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Mixer-Preamp Design Using MMICAD

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Abstract

The microwave circuit simulator MMICAD can be used to analyze and optimize the small-signal conversion and noise performance of a mixer-preamplifier. The mixer is represented as a noisy five-frequency five-port network using imported conversion and noise correlation matrices, with MMICAD's NCSCOR5 element which contains five correlated noise sources.

Introduction

The conversion gain, RF input impedance, noise figure, and IF bandwidth of a heterodyne receiver are all strongly dependent on the IF amplifier and the coupling circuit between the mixer and the amplifier. 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, attempting to match the IF port of the mixer is likely to 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 which case the electrical distance between the mixer and IF amplifier can strongly affect the overall noise performance. An IF isolator or balanced amplifier [1] can minimize variation of the noise figure across the IF band, but then thermal noise added by the termination of the isolator (or by the termination of the input quadrature hybrid of the balanced amplifier) can add substantially to the overall noise temperature, and the IF bandwidth is limited to that of the isolator or hybrid. These limitations are overcome by mounting the IF amplifier electrically close to the mixer, as described by Padin *et al.* [2], with an appropriately designed coupling network between the mixer and amplifier. In all cases, the design of a mixer-preamp is greatly facilitated by a microwave circuit simulator which can handle multi-frequency multi-port networks containing correlated noise sources. This report describes the use of MMICAD [3] for this purpose.

Mixer characterization in MMICAD

To optimize the performance of a complete receiver, including the overall gain, noise figure, and RF input SWR, the mixer itself is characterized as a noisy N-port network whose ports correspond to the sideband frequencies $|nf_{LO} + f_{IF}|$, where $-(N-1)/2 \le n \le (N-1)/2$ with N an odd integer. The admittance matrix **Y** of this network characterizes the small-signal properties of the mixer, and the mixer noise is described by the noise current correlation matrix **H** whose elements give the magnitude and correlation of equivalent noise current sources at the N ports. The elements of the $N \times N$ matrices **Y** and **H** are generated by a separate mixer analysis program and written to files from which they are imported into MMICAD. While much mixer design has been based on a three-frequency analysis (N = 3), a five-frequency analysis gives substantially more accurate results in many cases [4]. Padin *et al.* used MMICAD for a 3-frequency mixer analysis by representing the noisy 3-port mixer as an interconnection of three noisy two-ports, but recent versions of MMICAD have included noisy N-port networks up to N = 5, which are well suited to mixer simulation.

The matrices **Y** and **H** depend on the large-signal LO voltage and current waveforms at the nonlinear mixer element, which in turn depend on its I-V and C-V characteristics. When the LO voltage across the nonlinear element can be assumed sinusoidal, analytical solutions exist for the $Y_{i,j}$ in the case of an exponential diode (*e.g.*, ideal Schottky diode) or an ideal SIS junction. However the assumption of a sinusoidal LO voltage implies that all harmonics are short circuited, which is not always a good approximation. The more general situation requires an iterative solution by computer as described for Schottky-diode mixers in [5], and for SIS mixers in [6]. For SIS mixers, the assumption of a sinusoidal LO voltage in combination with a 5-frequency small-signal analysis has been found to give acceptable accuracy in many cases [4].

Knowledge of the large-signal voltage and current at the nonlinear element allows the elements of **Y** and **H** to be computed [5, 7, 8]. Both matrices are written in Touchstone format as admittance matrices, which are easily read into MMICAD. Once in MMICAD, the elements of **H** are converted to complex variables in the PROC block, ready for use as arguments of a noisy N-port network, NCSCOR5 or NCSCOR3, in the CKT block. It is important to note that MMICAD treats the Y-matrix as representing a physical network and assigns thermal noise to it according to the Twiss theorem [9] when it is used in a CKT block. It is therefore important to set the quantity T to zero in the Touchstone file containing the Y-matrix.

