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Mixers: Part 1 Characteristics and Performance

The mixer is a critical component in modern RF systems. Since it is usually the first or second device from the RF input, the performance of the mixer is crucial to the overall operation of the system. Such important mixer parameters as dynamic range, conversion loss, bandwidth, noise figure, interport isolation and VSWR (voltage standing wave ratio) must be optimized to produce the type of device necessary for today's sophisticated RF systems. This article explores the basics of mixer operation, and is intended to give the reader a base on which to build further understanding of today's mixer technology. The systems designer will find portions of this article helpful when integrating various types of mixers into his or her systems.

MIXER DEFINED

A mixer converts RF power at one frequency into power at another frequency to make signal processing easier and less expensive. Another, and perhaps more fundamental reason for frequency conversion, is to allow for the practical transmission of audio and other low-frequency information through free space. Audio signals have such long wavelengths that transmitting them directly would require a restrictively large antenna. But, by first converting the audio information up in frequency to center around a higher (carrier) frequency, antennas of practical size can be built to utilize the various channel characteristics of free space, such as ionospheric skip and atmospheric absorption, that depend on the carrier frequency. Receiving the transmitted signal involves capturing part of its electromagnetic energy and reconverting it down to the audio-frequency range to extract the original information. So, both the transmitting and receiving cases require the input signal to be converted; this is done through the mixing process.

Mixing the input signal having the desired information with a local oscillator signal yields upper and lower sidebands, each containing the identical information present in the input frequency. The upper sideband is the sum of the input and the local oscillator frequencies, and the lower sideband is the difference between the input and the local oscillator frequencies. The upper or lower sideband, whichever is selected for use, is called the intermediate frequency (IF). In most receiving systems, the lower sideband (the downconverted product) is used, whereas in transmitting systems the upper sideband (the upconverted product) is used.

Changing the frequency of a signal without altering the information it carries is necessary because signal processing components, such as amplifiers, are much less expensive and perform better when designed to operate at lower frequencies.

Since it is much less expensive to amplify a signal in the MHz range than in the GHz range, the incoming microwave signal is first downconverted in frequency and then processed. Likewise, in a transmitter it is less expensive to generate, modulate, and amplify a signal in the MHz range and then upconvert it in frequency into the GHz range.

Figure 1 shows the placement of a mixer in a receiver front end with the schematic symbol most commonly used for mixers. Sometimes X is used instead of I to denote the I-port. For testing purposes, attenuators are placed on all three ports for better matching [1] and to dampen intermodulation products exiting the mixer so that they are minimized in power level before the system reflects them back into the mixer to remix and cause further intermodulation products. When matching and intermodulation products are a problem in a system, isolators are used instead of attenuators on the R and I-ports so that system sensitivity is not degraded, and on the L-port if LO power is limited.

Since a mixer converts modulated power from one frequency to another, it is sometimes called a frequency converter, but the term frequency converter usually implies a mixer/amplifier or mixer/ oscillator combination. The term mixer more closely describes the mechanism through which frequency conversion occurs. Two inputs are mixed by means of nonlinearities and switching to produce a group of signals having frequencies equal to the sums and differences of the harmonies of the two input signals. Nonlinearities and switching will be discussed at greater length later in this Technotes series.

The input signal to the mixer that has the

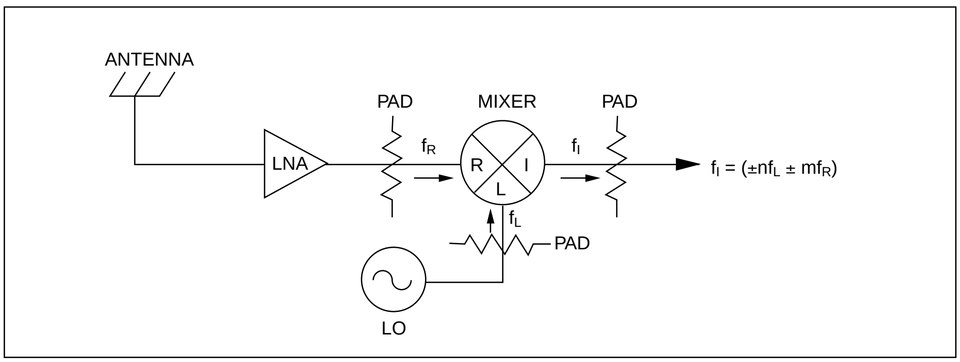

Figure 1. Schematic diagram showing mixer placement in a receiver front end.

desired information modulated onto it is called the received (input RF) signal, or f_R. The other input signal to the mixer, designated as f_L, is called the local oscillator (LO) signal, since it is generated by an oscillator physically located near the mixer in the system.

