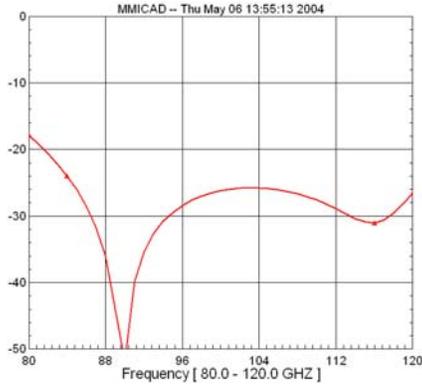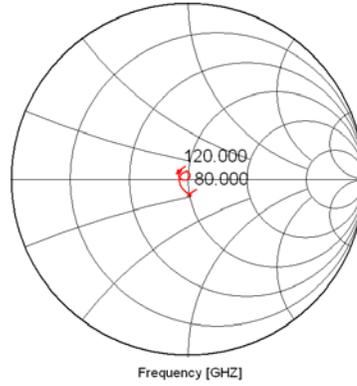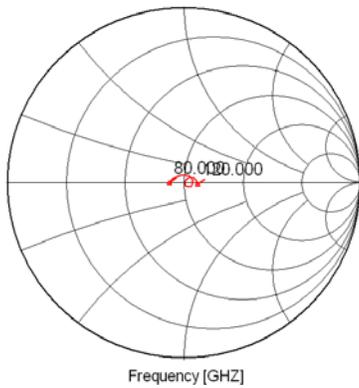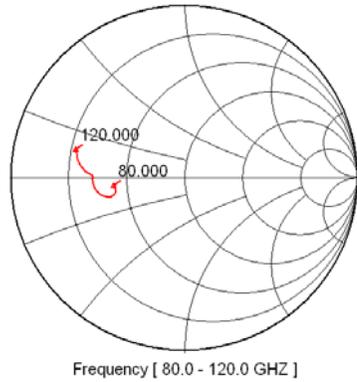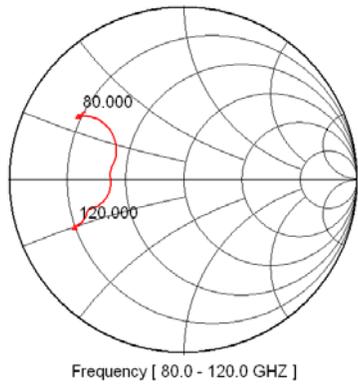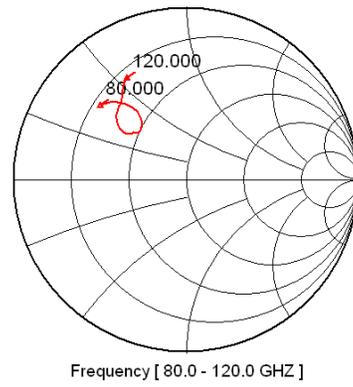
Fig. 4.   RF impedance transformation through matching circuit as seen at each of the labeled planes in Fig. 5: (A) Quickwave simulation of |S11| dB of the waveguide probe. (B) Impedance of the waveguide probe and the suspended microstrip to CPW transition. (C) Including the CLCPW line. (D) Including the LC impedance transformer. (E) Including the two stubs. (G) Including the RF choke. All charts in this figure are normalized to 50 ohms.
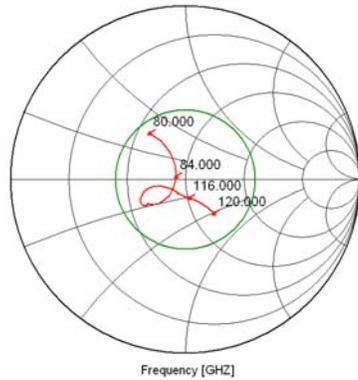
Fig. 5. The RF embedding impedance seen by the 4-junction array. The junction capacitance and the array inductance are taken as part of the embedding circuit. The Smith chart is normalized to 35 ohms, the optimum source impedance. The circle is at $|\rho| = 0.4$.
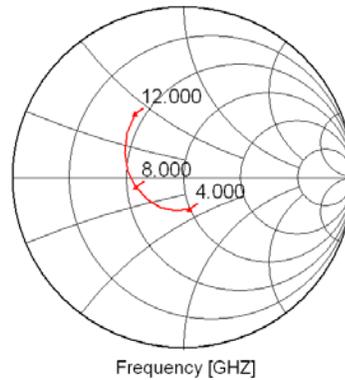