The MMICAD frequency variable FREQ is used to represent the intermediate frequency f_{IF}. An important characteristic of MMICAD is exploited to ensure that the Y- and H-coefficients do not change as MMICAD sweeps the IF frequency; namely, that if a network file contains only data for a single frequency, the same values are used at all frequencies. Hence **Y** and **H** remain the same as FREQ (f_{IF}) sweeps, as is appropriate in a swept IF measurement of a mixer with a fixed LO when $f_{IF} << f_{LO.}$ RF embedding impedances at $f_{LO} \pm f_{IF}$ and $2f_{LO} \pm f_{IF}$ can be computed in the VAR block as a function of f_{IF}.

The example in the following section demonstrates the use of MMICAD for analysis of a simple SIS mixer-preamp.

Example — An SIS mixer with IF amplifier and isolator

The SIS mixer-preamplifier circuit shown in Fig. 1 is analyzed using the .ckt file in the Appendix. For clarity, a simple circuit is used in this example, but the file is easily modified to include a more complex coupling circuit between mixer and amplifier and unequal or frequency dependent source impedances at the upper and lower sideband frequencies. Also, the isolator can be omitted, and the IF amplifier characterized by its own noisy circuit model in the CKT block. The small-signal conversion admittance matrix **Y** and the noise current correlation matrix **H** were computed in a separate program and written to the Touchstone files shown in Tables I & II. In these files, lines beginning with ! are comments and the line beginning with # specifies the frequency units, type of matrix (Y, Z, S), the format (real & imaginary or magnitude & angle), a scaling factor, and the physical temperature to be associated with the network for noise calculations (set to zero in **Y** and irrelevant in **H**).

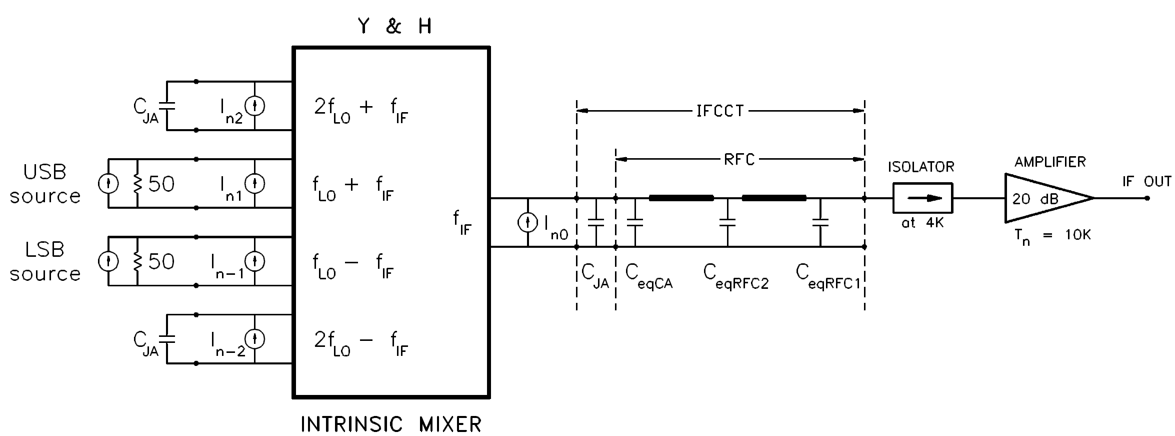

Fig. 1 Block diagram of the SIS mixer-preamplifier used in the example.

The results for this simple example are shown in Fig. 2. Fig. 3 shows the results for the same mixer-preamplifier, but with the physical temperature of the isolator reduced from 4 K to 0 K. This demonstrates the contribution to the receiver noise temperature of thermal noise from the internal termination in the isolator, which is partially reflected from the mixer's IF port back into the amplifier.