The LO signal is usually much stronger than the received signal; this causes the mixer to have better intermodulation suppression than would be possible if the LO and RF power levels were similar. The LO signal should be, in most cases, at least 20 dB higher in power than the RF input. The mixer output signal is the intermediate frequency and is designated, f_I. The intermediate frequency is so termed because it falls between the RF and information frequencies. This is simply stated as:

$$f_I = \pm m\, f_R \pm n\, f_L$$

where,

$$m = 0, 1, 2, 3, \text{etc.}$$
$$n = 0, 1, 2, 3, \text{etc.}$$

The output products most generally desired are the sums and differences of the fundamentals of the received and LO signals. This is the case for which.

$$m = n = 1$$

giving,

$$f_I = \pm f_L \pm f_R$$

While this formula implies that negative frequency products occur, these can be ignored in practical mixer applications in much the same way as incorrect roots can be ignored when calculating quadratic equations. For the case where $f_L > f_R$, which is called high-side LO, f_I, = $f_L \pm f_R$. When $f_L < f_R$, which is called low-side LO, $f_I = \pm f_L + f_R$.

Hereafter, in this discussion, the definition of the intermediate frequency products will be restricted to include only the four intermodulation products for which n = m = 1.

The higher-order products having m = 1, 2, 3, 4,...and n = 1, 2, 3, 4,... for which m and n are not simultaneously equal to 1, will be referred to as higher-order intermodulation products. Two other possible cases are m = 1, 2, 3,..., n = 0 and m = 0, n = 1, 2, 3,... In these cases, the fundamental and harmonics of the received and local oscillator signals, respectively, leak through the mixer to appear at the IF output port. This is caused by finite interport isolation, and occurs to a varying extent in all mixers.

A mixer is a three-port device, having two input ports and one output port. The port through which the received signal enters the mixer is called the R-port, and the port through which the local oscillator signal enters the mixer is called the L-port. The port through which all the output products exit the mixer is called the I-port. A mixer can also be a four-port device if it uses a DC bias for starved LO operation, which generally means LO input power is in the range of 0 to +6 dBm. Normal mixers using only the LO power to turn on the diodes require +6 to +20 dBm of LO power.

Most mixers use Schottky barrier diodes, but GaAs diodes are sometimes utilized for operation in the millimeter-wave frequency range. Mixers also use bipolar transistors, J-FETs, and GaAs FETs, all of which require a fourth port for a DC voltage. There are many parameters to consider when choosing a mixer; an introduction to the most important of these follows.

SINGLE SIDEBAND CONVERSION LOSS

Since a mixer converts power from one frequency to another, perhaps the most fundamental parameter is the measure of how efficiently frequency conversion occurs. This parameter is called conversion loss, and is defined as the difference in dB between the received signal power entering the R-port and the output IF power of the desired IF sideband exiting the I-port. Both the up- and downconverted products, or sidebands, exit the l-port. Since normally only one of these products is desired" the other product is filtered out, causing half the downconverted power to be lost. Hence, there is an automatic 3-dB SSB (single sideband) conversion loss minimum. Further power losses during frequency conversion occur because some of the down-converted power is also lost in the form of unwanted higher-order mixing products, heat due to the series resistance of the diodes, and mismatches at the mixer. These all add to cause typical SSB conversion loss to range from 6 to 9 dB. Conversion loss is a strong function of LO power, which radically affects mismatch between the system and mixer.

VSWR

VSWR is the measure of mismatch offered to the system by the mixer, and is usually specified over a given bandwidth as a function of LO power and temperature. It is calculated as follows.

$$\text{VSWR} = \frac{1 + |\rho|}{1 - |\rho|}$$

where,

$$\rho = \frac{Z_L - Z_o}{Z_L + Z_o}$$

ρ is the reflection coefficient.

Z_L is the input impedance of the mixer.

Z_o is the characteristic impedance of the system.

