

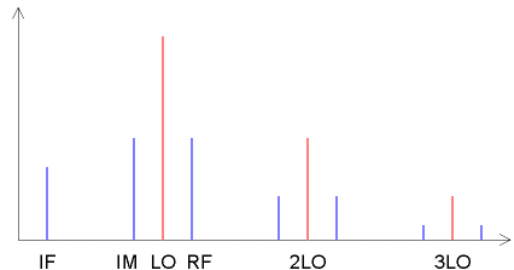
Noise in Ring Topology Mixers

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1 Introduction

For a classical double-balanced ring-diode mixer, it is expected that the conversion loss (4–5 dB) should match the noise figure. This document explores the formal definition of noise figure and shows the ADS noise figure definition. It is also shown that the noise figure for a mixer does not have to exceed its conversion loss, and that loss in the mixer baluns is an important source of noise that must be considered.

Throughout this discussion we assume a low-side injection, down-converting mixer, although the issues discussed are equally applicable to any mixer. RF is the input signal, LO is the local oscillator, and IF is the output signal. In terms of frequencies, $RF = LO + IF$ and there exists an input image $IM = LO - IF$ that can also mix down to the same IF as the RF. We are not concerned with the output image signal $LO + RF$.



Throughout this paper we will shift nomenclature back and forth between noise voltage (v_n), noise power (N) and equivalent noise temperature (T). They are all interrelated by the equation:

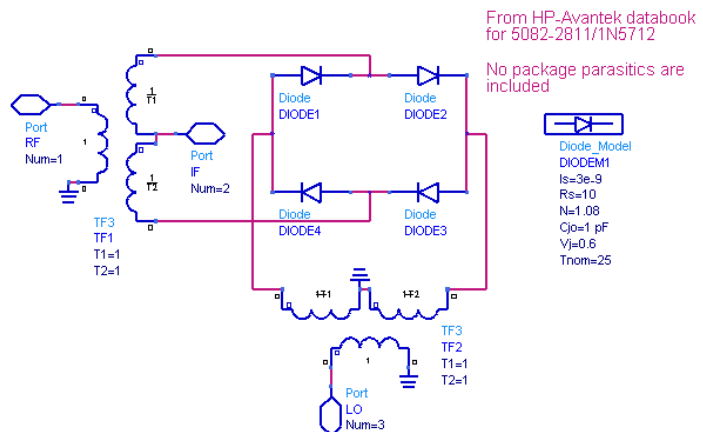
$$N = v_n^2 / R_L = kT \quad (1)$$

Noise temperature is used preferentially as it has reasonably sized numbers: 447 pV of noise into a 50Ω load is the same as 4×10^{-21} W is the same as 290K.

We try to use the rigorous definitions of noise factor and noise figure. The noise factor F is an algebraic quantity greater than or equal to one. The noise figure NF is the noise factor expressed in decibels and is greater than or equal to zero.

2 Ring-Diode Double-Balanced Mixer

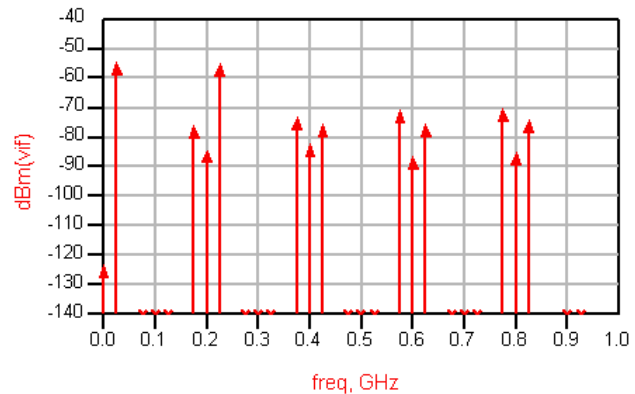
The ring diode double balanced mixer shown to the right consists of a ring of four diodes and two ideal center tapped transformers (baluns). One transformer applies the LO signal across the ring and another transformer applies the RF signal across the ring. The large signal LO voltage (typically driven at +7 dBm) alternately switches one pair of diodes (D2 and D3) and then the other pair (D4 and D3).



and D1) on. This switching action causes mixing of the RF signal applied to the diodes by the other transformer. This is a broadband mixer, limited mostly by the physical construction of the transformers. Typical commercial mixers such as the MiniCircuits JMS-1 will operate for LO and RF signals from 2 to 500 MHz.

2.1 Signal Performance

The spectrum to the right shows the simulated IF output from the mixer. The LO is 100 MHz at +7 dBm and the RF is 125 MHz at -50 dBm. Due to the double balanced nature of the mixer, the LO and RF signals are suppressed from the output. There are two primary output signals at $IF=RF-LO$ (25 MHz) and the output image at $RF+LO$ (225 MHz). The output does show even harmonics of the LO and even order mixing products from the RF and odd harmonics of the LO (e.g. 175 MHz = $3 \cdot 100$ MHz – 125 MHz, 4th order).