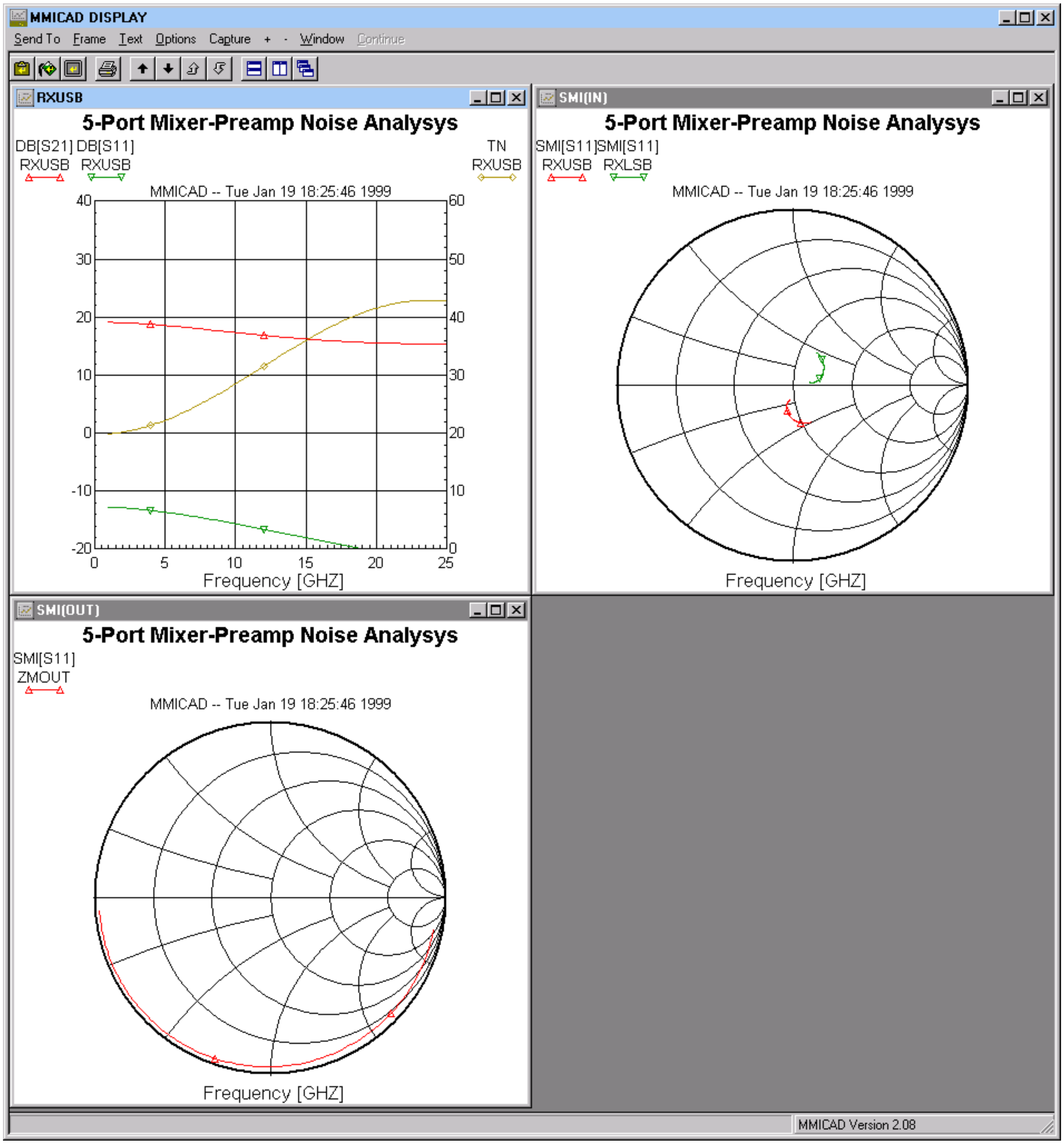

Fig. 2 Results for the mixer-preamplifier of Fig. 1.

