National Radio Astronomy Observatory
Electronics Division Technical Note

EDTN 226

SIS Receiver Design Using Microwave Office

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14 April 2020

Abstract

This report describes a Microwave Office program for the small-signal and noise analysis of a millimeter-wave SIS receiver. It is based on an earlier MMICAD program used to design the ALMA Band-6 SIS receivers.

The program requires following input information:

- The complex five-frequency conversion admittance matrix of the pumped SIS junction or array of junctions.
- The complex five-frequency noise current correlation matrix of the pumped SIS junction or array of junctions.
- The IF circuit of the mixer chip.
- The interstage network connecting the mixer chip to the IF amplifier.
- The circuit of the IF amplifier, or its scattering and noise parameters.

Introduction

For many years the design of millimeter wave SIS receivers at NRAO has used a MMICAD microwave circuit analysis program to optimize the gain and noise characteristics given the five-frequency conversion admittance and noise current correlation matrices of the pumped junction or array of junctions [1]. MMICAD is now obsolete, and it does not run on current operating systems. A replacement program written in Microwave Office is described here.

While an SIS junction driven by a local oscillator generates voltage and current components at harmonics of the LO frequency, it has been found that the performance of an SIS mixer can be determined with good accuracy if the LO voltage is taken as sinusoidal [2]. This is tantamount to providing short-circuit terminations at the LO harmonics nf_{LO} , $n > 1$. The substantial capacitance of SIS junctions probably helps to approximate this sinusoidal pump voltage condition. However a short-circuit should not be assumed for the second harmonic sidebands at $2f_{LO} \pm f_{IF}$. Hence the small-signal equivalent circuit of the mixer has five frequencies: f_{IF}, the upper and lower sideband frequencies $f_{LO} \pm f_{IF}$, and the second harmonic sideband frequencies $2f_{LO} \pm f_{IF}$. This five-frequency equivalent circuit is defined by its admittance matrix and noise current correlation matrix which provide the input for the MWO program described here. These matrices are computed from the DC current-voltage characteristic of the SIS junction or array of junctions using Tucker's quantum mixer theory [3][4].

Sideband numbering convention

The sideband numbering convention used here is that of Saleh [5], which is used in most modern mixer analysis. The lower sideband frequencies are negative.

$f_1 = -2f_{LO} + f_{IF}$	second harmonic lower sideband
$f_2 = -f_{LO} + f_{IF}$	lower sideband
$f_3 = f_{IF}$	IF
$f_4 = f_{LO} + f_{IF}$	upper sideband
$f_5 = 2f_{LO} + f_{IF}$	second harmonic upper sideband

Noise temperatures

The noise temperatures of the terminations at the higher frequencies are related to their physical temperature by the Callen & Welton formula as described in [6] which includes the vacuum fluctuation term $hf/2k$: $T_N = (hf/k)/[\exp(hf/kT) - 1] + hf/2k$. For $T = 4$ K and $f = 240$ GHz, T_N is 6.6 K, and for the second harmonic sidebands near 480 GHz it is 11.6 K.

Mixer circuit description in MWO

Data Files:

Conversion admittance matrix.

The 5 x 5 conversion admittance matrix (UV230a5y in the example) is entered as a Touchstone file for a single LO frequency. The RF embedding impedance can be different in the upper and lower sidebands, but it is assumed to remain unchanged within each sideband; the program sweeps only the IF. Formatting idiosyncracies with Touchstone files in MWO make it easier to import the 5 x 5 complex Y-matrix as a RAW data file.

Noise current correlation matrix

MWO's INCOR5 element defines five correlated noise current sources as a complex 5 x 5 matrix. The on-diagonal elements are the mean square noise currents in pA^2/Hz, and the off diagonal elements are the (dimensionless) complex correlation coefficients. This differs from the NCSCOR5 element in MMICAD.

The shot noise of the SIS junction or array, and the correlation between the noise components at the five sideband frequencies is entered as 5 x 5 complex matrix via a Text file. This file is associated with MWO's INCOR5 element via the functions H and cl defined in the Global Definitions 1 block:

H=DataFile("UV230a5h") and cl(n) =n.