2.2 Mixer Gains to IF

Just as the mixer shows a number of output tones at different frequencies, the mixer is also capable of converting a number of different input frequencies to the IF at 25 MHz. This balanced mixer will convert any input frequency ($k \cdot f_{LO} \pm 25 \text{ MHz}$) to IF, where k is odd. If there is any imbalance, then it will also convert from those frequencies where k is even. The primary conversions will be from the RF frequency at 125 MHz and the input image at 75 MHz. The simulated conversion gains from all possible input sidebands are shown to the right. The input frequency is $LS \cdot f_{LO} + \text{Sideband} \cdot f_{IF}$ ($LS \cdot 100 \text{ MHz} + \text{Sideband} \cdot 25 \text{ MHz}$).

The conversion gain from the RF frequency, 125 MHz, is -4.840 dB (0.33127) and the conversion from the image input frequency, 75 MHz, is -4.798 dB (0.32812). The sum of the conversion gains from all of the higher order harmonic input images is -13.47 dB (0.04501). The sum of all conversion gains is -1.522 dB (0.7044). These higher order gain terms will be important later when we discuss the measurement of the mixer noise figure.

$$\text{Eqn Gain_dB} = \text{dBm}(\text{vif}[:, :, 1]) + 50$$

$$\text{Eqn Gain} = 10^{(\text{Gain_dB}/10)}$$

LS	Gain_dB	
	...band=-1.0000	...band=1.0000
0.0000	50.0000	-296.1282
1.0000	-4.7981	-4.8397
2.0000	-297.8281	-310.4747
3.0000	-17.0090	-17.1690
4.0000	-304.3694	-310.6719
5.0000	-26.8848	-27.2430
6.0000	-321.3516	-312.1211
7.0000	-35.4851	-35.5527
8.0000	-308.0145	-316.0028
9.0000	-31.4185	-31.6042

LS	Gain	
	...band=-1.00000	...band=1.00000
0.00000	100000.00000	0.00000
1.00000	0.33127	0.32812
2.00000	0.00000	0.00000
3.00000	0.01991	0.01919
4.00000	0.00000	0.00000
5.00000	0.00205	0.00189
6.00000	0.00000	0.00000
7.00000	0.00028	0.00028
8.00000	0.00000	0.00000
9.00000	0.00072	0.00069

2.3 Ideal Switching Mixer

The output spectrum of an ideal switching mixer can be shown to have the form [6]:

$$V_{IF} = \frac{2}{\pi} \left(\begin{aligned} &\cos(2\pi(f_{RF} + f_{LO})t) + \cos(2\pi(f_{RF} - f_{LO})t) \\ &-\frac{1}{3}\cos(2\pi(f_{RF} + 3f_{LO})t) - \frac{1}{3}\cos(2\pi(f_{RF} - 3f_{LO})t) \\ &+\frac{1}{5}\cos(2\pi(f_{RF} + 5f_{LO})t) + \frac{1}{5}\cos(2\pi(f_{RF} - 5f_{LO})t) + \dots \end{aligned} \right) \quad (2)$$

The coefficients in terms of the LO order are reproduced in the table below.

LO order	mag(V)	mag(V ²)	dB(V ²)
1	0.6366	0.4053	-3.92
3	0.2122	0.0450	-13.46
5	0.1273	0.0162	-17.90
7	0.0909	0.0083	-20.82
total		1.0000	0.00

The last column shows the conversion gains from a single input to each of the output frequencies $k \cdot f_{LO} \pm f_{RF}$. An ideal switching mixer will have a -3.92 dB conversion loss for the primary conversion $f_{LO} \pm f_{RF}$. The total normalized power in the output spectrum is 1.00; power is conserved as there are no losses in the ideal switching mixer. By reciprocity, these terms also represent the conversion gains from the odd order terms $k \cdot f_{LO} \pm f_{IF}$ to f_{IF} .

3 Noise Figure

3.1 A Bad Definition of Noise Figure for a Mixer

A popular book on mixer design [1] gives an interpretation of the mixer noise factor:

$$F = \frac{T_{SSB} + T_0}{T_0} \quad (3)$$

where T_{SSB} is the total input-referred noise added by the mixer. The context of this equation explicitly states that noise from the input image is not considered (but as will be shown later, should be). This does match the definition of noise figure used for linear circuits such as amplifiers, but as will be shown, should not be applied to mixers. Rewritten in simulation terms,

$$F = \frac{v_n^2 / R_L + k T_0 G_1}{k T_0 G_1} \quad (4)$$

where v_n is the noise voltage present at the IF port when the RF and IF terminations are noiseless; this is the output-referred noise added by the mixer. The +1 term represents the input termination noise that mixes down from the RF frequency to the IF frequency ($k T_0 G_1$). This noise factor definition is the same as that used for linear two ports. In a linear circuit there is no frequency translation and thus only one gain G exists. Noise factor can also be thought of as the sum of the noise generated by the mixer and the noise generated at the input processed through

the mixer divided by the noise generated at the input signal processed through the mixer.