Since VSWR does not include the phase of the reflection coefficient, the system designer does not know if the input impedance is above or below the normal 50-ohms characteristic impedance. For example, if the L-port VSWR is 2:1, measured in a 50-ohm system, the system designer does not know if the L-port input impedance is 25 ohms or 100 ohms. Actually, the input impedance of a broadband mixer swept over a frequency range of an octave or more, usually rotates through the low and high impedances, roughly producing a circle centered at 50 ohms, as viewed on a Smith Chart. So a given mixer having L-VSWR of 2:1 over an octave bandwidth will have an input impedance varying from 25 ohms to 100 ohms, passing through an infinite number of complex impedance combinations as the LO frequency changes. R, L, and I VSWRs are direct functions of LO power, which establishes the operating point of the diodes. Changing the LO power alters the diode operating point, resulting in a different impedance for all mixer ports, causing a corresponding change in VSWR. RF input power, which is at least 20 dB lower than LO input power, does not appreciably alter the diode bias point and, consequently, has little affect on VSWR. When the diode impedance changes, the input impedances of all three ports change. Hence, varying the LO power level will affect the VSWR of all three ports.

One mark of a good mixer design is that its VSWRs are optimized for the LO power that is in the middle of the normal operating power range of the mixer diodes used. This allows for good VSWRs over the maximum range of LO power levels. When designing a mixer, the L-VSWR is first optimized by adjusting the L-port circuit, allowing the LO power to properly bias the diodes and set the R- and I-port VSWRS. Then, the R- and I-port circuits are adjusted to properly match the diodes to the RF input and IF output loads.

ISOLATION

Interport isolation is the measure of insertion loss between any two mixer ports. It is measured in dB and usually specified over a given bandwidth as a function of LO drive and temperature. Maximizing isolation between ports in mixers is necessary because unwanted signal feedthrough wastes RF power and can obscure the desired IF output, as well as cause electromagnetic interference. Normally, only the isolation between L and R, and L and I ports is specified, because the LO input power, after leaking through the mixer, is comparable to the output IF power, whereas the RF input power usually is not. For instance, if the RF input power is -10 dBm and the R-to-I isolation is 20 dB (both are typical numbers), -30 dBm of RF power leaks out the I-port. If SSB conversion loss is 6 dB, the desired IF signal level is -16 dBm, which is 14 dB higher in power than the undesired RF feed through signal, also exiting the I-port. Such a relative power difference is usually sufficient. If LO power is +20 dBm and L-to-I isolation is 30 dB, -10 dBm of LO power leaks out the I-port, which is 6 dB higher in power than the -16 dBm IF product. If the LO frequency falls inside the IF band, this feed through can seriously obscure the desired IF output product. Hence, L-to-I isolation is more important to specify than R-to-I isolation. R-to-I isolation is specified only when the relative power level of RF feedthrough and IF output power is critical, and, only for mixers having broadband IF outputs, thus allowing the frequency of the RF feed through power to fall in the IF band.

If the LO input power is +20 dBm and the L-to-R isolation is 30 dB, -10 dBm of LO power leaks out the R-port to become incident at the amplifier or antenna feeding the R-port. When the R-port has no buffer between it and the receiving antenna, LO feed through power can radiate out the receiving antenna. Hence, L-to-R and L-to-I isolations are most important, and normally the only ones specified. Various factors such as diode match and circuit balance influence isolation in mixers, and will be explored in detail later.

DYNAMIC RANGE

Dynamic range is measured in dB and is the input RF power range over which the mixer is useful. The lower limit of dynamic range is the noise floor, which depends on the mixer and system. The upper limit of dynamic range is generally taken to be the mixer 1-dB compression point. This is measured in dBm, and is the input RF power level at which conversion loss increases by 1 dB. Other definitions of dynamic range have been specified [2]. Beginning at the low end of the dynamic range, just enough input RF power is fed into the mixer to cause the IF signal to be barely discernable above the noise. Increasing the RF input power causes the IF output power to increase dB-for-dB of input power, continuing until the RF input power increases to a level at which the IF output power no longer increases dB-for-dB, but instead begins to roll off, causing an increase in conversion loss. The input power level at which the conversion loss increases by 1 dB is the 1-dB compression point.