Fig. 6. MMICAD simulation of the IF output impedance of the SIS mixer, measured at the bonding pad on the mixer substrate, at an LO frequency of 100 GHz. Normalized to 50 ohms.

III   FABRICATION

The Band 3 mixers were fabricated in the University of Virginia Microfabrication Laboratory [15] on 30‑mm diameter amorphous quartz wafers. The system used to deposit the low-stress Nb/Al-oxide/Nb trilayer + Cr/Au films for these devices has been described in [16,17]. For our system, the critical current density is related to the oxygen exposure dose by J_C (kA/cm^2) = 20.5 x E^{-4} (T-sec), and for the present mixers an oxygen exposure dose E = 192 Torr-sec was used. The Nb film stress for these mixers is less than 1 x 10^9 dyne/cm^2. The junctions are fabricated using a modification of our quad-level resist process [18] whereby a fifth layer is added to the resist stack. A thin (10-nm) Nb layer added between the polyimide and Ti layers results in the production of less debris by preventing interaction between the Ti and polyimide layers. The junction insulation is by a gold overlayer process [9,19] which eliminates the need for physical cleaning of the junction counter electrode before depositing the Nb wiring layer. Sublimated SiOx films were used for both dielectric layers; the dielectric constant of these films was measured to be 4.2. All film thicknesses were within 7% of the design values.
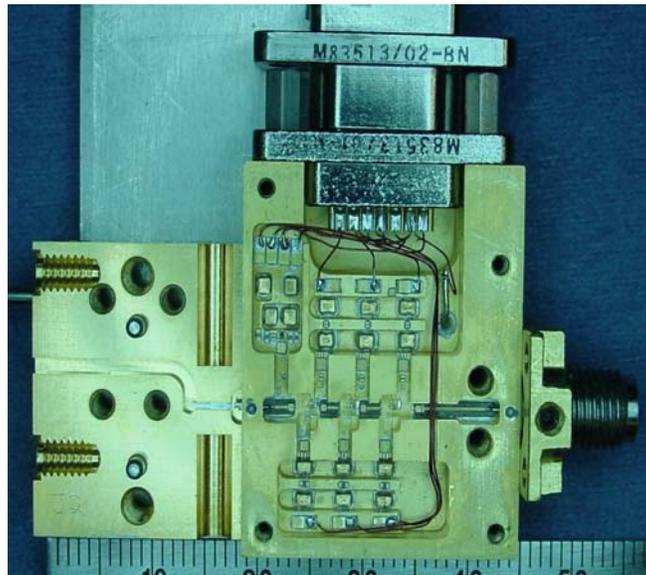

Fig. 7. The integrated mixer-preamplifier assembly with the top half of the mixer and the amplifier cover removed. The mixer is the left module and the 4-12 GHz preamplifier is on the right. The bias-T for the mixer is in the upper left corner of the preamplifier.

The quartz mixer substrate is mounted in an E-plane split waveguide block. The ground connections between substrate and block are made by two gold crush wires, 0.025-mm diameter, on the shoulders of the substrate channel, which are compressed when the block halves are assembled. The mixer block is designed so that it can either accommodate a 2.9-mm connector or be connected directly to an IF preamplifier by a wire bond to the input of the preamplifier. Figure 7 shows a photograph of the integrated mixer-preamplifier assembly with the top half of the mixer block and the amplifier lid removed. The 3-13 GHz, three-stage InP HFET cryogenic low-noise preamplifier was designed according to the general guidelines presented in [20], with the mixer bias circuit inside the preamplifier housing as in [2] to minimize the distance between the mixer and preamplifier. The mixer is connected to the preamplifier by a bond wire 0.001" diameter x 0.020" long. With a 50-ohm source, the preamplifier has a noise temperature of ~ 4.5 K with 35 dB gain over 4-12 GHz when operated at 4.2 K. The power dissipation of the amplifier is 7.7 mW at 4.2 K.