Example What numbers does this generate for a mixer? Simulating gives $v_n=166.2$ pV and $G=0.32812$ (-4.84 dB), so:

$$F = (v_n^2/k R_L + T_0 G) / (T_0 G) = (40.01+95.15) / 95.15 = 1.4205 \text{ (1.52 dB)}$$

A mixer with a 4.84 dB conversion loss gives a noise figure of 1.52 dB. Shocking!

It is assumed that the output termination is noiseless (questionable for the ring diode mixer; see below) and that only noise at the input termination at the RF frequency is mixed to the output at the IF frequency. This second assumption is incorrect, and is caused by an incorrect reading of the IEEE definition of noise figure, or by using the noise figure definition for networks without frequency translation.

The author of [1] does point out that this ignores input termination noise from the input image frequency, and does include that term in an alternative SSB noise figure definition:

$$F = \frac{T_{SSB} + 2T_0}{T_0} \quad (5)$$

Example For the same mixer:

$$F = (v_n^2/k R_L + 2 T_0 G) / (T_0 G) = (40.01+190.30)/95.15 = 2.4205 \text{ (3.84 dB)}$$

The noise figure now rises to 3.84 dB.

However, this ignores other sources of noise from input harmonic frequencies that can mix to the IF frequency. While small, these are present in the ring diode mixer, and indeed, most mixers. From a detailed reading of the noise factor definition, we shall see that all of these terms must be included in the definition.

3.2 IEEE Definition of Noise Factor

The IRE, predecessor to the IEEE, originally defined noise factor for linear twoports in 1960 [2]. This definition was clarified and extended to mixers in 1963 [3]. The 1963 definition reads:

At a specified input frequency the ratio of

- 1) the total noise power per unit bandwidth at a corresponding output frequency available at the output port when the noise temperature of its input termination is standard (290K) at all frequencies

to

- 2) that portion of 1) engendered at the input frequency by the input termination at the standard noise temperature (290K).

Note 1: For heterodyne systems there will be, in principle, more than one output frequency corresponding to a single input frequency and vice versa; for each pair of corresponding frequencies a noise factor is defined. 2) includes only that noise from the input termination which appears in the output via the principal-frequency transformation of the system, i.e. via the signal-frequency transformation(s), and does not include spurious contributions such as those from an unused image-frequency or an unused idler-frequency transformation.

Note 2: The phrase "available at the output port" may be replaced by "delivered by system into an output termination".

Note 3: To characterize a system by a noise factor is meaningful only when the admittance (or impedance) of the input termination is specified.

1) represents the numerator of the noise factor fraction and 2) represents the denominator. Clearly 1) is the total noise output power at the IF port and frequency, and says nothing about not containing noise due to the input termination at the image frequency (or any other frequency). Indeed, the text in the paper makes it clear that 1) includes all sources of noise, including any and all transformations of noise from the input termination to the IF port and frequency, all noise generated by the mixer itself, and noise arising from the output termination. This represents two departures from the definition of noise factor for non-frequency translating networks. First, the numerator should include all transformations of input termination noise to the IF port and frequency. The translation of this noise to IF is unavoidable and must be considered.

In discussing 1), the original paper divides the output noise power into two parts:

A) The contributions to the output noise power due to noise power available from the impedance terminations that are connected to all accessible ports except the output port under operating conditions. These contributions can be described by assigning appropriate noise temperatures to the input terminations at all of the various responses.

For the sake of modeling, the original paper splits the input terminations into a number of separate terminations, where each termination can represent a single source frequency that can be translated by the mixer to the specified IF frequency ("a response"). The appropriate noise temperatures for the input terminations are all the same temperature, the IEEE standard noise temperature (290K).

B) All other contributions to the output noise power. These include noise generated within the receiver components as well as noise resulting from any frequency conversions internal to the receiving system. *Noise generated in the load and reflected at the receiver output may also contribute to this output noise power.* [italics added]

In the framework of [3] the noise generated within the mixer NN is characterized by a single number, T_e :

$$N_N = k T_e (G_1 + G_2 + G_3 + \dots + G_n) \quad (6)$$

where G_1 is the primary conversion gain from RF to IF, G_2 is the conversion gain from the input image to IF, and G_3 and higher represent the other possible higher-LO order transformations to IF, including the possible leakage of input termination noise at the IF frequency to the output termination. A single number is used because this is noise that is common to all input responses.

For most mixers, G_1 and G_2 are approximately the same and are much larger than $G_3 \dots G_n$. Unfortunately, most texts and equations assume $G_1 = G_2$ and completely ignore $G_3 \dots G_n$ by assuming they are zero. While this may be true for a well-designed mixer with good filtering, for a broadband mixer such as the ring-diode double balanced mixer they are not zero. For example, $G_1 = 0.331$, $G_2 = 0.328$ and $G_3 + \dots + G_n = 0.045$.

Everyone's interpretation of 2) is correct, in that it represents only the transformation of noise at the RF port and frequency to the IF port and frequency (the "principal transformation"). By

dividing by only 2) gives the single sideband noise figure, as it is assumed that only a signal at one input sideband is of interest.