IF amplifier

The IF amplifier is defined by its MWO circuit model or as an s2p Touchstone file which includes the noise parameters of the amplifier. Some Touchstone files contain a header NOISE above the noise parameters. This should be commented out (! NOISE) to be compatible with MWO.

Project options

The current version of the program has the Project Options/Global Units set as follows:

Frequency: GHz	Temperature: K	Time: ps	Resistance: Ohm	Conductance: S
Inductance: pH.	Capacitance: fF	Length: μm		

Global Definitions

The global definitions shown here are for the mixer-preamps used in the current NRAO/ALMA Band 6 receiver as described in [7].

```
_TEMPK=4

H=DataFile("UV230a5h")

RS=40
    XS1=-100
    XS2=1e9
    XS3=100
RN=63.2
WRC=4

CJA=55.35

R2=RS
R4=RS

X1={-RN/(2*WRC)}
X5={-RN/(2*WRC)}
```

_TEMPK = 4 K is the global noise temperature ascribed to elements in those schematics which do not contain an over-riding _TEMPK value.

For historical reasons the RF source admittance seen by the SIS junction or array is defined as the parallel combination of resistance RS and reactance XS: YS = 1/RS - j/XS. In this example XS is swept with the values XS1, XS2, XS3.

RN is the normal resistance of the junction or array of junctions.

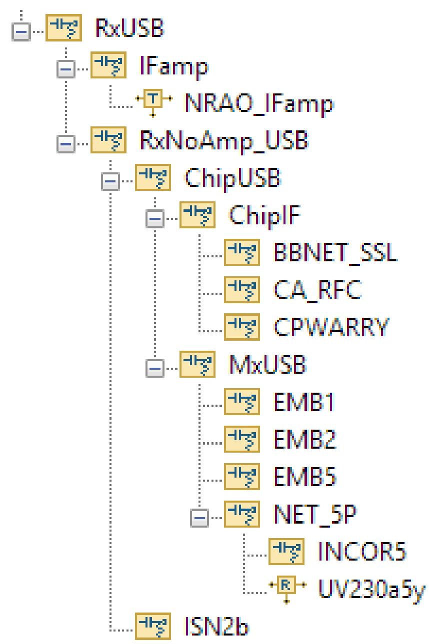
WRC is the $\omega R_N C_J$ product of the SIS junctions at the LO frequency.

CJA is the capacitance of the junction or array. For an array of n identical junctions, CJA is 1/n times the individual junction capacitance.

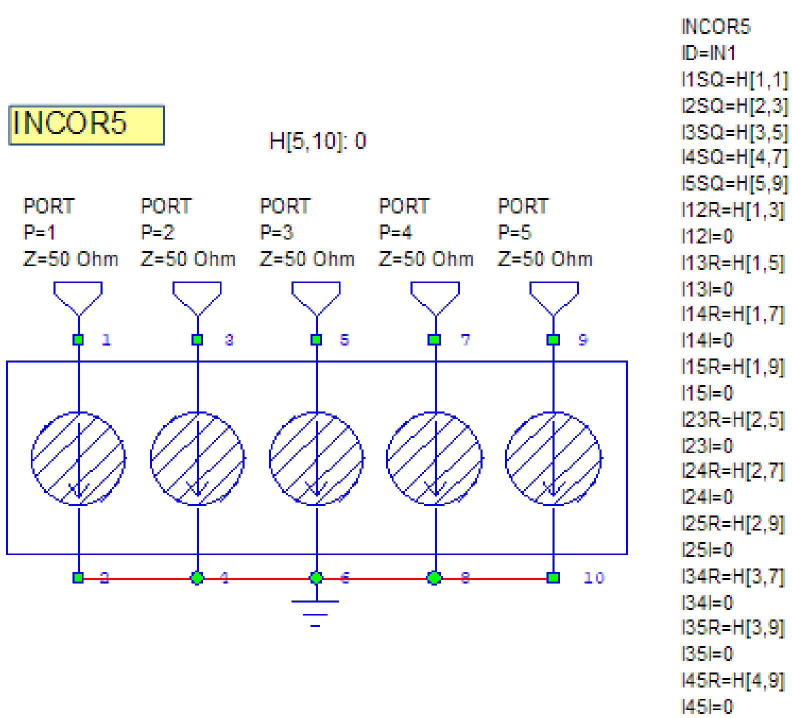
X1 and X5 are the embedding reactances seen by the junctions at the second harmonic sideband frequencies $2f_{LO} \pm f_{IF}$, which in this example are assumed to be reactively terminated in the junction capacitance. In the low- IF case, X1 = X5 = -RN/(2.WRC).