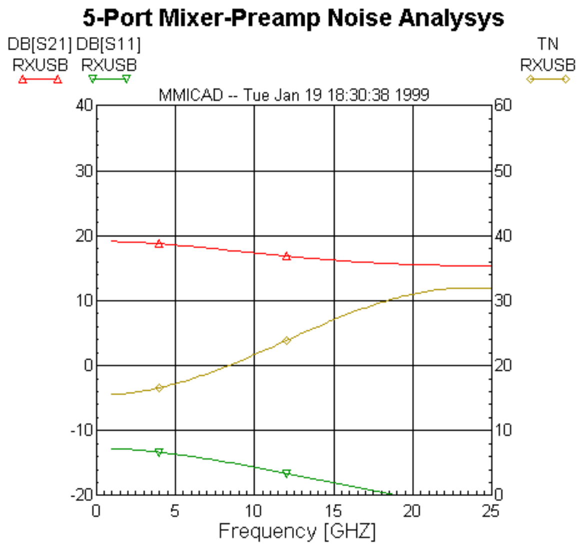

Fig. 3 Results for the same mixer-preamplifier, but with the physical temperature of the isolator reduced from 4 K to 0 K.

Table I — Conversion Admittance Matrix in Touchstone format

```
! C:\QBASIC\MISC\SISDATA\UV230a5.Y
! NA = 0    x = 0    NS = 1    VB = 0.0139451     FS = 2.3E+11    NJ = 6    GN = 1.567568E-02    TB = 4.2
# GHZ Y    RI    R 1    T=0
  2.30E+11
  1.69E-02   2.97E-03  -2.70E-03   7.52E-03  -9.82E-04  -3.21E-03   2.05E-03  -9.61E-04  -2.89E-05   2.86E-05
  7.71E-03   3.76E-03   2.04E-02   2.06E-03   4.49E-03   1.29E-02  -2.29E-03  -2.83E-04  -7.39E-04  -4.81E-04
 -2.29E-03     0        1.81E-02     0        5.31E-03     0        1.81E-02     0       -2.29E-03     0
 -7.39E-04   4.81E-04  -2.29E-03   2.83E-04   4.49E-03  -1.29E-02   2.04E-02  -2.06E-03   7.71E-03  -3.76E-03
 -2.89E-05  -2.86E-05   2.05E-03   9.61E-04  -9.82E-04   3.21E-03  -2.70E-03  -7.52E-03   1.69E-02  -2.97E-03
```

Table II — Noise Current Correlation Matrix in Touchstone format

```
! C:\QBASIC\MISC\SISDATA\UV230a5.H
! NA = 0    x = 0    NS = 1    VB =  0.0139451    FS = 2.3E+11    NJ = 6    GN = 1.567568E-02    TB = 4.2
# GHZ  Y    RI     R 1
  2.30E+11
  1.04E-23     0      2.09E-24     0     -4.32E-25     0     -1.49E-25     0     -1.71E-25     0
  2.09E-24     0      6.80E-24     0      4.15E-24     0      1.98E-24     0     -1.49E-25     0
 -4.32E-25     0      4.15E-24     0      4.61E-24     0      4.15E-24     0     -4.32E-25     0
 -1.49E-25     0      1.98E-24     0      4.15E-24     0      6.80E-24     0      2.09E-24     0
 -1.71E-25     0     -1.49E-25     0     -4.32E-25     0      2.09E-24     0      1.04E-23     0
```

<u>Description of the .CKT file</u>

Line 3 — Mode sets *Noise* on.
Lines 4-6 — Units defined.

FILES block — Here **Y** and **H** are imported as 5-port networks MXR and HMAT.
Lines 8-14 — The contents of these files are given in Tables I and II. Note the statement *T=0* in the # line of Table I, which zeros the thermal noise MMICAD associates with the Y-matrix. The elements of H have the unit A^2/Hz.

VAR block — Contains the values of all the circuit parameters.