There has been some concern as to what type of gain should be used in these equations: available or transducer. Available gain measures the power that could be delivered to a load that is conjugately matched to the output port to that available from the input source. Transducer gain measures the power that is delivered to the actual load, matched or not, to that available from the input source. While the definition of noise figure includes the word ‘available’ (“the total noise power ... available at the output port”), Note 2 states that “available at the output port” may be replaced by “delivered by the system into an output termination”, which sounds like transducer gain. In the text of the paper, the gain is clearly defined as a transducer gain: the ratio of “the signal power delivered ... into the output circuit” to “the signal power available” at the input. The text also clearly uses the phrase ‘transducer gain’ at several points.

3.3 ADS Implementation of Mixer Noise Figure

So let’s apply our knowledge from reinterpreting the definition of noise figure and see what it gives to our mixer.

$$F = \frac{v_n^2 / R_L + k T_0 (G_1 + G_2 + \dots + G_n)}{k T_0 G_1} \quad (7)$$

The numerator consists of two terms. The first term is the noise contributed by the mixer itself and has not changed from the old definition (4). The second term is the noise due to noise at the input termination at all frequencies that mix to the IF frequency, including the possible direct conversion of input termination noise at the IF frequency to the output termination at the same frequency. In the original definition this term was represented only the noise at the RF frequency ($k T_0 G_1$). The IF termination is still treated as noiseless.

Example Running the numbers: $G_1=0.32812$, $G_2=0.33127$, $G_3+\dots+G_n=0.04501$.

$$F = (40.01 + 204.28) / 95.15 = 2.5674 \text{ (4.10 dB)}$$

The noise figure is now 4.10 dB by including all of the possible conversions of input noise.

3.4 Inclusion of Output Termination Noise

[3] specifically states about the total noise at the output B):

Here, NL is a term that takes into account the contribution of noise generated in the load and reflected at the output of the receiver, since the effective input noise temperature definition does not include such a contribution. In order to evaluate NL one must know the impedance and the equivalent noise temperature of the load, and the output impedance of the receiver. In most cases, NL will be negligible compared to the other terms in this expression. The contribution NL may be of importance in systems with insufficient gain...

Further:

A few words of explanation may be in order for the reason why T_e [the input referred mixer generated noise] excludes the load noise contribution and T_{op} [the total output

noise] includes it. In excluding the load noise from the definition of T_e the effective input noise temperature of a single response two-port is brought into direct correspondence with its noise figure F according to the formula $T_e = 290(F-1)$. The noise figure cascading formula of single response two-ports may thus be adapted to T_e . The cascading formula facilitates the evaluation of T_e of an amplifier chain. The operating noise temperature T_{op} is intended to be a measure of the noise of a receiving system. The inclusion in T_{op} of the contribution of the load-noise gives a more realistic measure of system noise performance in those cases in which the load noise is appreciable.

Sadly the next paragraph reads:

Henceforth, we shall disregard N_L , because in most cases of interest it is negligible.

and everyone who has published anything further on mixer noise has ignored it. This neglect of N_L is consistent with the standard view of noise factor for linear networks.

Yet as we can see from simulation, or consider from common sense, a low noise mixer with a conversion gain less than unity will attenuate any input noise and signal and add little noise of its own, so any noise generated in the output termination will be non-negligible and should play a part in the signal to noise ratio at the output.

3.4.1 Termination Noise at the IF Frequency

If S_{22} is the output reflection coefficient and the termination is at the standard noise temperature (290K) then the amount of noise present at the output termination due to noise generated by the output termination at the IF frequency is:

$$N_L = k T_0 |1 + S_{22}|^2 \quad (8)$$

But if the termination is matched ($S_{22} = 0$) then only a noise power of $k T_0$ will be seen. To compensate for the matched case, we should reduce N_L by $k T_0$ to consider only the excess noise from the load mismatch:

$$N_L = k T_0 (|1 + S_{22}|^2 - 1) \quad (9)$$

Adding this to the numerator of the noise factor definition gives:

$$F = \frac{v_n^2 / R_L + k T_0 (G_1 + G_2 + \dots + G_n) + N_L}{k T_0 G_1} \quad (10)$$

Example Simulation of the noise from the IF port at the IF freq gives 540 pV, which corresponds to 422.41 K. Subtracting $T_0 = 290$ gives:

$$F = (40.01 + 204.28 + 132.41) / 95.15 = 3.959 \text{ (5.98 dB)}$$

By including noise generated by the mismatched output termination, this brings the noise figure up to 5.98 dB.

3.4.2 Termination Noise at Frequencies Other Than IF

There is another interesting phenomenon that takes place in the ring-diode double-balanced mixer at the output termination: self mixing. The output termination generates broadband noise. The noise at some frequencies can enter the mixer at the output, get processed by the

nonlinearity and reappear at the IF frequency of interest at the output termination. This adds a non-negligible noise source that should be included in the total output noise.

Let us define H_i as the conversion reflection gain at the output port from frequency i to the IF frequency. We will define H_2 and higher, considering that H_1 (conversion from IF frequency to IF frequency) is really what we are computing above in N_L . The additional noise due to the output termination is then:

$$N_{SM} = kT_0(H_2 + H_3 + \dots H_n) \quad (11)$$

Note that the frequencies at the output that translate to IF are not necessarily the same ones that translate to IF from the input.