The 1-dB compression point is generally taken to be the top of the dynamic range because the input RF power that is not converted into desired IF output power, is instead converted into heat and higher-order intermodulation products. The intermodulation products that begin to appear when RF power is increased beyond the 1-dB compression point can begin to obscure the desired IF output. Generally, the 1-dB compression point is 5-to-10 dB lower than the LO input power, so a high-level mixer has a higher 1-dB compression point than a low level mixer and, hence, a wider dynamic range. Table 1 shows the LO power levels generally associated with very high-, high-, medium- and low-level mixers. These power levels apply specifically to mixers using Schottky barrier diodes, but can also be applied in a more general way to mixers using other devices. The type and number of Schottky barrier diodes and resistor elements that may be used determine the level of LO input power.

INTERMODULATION PRODUCTS

Intermodulation (IM) products are undesir-

Level	LO Power Range (dBm)
Very High	+27 to +15
High	+20 to + 13
Medium	+13 to +l0
Low	+10 to +6

Table 1. Mixer LO power levels.

able mixer-generated output products exiting the mixer from any port. Two types exist: single-tone and multiple-tone. Intermodulation products are composed of a single input RF signal mixing with the LO, and have the following frequencies:

$$f = \pm\, m\, f_R \pm n\, f_L \qquad (1)$$

where,

$$m = 1, 2, 3,...$$
$$n = 1, 2, 3,...$$

Multiple-tone intermodulation products are composed of two or more input RF signals mixing with the LO, and have the following frequencies:

$$f = (\pm\, m_1\, f_{R_1} \pm m_2\, f_{R_2} \pm m_3\, f_{R_3}...) \pm n\, f_L \qquad (2)$$

where,

$$m_1, m_2, m_3,... = 0, 1, 2, 3,...$$
$$n = 0, 1, 2, 3,...$$

Multiple-tone intermodulation products for which all but one of the coefficients, m, are zero, resemble single-tone intermodulation products because their frequencies contain harmonics of the LO and harmonics of the one RF input that has the non-zero coefficient, m. Hence, single-tone intermodulation products can be present when multiple-input RF signals are incident at the R-port, because output products can be generated that have frequencies in the form of Equation (1). The level of output power of individual intermodulation products is very much affected by input LO and RF power levels and frequencies.

Charts exist that show trends in inter-modulation suppression as a function of input power and frequency. Figure 2 is a single-tone intermodulation chart showing the power level of various inter-modulation products relative to the IF output power. Intermodulation charts are not generally tabulated for multiple-tone intermodulation products because each coefficient (m_1, m_2, m_3,... and n) requires its own axis on the chart, whereas charts for single-tone intermodulation products require only two axes for m and n. Each box in an intermodulation chart represents one of the infinite integral harmonic combinations of f_R and f_L. Each box in this particular chart contains two rows that each have three values of intermodulation signal suppression. In each row, the first value is for a "Class 1" mixer having +7 dBm of LO drive; the second value is for a "Class 2" mixer having +17 dBm of LO drive; and the third value is for a "Class 3" mixer having +27 dBm of LO drive. These mixers are discussed more fully later in this Tech-notes series. The top row in each box gives intermodulation suppression for RF input power of 0 dBm; the bottom row gives intermodulation suppression for RF input power of -10 dBm. Notice that the even-by-even intermodulation signals for which both m and n are even, are suppressed more than the odd-by-odd products. This is due to the circuit balance in double-balanced mixers. If diode match and mixer balance were perfect, only the odd-by-odd products would exit the I-port, and all other products would show infinite suppression on the chart. Notice also that the two bottom rows for m = 0 implicitly give L-to-I isolation for various harmonics of f_L calculated as follows:

L-to-I isolation (dB) = [LO drive level (dBm) - RF drive level (dBm)] + [SSB conversion loss (dB)] + [Suppression from Chart (dBc)]

For example, for the Class 1 mixer with +7 dBm of LO drive, -10 dBm of RF drive and 6 dB of conversion loss, L-to-I isolation is:

L-to-I isolation = (+7 + 10) + 6 + 26 = 49 dB

L-to-I isolation determined this way takes into account RF input power as well as that of the LO, and so may yield different results than the guaranteed L-to-I isolation specification, which is normally measured without any RF input power.

Intermodulation charts for a particular mixer reveal much about how it handles various input power levels. However, since intermodulation suppression is a function of many parameters, such as diode manufacturer and production lot, and mixer assembly and test, inter-modulation charts should only be used to evaluate trends in intermodulation suppression, and not to specify it concretely. A more in-depth discussion of this particular chart is given in the reference literature [3].