Lines 16-21 The values of the parameters R_N, and ωRC of the series array of four SIS junctions are defined. F_0 is the LO frequency, and $R_{OPT,A}$ is the optimum source resistance. The capacitance $C_{J,A}$ of the array is calculated.

Lines 22-28 The embedding admittance seen by the array of junctions is defined at the five sideband frequencies $|nf_{LO} + f_{IF}|$. Suffixes denote the sidebands as follows:

1– second harmonic lower sideband ($2f_{LO}$ - f_{IF}),
2 – lower sideband (f_{LO} - f_{IF}),
3 – IF (f_{IF}),
4 – upper sideband ($f_{LO} + f_{IF}$),
5 – second harmonic upper sideband ($2f_{LO} + f_{IF}$).

For the present example, the second-harmonic sidebands ($n = \pm 2$) are assumed terminated in just the junction capacitance. The upper- and lower-sideband source impedances are 50 ohms, and it is assumed that the junction capacitance is tuned out at these frequencies. The IF load is not defined here as it depends on the other IF circuit elements and is determined in the CKT block. (Note that the embedding admittances here are given as parallel *resistance* and *reactance* components — a convention used by some SIS mixer designers.)

Lines 29-35 Equivalent circuit parameters of the RF choke.

CKT block (first of two) —

Lines 38-50 The embedding admittances from the VAR block are used to form 1-port embedding networks EMB1, EMB2, EMB4, and EMB5 according to the above suffix convention.

PROC block

Lines 52-77 The elements of the imported noise current correlation matrix (A^2/Hz) are assigned to the MMICAD complex variables $H_{i,j}$, i,j = 1..5.

Lines 78-93 The units of the elements $H_{i,j}$ are converted to pA^2/Hz consistent with the MMICAD NCSCORn element.

CKT block (second) —

Lines 95-105 The noiseless intrinsic 5-port mixer, MXR, is connected in parallel with its equivalent noise current sources using the NCSCOR5 element, resulting in the noisy intrinsic mixer MXRN.

Lines 106-114 The IF circuit, the 2-port IFCCT, is constructed.

Lines 115-123 The 5-port augmented network AUGMXR is formed from MXRN, the embedding impedances EMBn, and the IF circuit.

Lines 124-130 To determine the mixer's upper-sideband conversion characteristics, the noisy intrinsic mixer MXRN is terminated in the appropriate embedding impedances EMBn at all but the USB and IF, resulting in the (noisy) 2-port USBMXR.

Lines 131-137 To determine the mixer's lower-sideband conversion characteristics, the noisy intrinsic mixer MXRN is terminated in the appropriate embedding impedances EMBn at all but the LSB and IF, resulting in the (noisy) 2-port LSBMXR.

Lines 138-141 The IF isolator, including thermal noise from its internal termination at 4 K, is defined as the 2-port ISN.

Lines 142-146 The noisy IF amplifier, with 20 dB gain and noise temperature 10 K (noise figure = 0.147 dB), is defined as 2-port AMP.

Lines 147-153 To determine the upper-sideband conversion characteristics of the complete receiver, the 2-port USBMXR is combined with the IF circuit IFCCT, isolator ISN, and amplifier AMP, giving 2-port RXUSB.

Lines 154-160 To determine the lower-sideband conversion characteristics of the complete receiver, the 2-port LSBMXR is combined with the if circuit IFCCT, isolator ISN, and amplifier AMP, giving 2-port RXLSB.

Lines 161-164 To determine the input impedance of the whole receiver, seen at the upper-sideband frequency, the USB receiver RXUSB has its IF port terminated in 50 ohms, giving the 1-port ZINUSB.

Lines 165-168 To determine the input impedance of the whole receiver, seen at the lower-sideband frequency, the LSB receiver RXLSB has its IF port terminated in 50 ohms, giving the 1-port ZINLSB.