Adding this to the numerator of the noise factor definition gives:

$$F = \frac{v_n^2/R_L + kT_0(G_1 + G_2 + \dots + G_n) + kT_0(|1 + S_{22}|^2 - 1) + kT_0(H_2 + H_3 + \dots + H_n)}{kT_0 G_1} \quad (12)$$

Example Simulation of the self-mixing noise is demonstrated in `tb_selfmix`. Here noise is injected at the IF port at every frequency except IF, and the amount of noise coming back to the IF is measured. For this mixer 121.9 pV of noise was observed, corresponding to 21.53K.

$$F = (40.01 + 204.28 + 132.41 + 21.53) / 95.15 = 4.185 \text{ (6.22 dB)}$$

The noise figure is now 6.22 dB by including all of the output self-mixing noise.

This effect is negligible in active mixers built with bipolar and field-effect transistors, including FET-ring mixers. This is because the three terminal nonlinear device provides some isolation between its terminals and each signal (RF, IF, LO) can be associated with a terminal. But in diode mixers, the three signals must be shared among two terminals, reducing the isolation. (We use the term “isolation” here in a manner different than normally used in mixers to discuss LO-IF, RF-IF isolation).

3.5 Summary of Noise Figure Contributions

Let's now itemize all of the terms in the numerator of the noise figure equation and their contribution to the single sideband noise figure.

Name	Value (K)	Partial Noise Figure	
k To G1	95.15	0.00	
Diodes	40.01	1.52	
k To G2	96.07	3.86	
k To (G3+...+Gn)	13.05	4.09	ADS NFssb value
IF mismatch	132.41	5.98	
IF self-mixing	21.53	6.22	

The partial noise figure is computed for each term by summing from the top to each line the total noise to form the numerator and dividing by the first term: $F = \sum \text{terms} / (T_0 G_1)$.

4 Measurement of Noise Factor

4.1 Measurement Equipment

Noise figure is measured with a noise figure meter such as the Agilent 8970B. A noise figure meter works via the hot-cold method. The input termination is replaced by a noise source that is switched between a cold temperature (room temperature or 290K) and a high temperature (1,000K for a +5.5 dB excess noise ratio (ENR), 10,000K for a +15.5 dB ENR). By measuring the output noise in both the cold and hot states and knowing the ENR, the noise factor can be computed.

$$F = \frac{T_{hot} - 290}{290} \cdot \frac{N_{cold}}{N_{hot} - N_{cold}} \quad (13)$$

The hot-cold technique is only capable of measuring the all sideband noise figure, normally called the double sideband noise figure (which neglects the higher order down conversion products). The above equation is equal to:

$$F_{ASB} = \frac{v_n^2 / R_L + k T_0 (G_1 + G_2 + \dots + G_n)}{k T_0 (G_1 + G_2 + \dots + G_n)} \quad (14)$$

What most texts and noise figure meters do when converting to a single sideband noise figure is drop the higher LO order conversion terms $G_3 \dots G_n$ and assume $G_1 = G_2 = G$ when deriving their version of (14). This erroneously gives:

$$F_{DSB} \approx \frac{v_n^2 / R_L + 2k T_0 G}{2k T_0 G} \quad (15)$$

This is converted to single sideband by dividing by 2:

$$F_{SSB} \approx \frac{v_n^2 / R_L + 2k T_0 G}{k T_0 G} \quad (16)$$

But for a mixer with any measurable conversion from the higher frequencies, this will be in slightly error. The correct equation is:

$$F_{SSB} = \frac{v_n^2 / R_L + k T_0 (G_1 + G_2 + \dots + G_n)}{k T_0 G_1} \quad (17)$$

and the error in the faulty approximation is:

$$dF_{SSB} = \frac{G_1 + G_2 + \dots + G_n}{2G_1} \quad (18)$$

The 8970B reports to the user the all sideband conversion gain $G_1 + G_2 + \dots + G_n$ and noise figure. To correct these to single sideband, the factor $(G_1 + G_2 + \dots + G_n) / G_1$, in decibels, should be added to both values.

$$F_{SSB} = F_{8970} \frac{G_1 + G_2 + \dots + G_n}{G_1} \quad (19)$$

The 8970B can make its own +3 dB correction $(G_1 + G_2)/G_1$ when reporting the results, but we have shown that this can be in error by up to 0.5 dB for a typical mixer due to higher order conversions that are included in the measurement.

Example For our example mixer, 2 should be replaced by $(G_1 + \dots + G_n)/G_1 = 2.126$. The error in the noise figure for ignoring this is $2.126/2$ or 0.265 dB; the actual noise figure is 0.265 dB higher than the meter-corrected SSB noise figure.

The table below shows the underestimated error for several different mixer circuits that would be made if a noise figure meter converted the measured double sideband noise figure to single sideband by dividing by two.