HARMONICS OF f_R	HARMONICS OF f_L: 0	1	2	3	4	5
7	79 >99 >99	69 79 >99	88 >99 >99	74 78 >99	83 >99 >99	63 78 >99
	>90 >90 >90	>90 >90 >90	>90 >90 >90	>90 >90 >90	>90 >90 >90	87 >90 >90
6	90 >99 >99	86 >99 >99	91 >99 >99	91 >99 97	90 >99 >99	84 >99 >99
	>90 >90 >90	>90 >90 >90	>90 >90 >90	>90 >90 >90	>90 >90 >90	>90 >90 >90
5	72 93 >99	70 73 96	71 87 >99	52 72 95	77 88 >99	46 66 >99
	>90 >90 >90	80 >90 >90	>90 >90 >90	71 >90 >90	>90 >90 >90	68 >90 >90
4	80 96 83	79 80 91	82 96 >99	77 80 92	82 95 90	76 82 95
	86 >90 >90	>90 >90 >90	86 >90 >90	88 >90 >90	88 >99 >99	85 >90 >90
3	51 63 81	49 58 73	53 65 85	51 60 69	55 65 85	48 55 68
	67 87 >90	64 77 >99	69 87 >99	50 78 >99	77 >99 >99	47 75 >90
2	69 68 64	72 67 71	79 76 62	67 67 70	75 80 63	66 66 70
	73 86 73	73 75 83	74 84 75	70 75 79	71 86 80	64 74 80
1	25 25 24	0 0 0	39 39 35	13 11 11	45 50 42	22 16 19
	24 23 24	0 0 0	35 39 34	13 11 11	40 46 42	24 14 18
0		36 39 29	45 42 20	52 46 32	63 58 24	45 37 29
		26 27 18	35 31 10	39 36 23	50 47 14	41 36 19

Figure 2. Example of an intermodulation chart showing the power level of various intermodulation products relative to the IF output power.

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INTERCEPT POINT

Intercept point, measured in dBm, is a figure of merit for intermodulation product suppression. A high intercept point is desirable. Two types are commonly specified: input and output intercept point (IIP and OIP, respectively). Input intercept point is the level of input RF power at which the output power levels of the undesired intermodulation products and IF products would be equal; that is, intercept each other if the mixer did not compress. This output power level is the output intercept point, and equals the input intercept point minus conversion loss. As input RF power increases, the mixer compresses before the power level of the intermodulation products can increase to equal the IF output power. So, input and output intercept points are theoretical and are calculated by extrapolating the output power of the intermodulation and IF products past the 1-dB compression point until they equal each other. A high intercept point is desirable because it means the mixer can handle more input RF power before causing undesired products to rival the desired IF output product, and essentially means the mixer has a greater dynamic range. Dynamic range, 1-dB compression point, and intercept point are all interrelated, but Cheadle has shown that, in general, no dB-for-dB rule of thumb exists to easily correlate 1-dB compression point with intercept point [3].

The concept of intercept point can be applied to any intermodulation product; however, it normally refers to two-tone, third-order intermodulation products. If two input RF signals are incident at the mixer R-port, they cause the mixer to generate the following two-tone intermodulation products:

$$(\pm m_1 f_{R_1} \pm m_2 f_{R_2}) \pm n f_L$$

where, m_1, m_2, n = 0, 1, 2, 3,..., m and n are integers and can assume any value. Two-tone, third-order intermodulation products have the following frequencies:

$$(\pm 2f_{R_1} \pm f_{R_2}) \pm f_L \quad \text{and} \quad (\pm f_{R_1} \pm 2f_{R_2}) \pm f_L$$

They are called third-order products because the coefficients of f_{R_1} and f_{R_2} sum to equal 3. Notice that the order of intermodulation products refers only to coefficients of the RF inputs and does not include that of the LO. The order of the intermodulation product is important because a 1-dB change in the power level of each input RF signal causes the power level of each intermodulation product to change by an amount of dB equal to its order. A 1-dB change in power of each of the two input RF signals causes the power level of each two-tone, third-order product to change by 3 dB.