Circuit Schematics

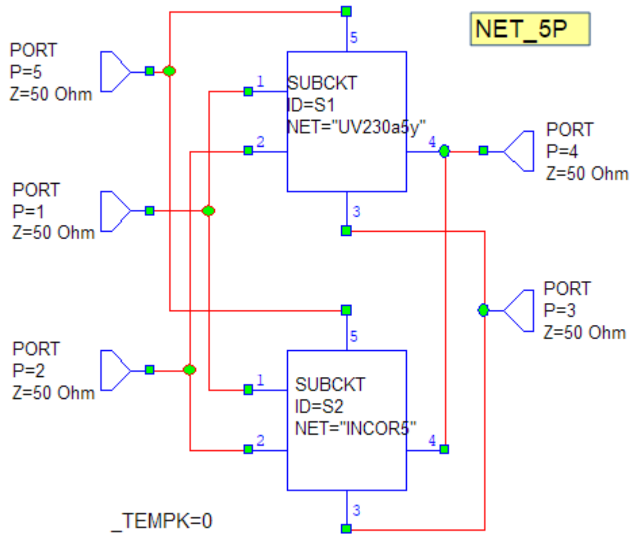
In MWO the mixer-preamp is defined by the schematics as shown in the component tree. The example uses the ALMA Band-6 SIS mixer with the NRAO-UVML mixer chip defined by its 5-port conversion admittance matrix UV230a5y and noise current correlation matrix UV230a5h as described above.



INCOR5 contains the five correlated noise sources corresponding to sideband frequencies f_1 to f_5.



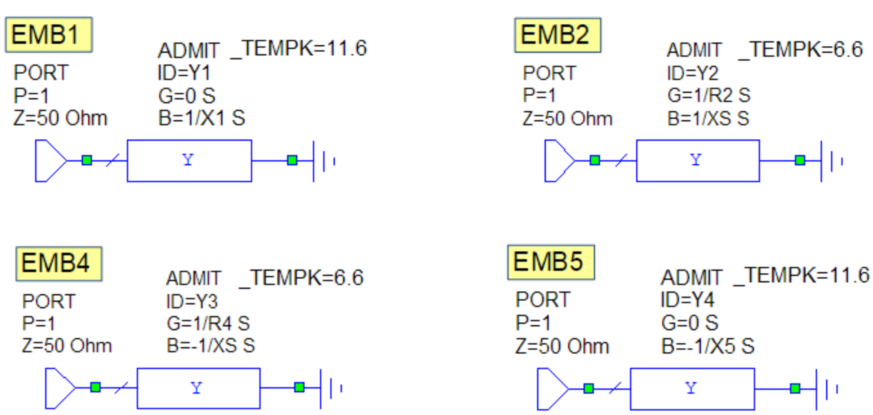
NET_5P connects the correlated shot noise sources to the five-port small signal conversion admittance matrix of the pumped SIS junction or array of junctions.



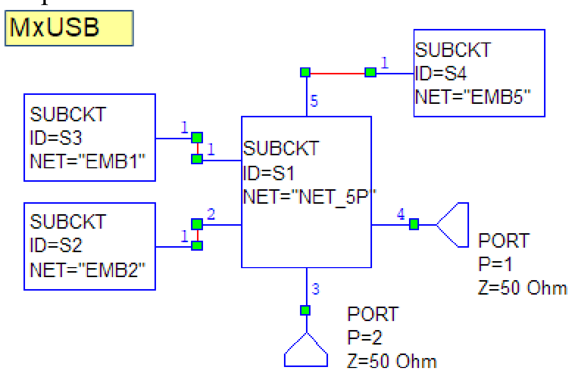
EMB1, EMB2, EMB4, EMB5 are the embedding impedances seen by the SIS junction or array at the sideband frequencies:

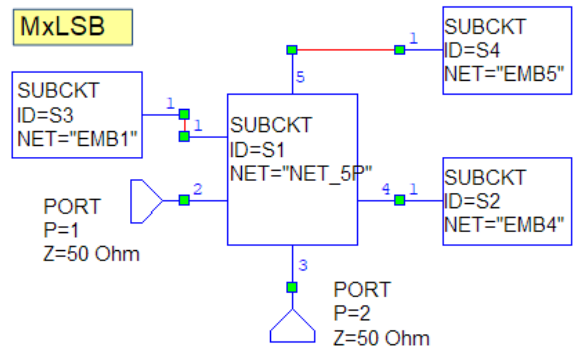
$f_1 = -2f_{LO} + f_{IF}$	second harmonic lower sideband
$f_2 = -f_{LO} + f_{IF}$	lower sideband
$f_4 = f_{LO} + f_{IF}$	upper sideband
$f_5 = 2f_{LO} + f_{IF}$	second harmonic upper sideband

As explained above, the lower sideband frequencies f_1 and f_2 are negative. Hence the susceptance values in EMB1 and EMB2 are given as B = 1/X as opposed to B = -1/X as for the positive-frequency terminations EMB4 and EMB5. The _TEMPK equations define the noise temperatures of any lossy elements in the sideband terminations.

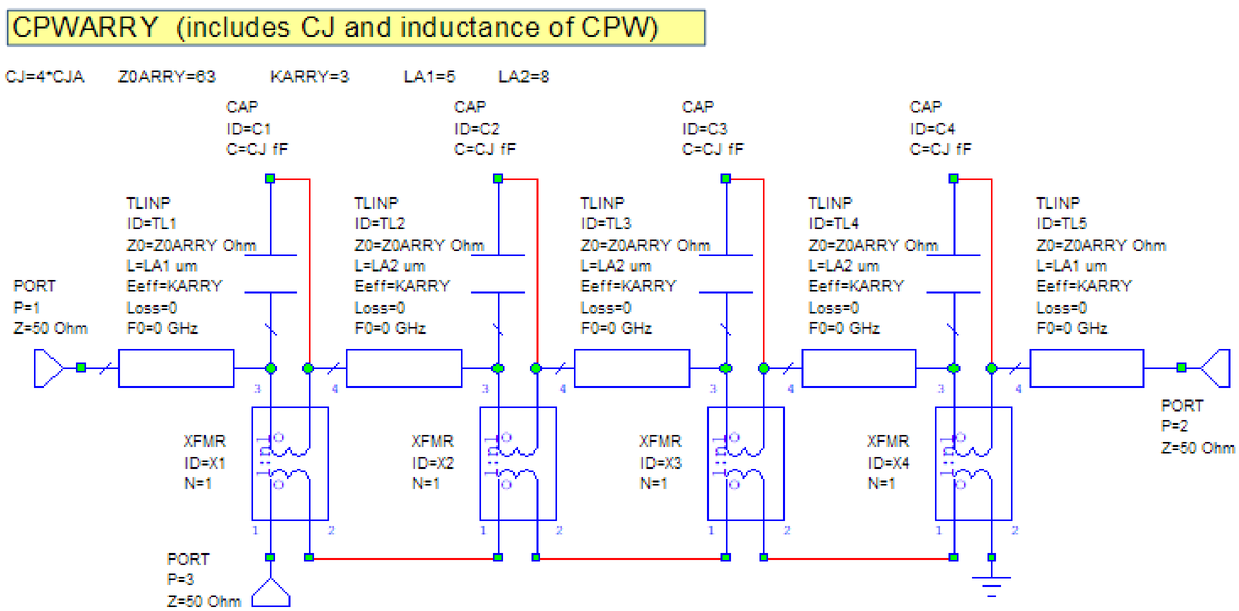


MxUSB, MxLSB connect the image and second harmonic sideband terminations to NET_5P, resulting in a two-port network.