Name	Description	$(G_1 + \dots + G_n)/G_1$	$G_1/2(G_1 + \dots + G_n)$, dB
mix01a	ring diode mixer	2.142	0.30
jmixer1	JFET ring mixer	2.200	0.41
mix04	Gilbert cell with amps	2.070	0.15
ne602	Gilbert cell	2.052	0.11
mix03	NE600 unbalanced BJT	4.789	3.79
mix02	ADS Mixer NF=6	2.000	0.00
rep11a	single diode	2.225	0.46
mix30	Lange coupler, 2 diodes	2.205	0.42
mix31	BJT single balanced	4.481	3.50
mix05	Ratrace, 2 diodes	14.046	8.47
mix10	pager_mixer, 1 BJT	2.062	0.13
	ideal switching mixer	2.467	0.91

4.2 Simulating a Hot-Cold Measurement

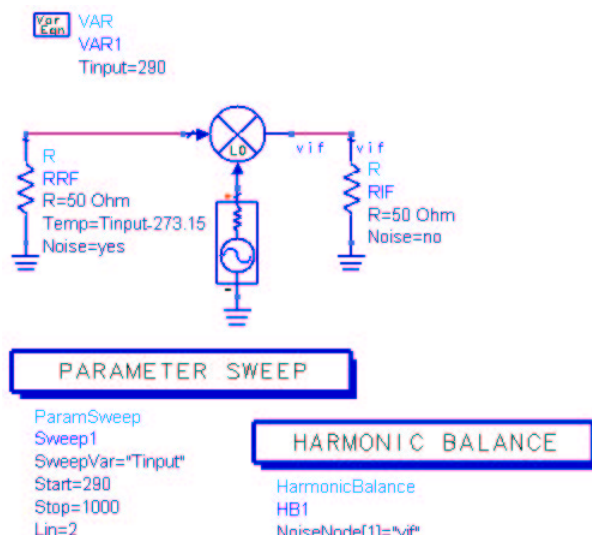
ADS 2001 adds two output variables: NFssb and NFdsb. NFssb is the IEEE standard single sideband noise figure defined in (7) or (17), and NFdsb is the all (double) sideband noise figure defined in (14). and is equivalent to what is measured by a noise figure meter using the hot-cold technique.

We can also perform a hot-cold measurement manually in ADS to simulate what the noise figure meter would measure. The picture below shows the simulation setup required. The input termination is replaced with a resistor whose temperature is swept between 290K and 1000K. The output termination is replaced by a noiseless resistor. The noise voltage at the output termination is measured and used to compute the all-sideband noise figure in the data display server using the following equations:

```

Tc=HB.Tinput[0]
Th=HB.Tinput[1]
Nc=vif.noise[0,0]**2/(50*boltzmann)
Nh=vif.noise[1,0]**2/(50*boltzmann)
Fasb=(Th-Tc)/Tc*Nc/(Nh-Nc)

```



```

NFasb=10*log(Fasb)
Gasb=(Nh-Nc)/(Th-Tc)
IGasb=10*log(Gasb)

```

Example Simulation gives Ncold=248K and Nhot=755K. This gives:

```

Fasb = 1.20 (0.79 dB)
Gasb = 0.714 (-1.47 dB)
Fssb = Fasb * (G1+...+Gn)/G1 = 2.55 (4.07 dB)
Gssb = Gasb * G1/(G1+...+Gn) = 0.336 (-4.74 dB)

```

which matches the computation done above.

4.3 Filtering for SSB

Most references on measuring noise figure state that single sideband noise figure can be measured simply by putting a narrow bandpass filter in front of the RF input port that only passes RF, so that the mixer has no conversion gains from frequencies other than RF. Note that this can dramatically change the noise figure. A bandpass filter will have $S_{11}=0$ and $S_{21}=1$ in the passband and $S_{11}=\pm 1$ and $S_{21}=0$ everywhere else. This dramatically changes the input load that the mixer sees and changes the conversion gain and the generation of noise. The single-sideband measurement can be made to work with a filter if the filter can have $S_{11}=0$ everywhere, but that is not typical of a physical bandpass filter.

Example Consider the mixer we have been examining so far. Without an input filter it has a conversion gain of -4.84 dB. A Chebychev bandpass filter (order=3) is placed at the RF input centered at RF (125 MHz). The mixer noise now has a conversion gain of -6.83 dB. If we add an ideal filter that passes only RF while maintaining a broadband $S_{11}=0$, the conversion gain remains at -4.84 dB. The simulated noise figures (properly adjusted to SSB) are:

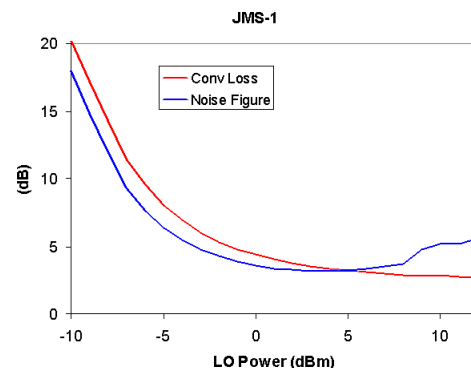
Filter	Cgain	NF0	NF1
None	-4.84	1.52	4.09
Chebychev	-6.83	2.73	2.73
Ideal	-4.84	4.08	4.08

Identical results are obtained though both the hot-cold simulation and the standard technique discussed above. When the filter is added, the SSB correction factor changes from $(G1+...+Gn)/G1=2.126$ to unity, because the filter changes $G2...Gn$ to zero.