Lines 169-173 To determine the IF output impedance of the mixer seen at the end of the RF choke, USBMXR has its RF port terminated in EMB4, and IFCCT connected to its IF port, giving 1-port ZMOUT. (LSBMXR could equally have been used, terminated in EMB2, with the same result.)

TERM block — Sets the impedance level Z0 to 50 ohms.

FREQ block — Sets the IF frequency range and step size.

MARKER block — Sets the frequency markers for the graphical displays.

OUT block — Defines the output frames and what they display.

GRID — Sets the scales for the graphical displays.

LABEL — Sets the label to appear on all graphical and tabular displays.

References

[1] A. R. Kerr, "On the Noise Properties of Balanced Amplifiers," *IEEE Microwave and Guided Wave Letters*, vol. 8, no. 11, pp. 390-392, Nov. 1998.

[2] S. Padin, D. P. Woody, J. A. Stern, H. G. LeDuc, R. Blundell, C.-Y. E. Tong, and M. W. Pospieszalski, "An Integrated SIS Mixer and HEMT IF Amplifier" *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, no. 6, pp. 987- 990, June 1996.

[3] MMICAD is a microwave circuit simulator from Optotek, Inc., Kanata, Ontario, Canada.

[4] 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.

[5] P. H. Siegel and A. R. Kerr, "Computer Analysis of Microwave and Millimeter-Wave Mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, no. 3, pp. 275-276, March 1980. For more detail, see: P. H. Siegel, A. R. Kerr, and W. Hwang, "Topics in the Optimization of Millimeter-Wave Mixers," NASA Technical Paper 2287, March 1984.

[6] S. Withington and P. Kennedy, "Numerical procedure for simulating the large-signal quantum behavior of superconducting tunnel-junction circuits," *Proc. IEE*, part G, vol. 138, no. 1, pp. 70-76, Feb. 1991.

[7] A. Uhlir, "Shot noise in p-n junction frequency converters," *Bell System Tech. J.*, v. 37, no. 4, pp.951-988, July 1958.

[8] J.R. Tucker and M.J. Feldman, "Quantum detection at millimeter wavelengths," *Rev. Mod. Phys.*, vol. 57, no. 4, pp. 1055-1113, Oct. 1985.

[9] R. Q. Twiss, "Nyquist's and Thevenin's theorems generalized for nonreciprocal linear networks," *J. Appl. Phys.*, v. 26, no. 5, pp. 599-602, May 1955.