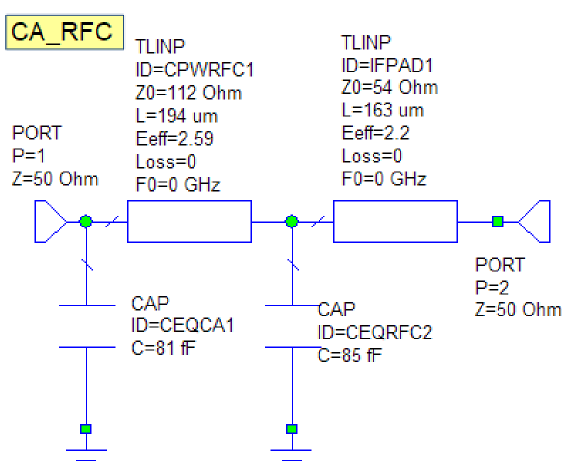




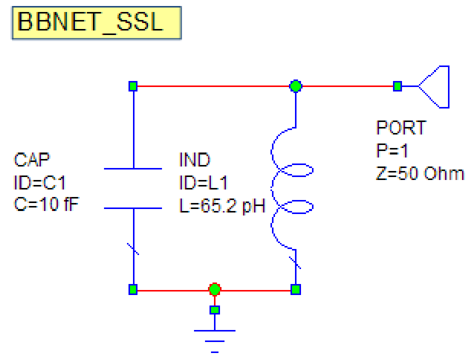
CPWARRY is the equivalent circuit of the series array of four SIS junctions in a coplanar transmission line.



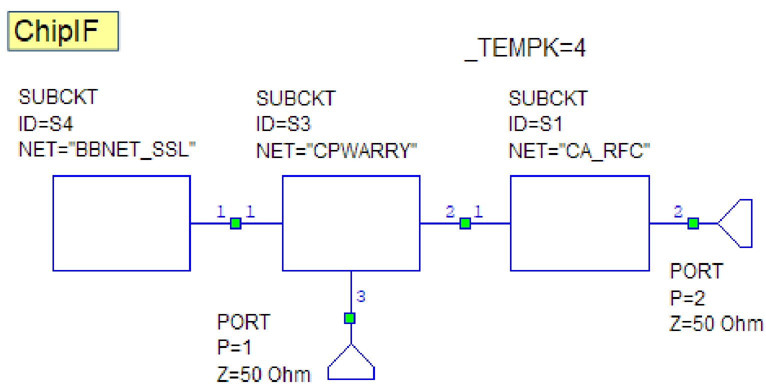
CA_RFC contains the array tuning capacitance CA, the RF choke, and the bonding pad at the end of the chip.



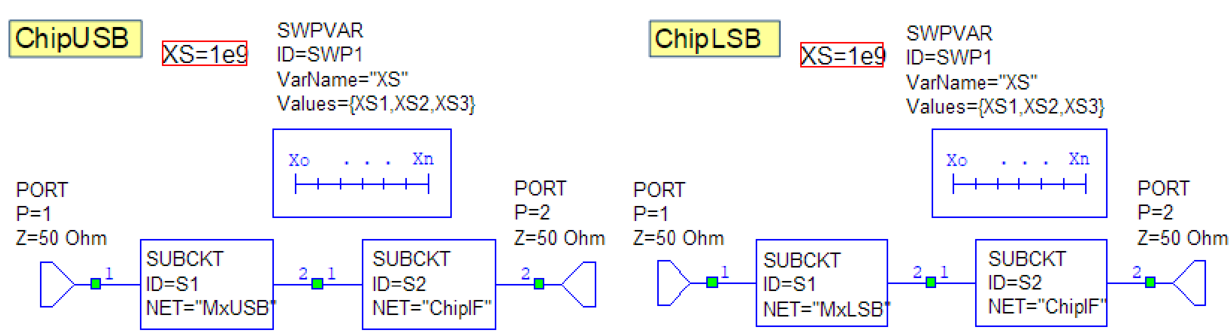
BBNET_SSL is the IF equivalent circuit of the two RF broadbanding resonators, the CPW RF impedance transformer circuit, and the suspended stripline waveguide probe.