4.4 Measured Data

A MiniCircuits JMS-1 mixer was measured on an Agilent 8970B noise figure meter. The LO was 255 MHz and the IF frequency was 40 MHz. The measured all-sideband conversion loss and noise figure are shown below as a function of the LO drive power. Below +5 dBm, the noise figure is lower than the conversion loss.

So how can the noise figure be less than the loss? If



we look at the noise figure definition for a mixer that generates no noise:

$$F = \frac{kT_0(G_1 + G_2 + \dots + G_n)}{kT_0 G_1} = \frac{G_1 + G_2 + \dots + G_n}{G_1} \quad (22)$$

The conversion loss is $1/G_1$. For an ideal switching mixer, the sum of the conversion gains is 1, giving a noise figure of $1/G_1$, identical to the conversion loss. But for a non-ideal mixer, there are additional losses due to the diodes and transformers, so the sum of the gains is less than 1, giving a noise figure of less than $1/G_1$. If the mixer has negligible higher order conversion gains, then $F = (G_1 + G_2)/G_1 \cong 2G_1/G_1 = 2$ (3 dB), independent of the conversion gain.

5 Influence of Balun Loss on Noise

The mixer simulated earlier was changed to include models of real baluns. Mixers were simulated using measured data for three different baluns. Surface mount center tapped transformers were purchased from MiniCircuits and their S parameters were measured from 10 kHz to 5 GHz. The measured S parameters were then used in the simulation of the mixer. Agilent HSMS-8202 Schottky diode pairs were also used in the mixers. The mixers were simulated with $f_{RF}=295$ MHz, $f_{LO}=255$ MHz, $P_{LO}=+7$ dBm and $f_{IF}=40$ MHz.

Model	Impedance Ratio	1 dB Bandwidth
TCM2-1T	2:1	3-300 MHz
TCM3-1T	3:1	5-300 MHz
TCM4-6T	4:1	3-350 MHz

The simulated noise results are shown below. The conversion gain and SSB noise figure are given. The equivalent noise temperature for the baluns and diodes are also listed. It can be seen that a significant amount of noise is generated by the baluns, similar to the amount of noise generated by the diodes. In the mixer that has been considered elsewhere in this paper, the baluns were ideal: lossless and noiseless.

	TCM2	TCM3	TCM4
Simulated conversion loss, SSB	-8.22	-7.73	-6.29
Simulated new noise figure, new SSB	7.52	6.95	5.46
Noise figure, new SSB neglecting baluns	5.12	4.90	4.89
Noise temperature (K), RF-IF balun	58.76	54.07	27.63
Noise temperature (K), LO balun	45.74	37.22	1.53
Noise temperature (K), all 4 diodes	48.40	46.21	63.88

It can be seen that neglecting the balun noise will change the noise figure by up to several dB.

6 Conclusion

Held and Kerr explained away many of the misconceptions about mixer noise figure starting in 1978 [4,5].

The misunderstanding seems to have arisen with the assumption, by Messenger and McCoy, that a mixer and a passive attenuator have similar noise properties and that the

temperature of this equivalent attenuator is “the time average of the static noise characteristic” of the diode. This led to a widely held belief that for a Schottky diode mixer, the noise-temperature ratio $t \cong 1$...

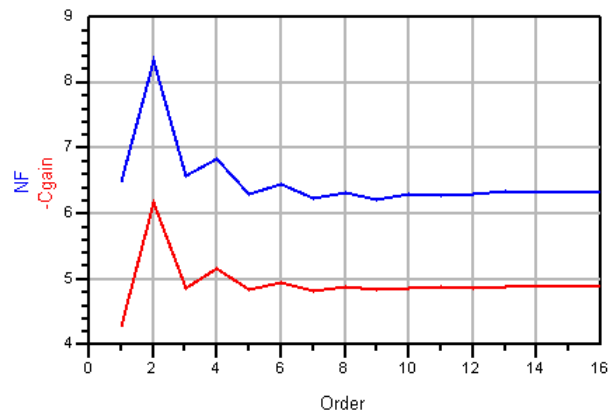
Of the early authors writing about mixer noise figure, those that wrote

$$F = \frac{N_{MIX}}{kT_0 G} + 1 \quad (23)$$

were justified in writing +1 because they explicitly stated that the input termination was either an open or a short circuit at the input image frequency. Higher order mixing products were either ignored or terminated in opens or shorts.

Appendix A: Influence of Order and OverSample on Simulation Results

Variation in the conversion gain and noise figure is observed as the order is varied. This effect is especially strong in the ring diode mixer as the diode current is an exponential of half a sine wave, requiring a large Fourier series to represent it accurately. Differences in the conversion gain are noticed when compared to a transient analysis, at least until Order=9 is used. The graph shows conversion gain and noise figure as a function of Order.