IV EXPERIMENTAL RESULTS

The integrated Band 3 mixer-preamplifier was tested in a liquid helium cooled dewar. Figure 8 shows a block diagram of the receiver and test setup. The incoming RF signal enters the dewar through a plastic film vacuum window supported by polystyrene foam [21], and an expanded PTFE infrared filter [22] attached to the 77 K radiation shield, and is coupled to the mixer by a pyramidal horn at 4.2 K. LO power is injected through a 23 dB branch-line directional coupler, also at 4.2 K. Josephson currents in the junctions were not suppressed by an applied magnetic field during the measurements; this is not necessary for ~ 100 GHz SIS mixer operation.
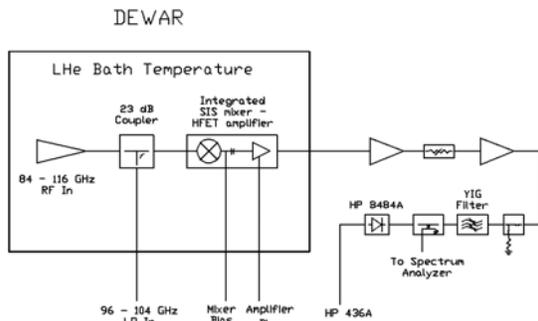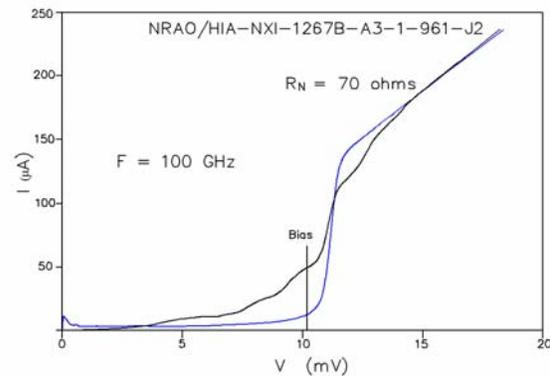

Fig. 8. Block diagram of the receiver and test setup.

Fig. 9. I(V) curves for the mixer at 4.2 K without LO power (blue) and with LO power (black). The bias voltage is indicated by the vertical line.
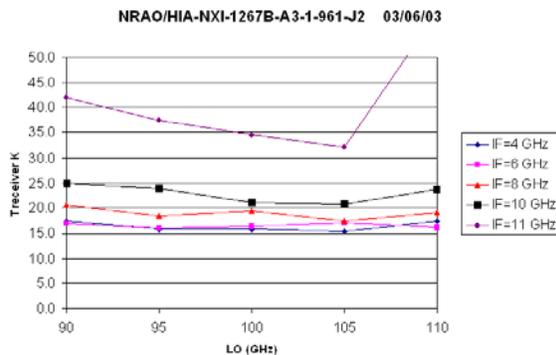

Fig. 10. Double-sideband noise temperature of the receiver, measured outside the receiver dewar, as a function of LO frequency, with intermediate frequency as parameter.
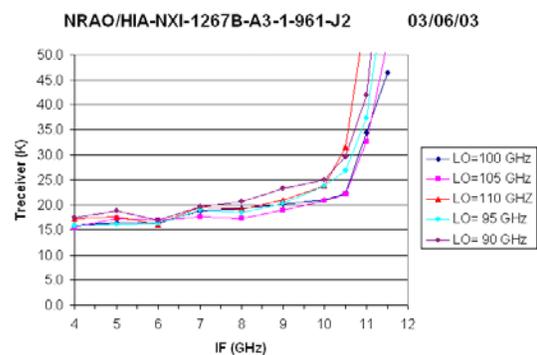

Fig. 11. Double-sideband noise temperature of the receiver, measured outside the receiver dewar, as a function of intermediate frequency, with LO frequency as parameter.