Input intercept point is normally associated with two-tone, third-order intermodulation products because the third-order product is closest in frequency to the desired IF output product of any two-tone intermodulation product. The even-order, two-tone intermodulation products that exit from double- and single-balanced mixers are suppressed far more than the odd-order products, due to mixer balance. Odd-order intermodulation products containing even-order LO harmonics are suppressed in double-, but not in single-balanced mixers. Third-order two-tone products follow the (m_1 + m_2) dB of output power to 1-dB-of-input-power rule much more closely than the other higher-order, two-tone intermodulation products. Two-tone intermodulation products with orders greater than 7 are rarely a problem unless RF input power comes within a few dB of LO input power.

To illustrate the use and importance of intercept point, consider Figure 3, which shows two input RF signals, two output IF signals, and two output two-tone intermodulation products, given the following input frequencies: f_R = 410 MHz, f_{R_1} = 400 MHz and f_L = 100 MHz. Assume the desired received signal is f_{R_1}, and that f_{R_2} is an unwanted input signal. Desired signal f_{R_1} mixes with f_L to yield 310 MHz and 510 MHz outputs, and f_{R_2} mixes with f_L to yield 300 and 500 MHz outputs. Signals f_{R_1} and f_{R_2} combine to intermodulate with the LO to produce outputs at 320 MHz, 520 MHz, 290 MHz and 490 MHz. Higher-order single- and multiple- tone intermodulation products are also produced. Changing input power levels of f_{R_1} and f_{R_2} affects the output power levels of the IF and intermodulation products differently. Initially, both f_{R_1} and f_{R_2} have -10 dBm of input power, causing IF products to have -16 dBm of output power, assuming SSB conversion loss for this mixer is 6 dB. This input power level of -10dBm causes third-order products for this particular mixer to have -62 dBm of power, which is 46 dBc; i.e., 46 dB down from the IF products. As input power for both f_R, and f_{R_2} increases by 20 dB to become + 10 dBm, the power level of both IF products increases by 20 dB to become +4 dBm.

The two, third-order intermodulation products, however, have increased by 60 dB to have -2 dBm of power, giving a smaller intermodulation suppression of only 6 dBc, as compared to 46 dBc when RF input powers were both -10 dBm. This highlights a key point: to specify intermodulation suppression, both the suppression (in dBc) and the input RF power levels must be specified because intermodulation suppression varies as a function of input RF power. Further increasing both input power levels by 3 dB brings them up to +13 dBm, causing a 3-dB increase in power for both IF products, bringing them each up to +7 dBm, This 3-dB increase in RF input power causes a 9-dB increase in output power for the intermodulation products, bringing them up to +7 dBm also, The IF and intermodulation power levels are equal here, so +7 dBm is the output intercept point, and +13 dBm is the input intercept point, because this is the power level of both input RF tones that would cause IF and intermodulation products to have the same output power if the mixer did not compress.

Intercept point is normally presented as shown in Figure 4. Input power is plotted

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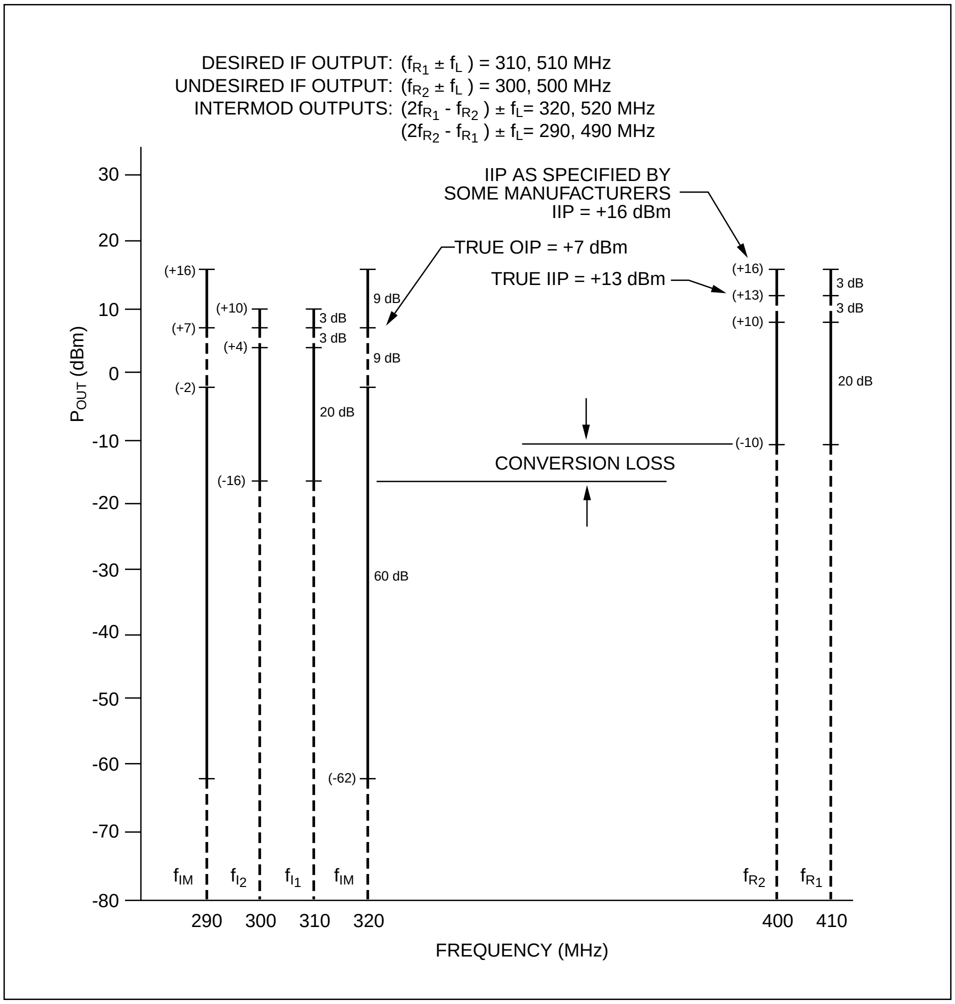