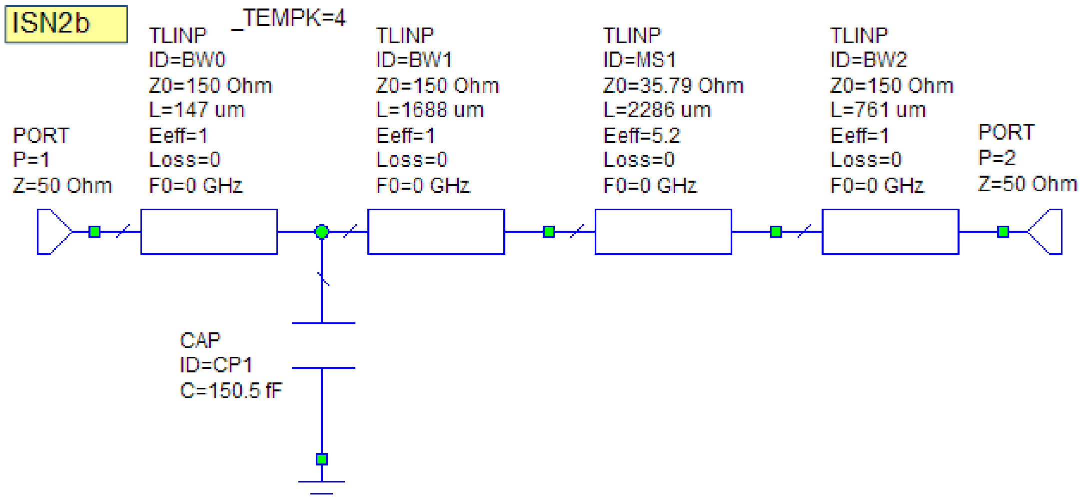
ChipIF adds the other on-chip IF components to MxUSB or MxLSB. These are:
CPWARRY: the equivalent circuit of the series array of four SIS junctions in series.
CA_RFC: capacitor CEQCA1, the capacitor C_A in Figs. 10 and 11 of [5], and the RF choke.
BBNET_SSL: The IF equivalent circuit of the RF matching circuit and waveguide probe, a simple LC circuit.



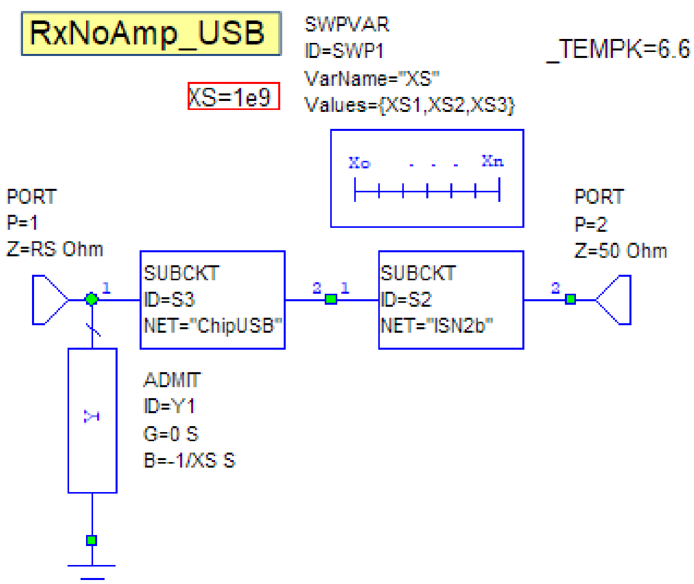
ChipUSB, ChipLSB represent the complete mixer chip and the image terminations. They include the SIS junctions, RF choke, the RF broadbanding circuit, and waveguide probe.



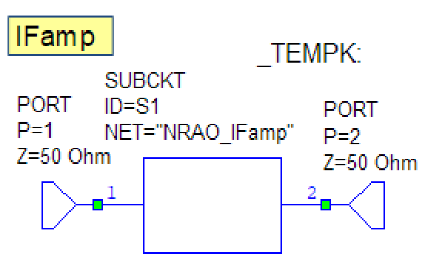
ISN2b: The interstage network, which connects the mixer chip to the IF amplifier, is shown in the schematic ISN2b. This is the version used in the main production run of ALMA Band-6 mixer-preamps.



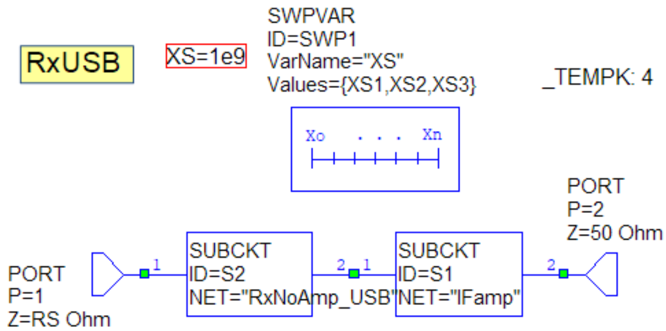
RxNoAmp-USB, RxNoAmp-LSB: the USB or LSB mixer chip and interstage network (ISN2b in this example).