The I(V) curve of the mixer at 4.2 K, with and without 100 GHz LO power applied, is shown in Fig. 9. Figure 10 shows the double sideband (DSB) noise temperature of the receiver, measured in front of the vacuum window of the dewar, as a function of LO frequency, with intermediate frequency as parameter. Figure 11 also shows the DSB noise temperature of the receiver, but as a function of intermediate frequency, with LO frequency as parameter. The noise rise at high IF (~ 10.5 GHz) is partly caused by the non-optimum mixer-amplifier coupling circuit and partly by the amplifier gain roll-off.

V   SIMULATION

Extensive simulations were carried out in designing the mixer. The mixer performance was calculated at an LO frequency of 100 GHz using the quasi five-frequency approximation [5] to Tucker's quantum mixer theory, with non-zero IF [4] and includes the excess Multiple Andreev Reflection (MAR) shot noise [6]. In order to compare the simulated results with the measurements, the measured I(V) curve, shown in Fig. 10, was used in the simulation, and the upper and lower sidebands were terminated in the simulated RF embedding impedance shown in Fig. 5. It is further assumed in the mixer simulation that (i) the second harmonic sidebands are terminated by the junction capacitance alone, (ii) the IF load impedance is 50 ohms, and (iii) the pumping parameter $\alpha = 1.2$. The complete receiver performance is calculated assuming an amplifier noise temperature of 4.5 K and an RF input loss of ~0.05 dB, with an added input noise of 3 K. The LO noise contribution injected through the 23 dB LO coupler is estimated to be 1.5 K in each sideband. Figure 12 shows the simulated and measured DSB receiver noise temperatures as functions of the intermediate frequency with the LO at 100 GHz.
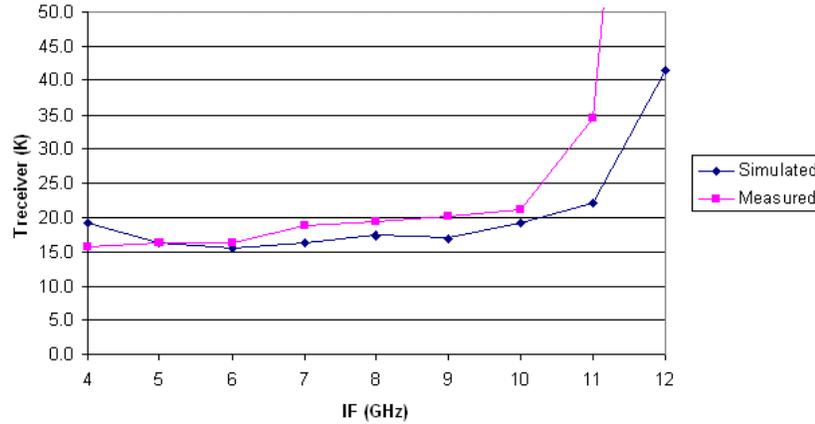

Fig. 12. Simulated (blue) and measured (magenta) DSB receiver noise temperatures, as a function of intermediate frequency, at an LO frequency of 100 GHz.

VI   CONCLUSION

An 84-116 GHz SIS mixer with a multi-octave IF bandwidth has been successfully developed without design iterations. The mixer can either be connected to the amplifier and IF isolator via a 2.9-mm connector or integrated directly with an IF preamplifier. With the integrated preamplifier, the DSB receiver noise temperature measured outside the Dewar was 16-20 K (3-4 $h\nu/k_B$) over the 84-116 GHz RF band, for most of the 4-12 GHz IF band. The receiver measurements agree well with the simulated results predicted by Tucker's theory using the actual array I(V) curve and the embedding impedances obtained by simulation during the mixer design. The success of this mixer is due to the quality of the SIS junctions and accurate modeling, which includes careful SIS device modeling and electromagnetic analysis of the passive matching structures.

The mixer is easy to build and is being used as a building block in the ALMA Band 3 sideband-separating receivers [23]. With minor modification, this mixer design can be scaled to other ALMA bands.

ACKNOWLEDGMENTS

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