<u>Appendix</u> .CKT file used in the example

```
! SMIX07a.CKT Monday, Jan 18, 1999 at 6:31:06 PM
! SIS mixer with ideal IF amplifier (TN = 10 K) and isolator at 4 K.

MODE   FREQ NOISE

GLOBAL
 DIM FREQ=1e+009 RES=1 COND=1 CAP=1e-015 IND=1e-012 LNG=1e-006 TIME=1e-012
 MSUB ER=12.2 H=100 T=1 RHO=1.2 TAND=0.001 @SUB1

FILES
 ! Mixer small signal conversion matrix file,
 ! generated by QuickBasic quantum mixer analysis program.
 !!** Remember to set T=0 in this file **!!
 C:\MMICADV2\MISC\SMIX\OPTOTEK\UV230A5.Y MXR 5P FREQ 101
 ! Mixer noise current correlation matrix file,
 ! generated by QuickBasic quantum mixer analysis program.
 C:\MMICADV2\MISC\SMIX\OPTOTEK\UV230A5.H HMAT 5P FREQ 101

VAR
! Array of 4 SIS tunnel junctions (the nonlinear mixer element)
 RN=63.8                                   ! Normal resistance of the array
 WRC=4                                     ! Omega*Ropt*Cj
 F0=250                                    ! LO frequency (GHz)
 ROPTA=50                                  ! Opt source resistance
 CJA={(WRC/(2*PI*F0*1E9*ROPTA))*1E15}      ! Capacitance of array

! Sideband terminations (defined for positive frequencies)
 X1={-RN/(2*WRC)}                          ! (2*fLO - fIF) termination
 R2=50                                     ! LSB (fLO - fIF) termination (parallel components)
 X2=1e+009                                 ! LSB (fLO - fIF) termination (parallel components)
 R4=50                                     ! USB (fLO + fIF) termination (parallel components)
 X4=1e+009                                 ! USB (fLO + fIF) termination (parallel components)
 X5={-RN/(2*WRC)}                          ! (2*fLO + fIF) termination

! RFC (RF Choke)
 CEQRFC1=77
 CEQRFC2=85
 CEQCA=81
 ZCPWRFC=112
 KCPWRFC=2.59
 LCPWRFC=194
!-------------------------------------

CKT
! Embedding Network
 NTEMP T=0
 ADM 1 0 G=0 B={1/X1}                      ! LSB2 (negative freq)
 DEF1P 1 EMB1
 NTEMP T=0
 ADM 1 0 G={1/R2} B={1/X2}                 ! LSB  (negative freq)
 DEF1P 1 EMB2
 NTEMP T=0
 ADM 1 0 G={1/R4} B={-1/X4}                ! USB
 DEF1P 1 EMB4
 NTEMP T=0
 ADM 1 0 G=0 B={-1/X5}                     ! USB2
 DEF1P 1 EMB5

PROC
! Noise currents (A^2/Hz) -- symmetrical
 H11=HMAT Y11
 H12=HMAT Y12
 H13=HMAT Y13
 H14=HMAT Y14
 H15=HMAT Y15
 H21=HMAT Y21
 H22=HMAT Y22
 H23=HMAT Y23
 H24=HMAT Y24
 H25=HMAT Y25
 H31=HMAT Y31
 H32=HMAT Y32
 H33=HMAT Y33
 H34=HMAT Y34
 H35=HMAT Y35
 H41=HMAT Y41
 H42=HMAT Y42
 H43=HMAT Y43
 H44=HMAT Y44
 H45=HMAT Y45
 H51=HMAT Y51
 H52=HMAT Y52
 H53=HMAT Y53
 H54=HMAT Y54
 H55=HMAT Y55

! Noise currents (pA^2/Hz) -- all real
 IR11=RE(H11)*1E24
 IR22=RE(H22)*1E24
```

```
 IR33=RE(H33)*1E24
 IR44=RE(H44)*1E24
 IR55=RE(H55)*1E24
 IR12=RE(H12)*1E24
 IR13=RE(H13)*1E24
 IR14=RE(H14)*1E24
 IR15=RE(H15)*1E24