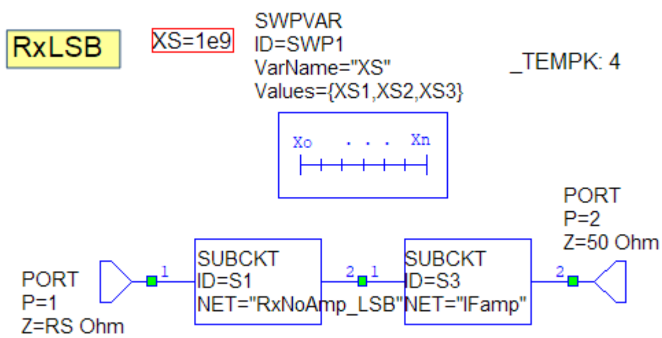


IFamp: the IF amplifier. In the example in this report, the amplifier is defined by its S- and noise-parameters in a Touchstone file.



RxUSB, RxLSB: the complete mixer-preamp, including mixer chip, interstage network, and IF amplifier. The source impedance is set to RS which is defined in Global Definitions 1.



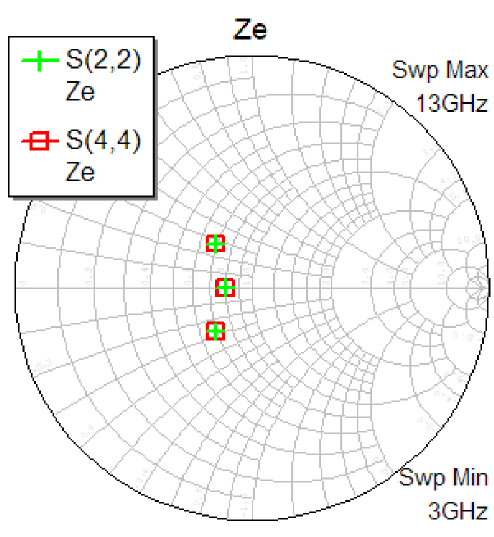


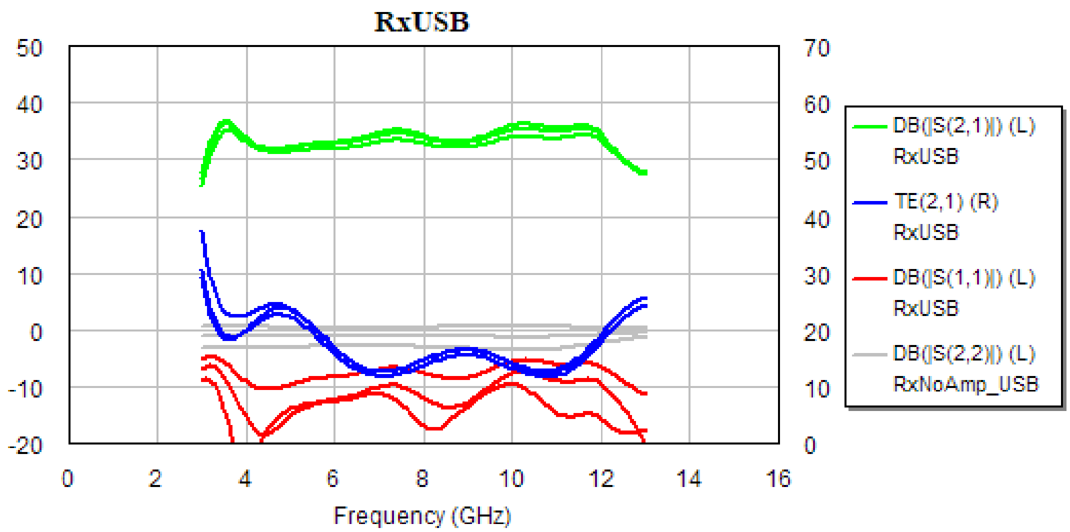
Example

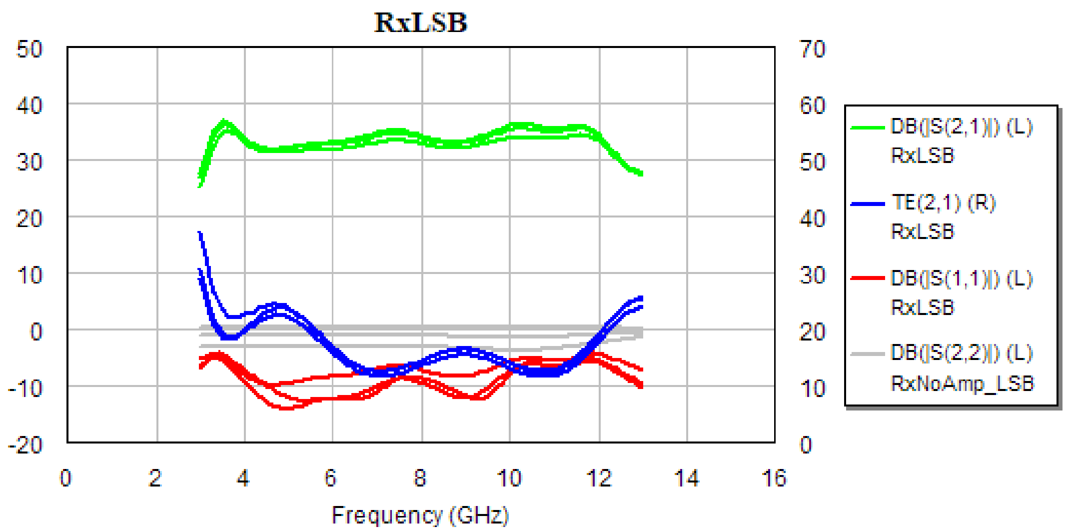
ALMA Band-6 mixer chip with ISN2b and the original production preamp

The parameters of the four-junction SIS array are given in the Global Definitions table below: R_N -- the normal resistance of the SIS array; $\omega R_N C_J$ – the Q of the junctions; and $C_{J,A}$ – the effective junction capacitance of the array. The Smith chart shows three embedding impedances used in the example. It is assumed in the example that the embedding impedances, shown here as S(2,2) (red) and S(4,4) (green), are is the same in the upper and lower sidebands.

```
_TEMPK=4

H=DataFile("UV230a5h")

RS=40
      XS1=-100
      XS2=1e9
      XS3=100
RN=63.2
WRC=4

CJA=55.35

R2=RS
R4=RS

X1={-RN/(2*WRC)}
X5={-RN/(2*WRC)}
```







References:

[1] A. R. Kerr and S.-K. Pan, "Mixer-preamp design using MMICAD," Millimeter Array Memorandum 249, National Radio Astronomy Observatory, Charlottesville VA, Feb. 1999. http://library.nrao.edu/public/memos/alma/memo249.pdf.