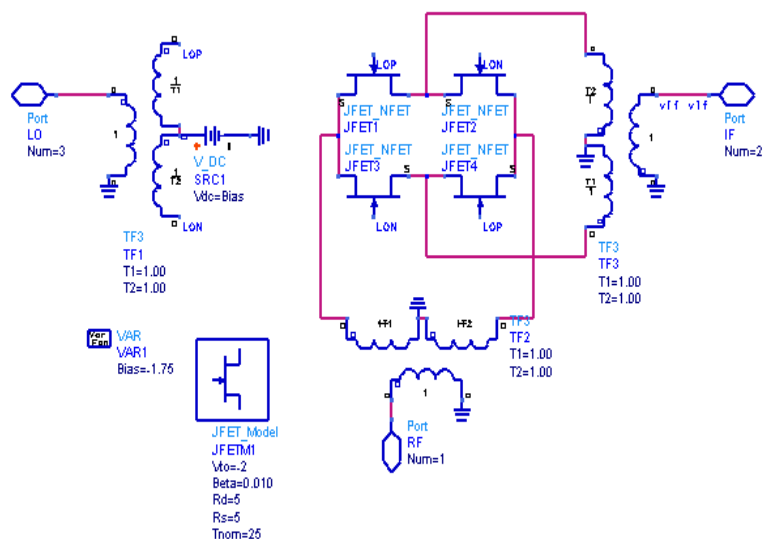


The results did not vary as OverSample was swept from 1 to 32.

Appendix B: FET Ring Mixers

Ring mixers can also be built with FETs [1]. The FETs are used as resistive switches and are operated in the linear region with $V_{ds}=0$. The LO is applied to the gate with a DC bias and the RF and IF are applied to source and drains. As long as the RF drive stays low, then V_{ds} can be considered to be zero. Any type of FET can be used, including GaAsFETs, MOSFETs or JFETs. An extra transformer is required in this design to extract the IF.

Consider the basic equation for FET drain current in the linear region:



$$I_{DS} = \beta V_{DS} [2(V_{GS} - V_T) - V_{DS}] (1 + \lambda V_{DS}) \quad (24)$$

There is one problem in the FET noise models. The standard FET channel noise model is $i_{DS}^2 = 8kT g_m / 3$. But for these FETs with $V_{DS} = 0$, $g_m = 0$:

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = 2\beta V_{DS} (1 + \lambda V_{DS}) \quad (25)$$

and therefore the FETs are noiseless. In this case the FET channel should be modeled as a resistance based on the small signal resistance g_d which is valid in the linear region:

$$g_d = \left. \frac{\partial I_{DS}}{\partial V_{DS}} \right|_{V_{DS}=0} = 2\beta (V_{GS} - V_T) \quad (26)$$

Noise generated by this resistance can be modeling by including a suitable noise source in parallel with the FET so that $i_n^2 = 4kT g_d$.

Let's now itemize all of the terms in the numerator of the noise figure equation and their contribution to the noise figure. This mixer has a conversion gain of -5.53 dB and the old ADS noise figure was 0.91 dB. With the new equation, the noise figure is 4.54 dB.

Name	Value (K)	Partial Noise Figure	
k To G1	81.20	0.00	
JFETs	18.83	0.91	
JFET channel	33.71	2.17	
k To G2	81.20	4.23	
k To (G3+...+Gn)	16.28	4.54	ADS
IF mismatch	110.48	6.24	
IF self-mixing	0.49	6.25	

Note that for this type of mixer, the IF self-mixing term is negligible. This may be attributed to the unidirectional nature of the FETs: noise coming into the source-drain does not translate back to the gate/LO side and then remix to the IF.

Acknowledgements

Thanks to Roger Branson of Nokia and Prof. Stephen Long of UCSB for first discovering this problem.

References

- [1] S. Maas, *Microwave Mixers*, 2nd ed., Artech House, p. 168, 1993.
- [2] IRE Subcommittee 7.9 on Noise, "IRE Standard on Methods of Measuring Noise in Linear Twoports, 1959", *Proceedings of the IRE*, vol. 48, pp. 60–68, 1960.
- [3] IRE Subcommittee 7.9 on Noise, "Description of the Noise Performance of Amplifiers and Receiving Systems", *Proceedings of the IEEE*, vol. 51, pp. 436–442, 1963.
- [4] D. N. Held and A. R. Kerr, "Conversion Loss and Noise of Microwave and Millimeter Wave Mixers: Part 1 – Theory", *IEEE Transactions on Microwave Theory and Techniques*, vol. 26,

pp. 49–55, Feb. 1978.

- [5] A. R. Kerr, “Shot Noise in Resistive Diode Mixers and the Attenuator Noise Model”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 27, pp. 135–140, Feb. 1979.
- [6] B. Gilbert, “Design Considerations for BJT Active Mixers”, lecture notes from Mead Microelectronics short course *RFIC Design for Wireless Communications Systems*, Santa Clara, April 1995.