 IR23=RE(H23)*1E24
 IR24=RE(H24)*1E24
 IR25=RE(H25)*1E24
 IR34=RE(H34)*1E24
 IR35=RE(H35)*1E24
 IR45=RE(H45)*1E24

CKT
! Intrinsic mixer with noise (5-port)
 NTEMP T=0
 MXR 1 2 3 4 5 0 M=1
 NCSCOR5 1 0 2 0 3 0 4 0 5 0 I1=IR11 R1=1e+010  &
  I2=IR22 R2=1e+010 I3=IR33 R3=1e+010 I4=IR44  &
  R4=1e+010 I5=IR55 R5=1e+010 CR12=IR12 CI12=0  &
  CR13=IR13 CI13=0 CR14=IR14 CI14=0 CR15=IR15  &
  CI15=0 CR23=IR23 CI23=0 CR24=IR24 CI24=0  &
  CR25=IR25 CI25=0 CR34=IR34 CI34=0 CR35=IR35  &
  CI35=0 CR45=IR45 CI45=0
 DEF5P 1 2 3 4 5 MXRN

! IF Circuit (including junction capacitance CJ and RF Choke)
 NTEMP T=4
 CAP 1 0 C=CJA                                  ! SIS array
 CAP 1 0 C=CEQCA
 TLINP 1 2 0 Z=ZCPWRFC L=LCPWRFC K=KCPWRFC A=0 F=0 SIGMA=0
 CAP 2 0 C=CEQRFC2
 TLINP 2 3 0 Z=ZCPWRFC L=LCPWRFC K=KCPWRFC A=0 F=0 SIGMA=0
 CAP 3 0 C=CEQRFC1
 DEF2P 1 3 IFCCT

! Augmented Mixer (5-port including embedding admittances)
 NTEMP T=4
 MXRN 1 2 3 4 5 0 M=1
 EMB1 1 0 M=1
 EMB2 2 0 M=1
 IFCCT 3 13 0 M=1
 EMB4 4 0 M=1
 EMB5 5 0 M=1
 DEF5P 1 2 13 4 5 AUGMXR

! USB Mixer (2-port)
 NTEMP T=4
 MXRN 1 2 3 4 5 0 M=1
 EMB1 1 0 M=1
 EMB2 2 0 M=1
 EMB5 5 0 M=1
 DEF2P 4 3 USBMXR

! LSB Mixer (2-port)
 NTEMP T=4
 MXRN 1 2 3 4 5 0 M=1
 EMB1 1 0 M=1
 EMB4 4 0 M=1
 EMB5 5 0 M=1
 DEF2P 2 3 LSBMXR

! ISN (Isolator)
 NTEMP T=4
 ISOLATOR 1 2
 DEF2P 1 2 ISN

! AMP
 NTEMP T=4
 NPAR FMIN=0.147 MAG=0 ANG=0 RN=0
 GAIN 1 2 A=20 AR=-50 SL=0 F=0
 DEF2P 1 2 AMP

! RxUSB (Complete receiver -- upper-sideband measurements)
 NTEMP T=4
 USBMXR 1 2 0 M=1
 IFCCT 2 3 0 M=1
 ISN 3 4 0 M=1
 AMP 4 5 0 M=1
 DEF2P 1 5 RXUSB

! RxLSB (Complete receiver -- lower-sideband measurements)
 NTEMP T=4
 LSBMXR 1 2 0 M=1
 IFCCT 2 3 0 M=1
 ISN 3 4 0 M=1
 AMP 4 5 0 M=1
 DEF2P 1 5 RXLSB

! ZIN (USB input impedance)
 RXUSB 1 2 0 M=1
```

```
 RES 2 0 R=50
 DEF1P 1 ZINUSB

! ZIN (LSB input impedance)
 RXLSB 1 2 0 M=1
 RES 2 0 R=50
 DEF1P 1 ZINLSB

! ZMOUT (at end of RFC)

 USBMXR 1 2 0 M=1
 EMB4 1 0 M=1
 IFCCT 2 3 0 M=1
 DEF1P 3 ZMOUT

TERM
 Z0=50

FREQ
 SWEEP 1 25 0.2

MARKER
 STEP 4 12

OUT
 RxUSB DB[S21] RxUSB                         ! USB receiver gain
 RxUSB DB[S11] RxUSB                         ! USB input return loss
 RxUSB TN RxUSB R                            ! USB receiver noise temperature

 RxLSB DB[S21] RxLSB                         ! LSB receiver gain
 RxLSB DB[S11] RxLSB                        ! LSB input return loss
 RxLSB TN RxLSB R                           ! LSB receiver noise temperature

 RXUSB SMI[S11] SMI(IN)                      ! USB S11 Smith chart
 RXLSB SMI[S11] SMI(IN)                      ! LSB S11 Smith chart

 ZMOUT SMI[S11] SMI(OUT)                     ! Mixer output S11 Smith chart

GRID
 RxUSB 0 25 5 -20 40 10 R 0 60 10
 RxLSB 0 25 5 -20 40 10 R 0 60 10

LABEL
5-Port Mixer-Preamp Noise Analysys
```