[2] A. R. Kerr, S.-K. Pan, and S. Withington, "Embedding Impedance Approximations in the Analysis of SIS Mixers," IEEE Trans. Microwave Theory Tech., vol. 41, no. 4, pp. 590-594, April 1993. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=231650

[3] J. R. Tucker, "Quantum limited detection in tunnel junction mixers," IEEE J. of Quantum Electron. vol. QE-15, no. 11, pp. 1234-1258, Nov. 1979. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1069931

[4] J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," Rev. Mod. Phys., vol. 57, no. 4, pp. 1055-1113, Oct. 1985. http://rmp.aps.org/pdf/RMP/v57/i4/p1055_1

[5] A. A . M. Saleh. Theory of Resistive Mixers. Cambridge, MA: MIT Press, 1971.

[6] A. R. Kerr and J. Randa, "Thermal Noise and Noise Measurements – a 2010 Update," IEEE Microwave Magazine, vol. 11, no. 6 (special issue on noise), pp. 40-52, Oct. 2010. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5564380

[7] A. R. Kerr, S.-K. Pan, S. M. X. Claude, P. Dindo, A. W. Lichtenberger, J. E. Effland and E. F. Lauria, "Development of the ALMA-North America Sideband-Separating SIS Mixers," IEEE Trans. Terahertz Science and Technology, v. 4, no. 2, pp. 201-212, Mar 2014. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6740089