Figure 3. Relative power levels of input RF, output IF, and output intermodulation products as a function of frequency.

along the horizontal axis, and output power is plotted along the vertical axis. Two lines are plotted: one relating IF output power to RF input power, and another relating intermodulation output power to RF input power. Two points on each line are required to plot them. Recall that for -10 dBm of input RF power, the IF output power is -16 dBm, and intermodulation output power is -62 dBm. So, (-10, -16) is the first point for the IF line, and (-10, -62) is the first point for the intermodulation line. Also, recall that +10 dBm of input power causes the IF output power to be +4 dBm and intermodulation output power to be -2 dBm. So, (10, 4) is the second point on the IF line, and (10, -2) is the second point on the intermodulation line. The two lines can now be drawn. The point at which they intersect gives the input and output intercept points for the mixer at a particular set of input frequencies for a given LO power level and temperature.

The reason why so much effort is spent extrapolating out the intercept point instead of simply specifying the desired suppression and input RF power levels is that intercept point assumes intermodulation suppression to be zero dBc. This means that only one piece of information needs to be transferred between system designer and mixer manufacturer; namely, the input RF power level at which intermodulation suppression would be zero dBc, which is the input intercept point. So, instead of needing to specify two numbers, only one is necessary. This is the reason for using the intercept method.

A simple formula exists for calculating input intercept point, given the level of intermodulation suppression, the order of the intermodulation, and the input RF power levels giving rise to this level of suppression.

$$\text{IIP} = \frac{[\text{Intermodulation Suppression (dBc)}]}{3(\text{order} - 1) + [\text{input RF power (dBm)}]}$$

For example, when each input tone has -10 dBm of power, the third-order, two-tone intermodulation suppression is 46 dBc. This gives:

$$\text{IIP (dBm)} = \frac{46}{3 - 1} + (-10\text{ dBm}) = +13\text{ dBm}$$

This agrees with the +13 dBm IIP determined graphically.

Also, output and input intercept are related by the mixer conversion loss or gain (for active mixers):

$$\text{OIP (dBm)} = \text{IIP (dBm)} \begin{cases} -\text{mixer conversion loss (dB)} \\ \text{or} \\ +\text{mixer conversion gain (dB)} \end{cases}$$

Two more details need to be mentioned about intercept point. The first is that when determining intercept point, input RF power for each tone should be no greater than -20 dBm for Class 1 mixers, -10 dBm for Class 2 mixers, and 0 dBm for Class 3 mixers [3].

If these RF input powers are exceeded, intermodulation output power as a function of input RF power deviates from the (m_1 + m_2 +...) dB output power to 1-dB-input-power rule, causing the wrong intercept point to be extrapolated, Secondly, one confusing aspect connected to intercept point is the way in which it is specified by different manufacturers. While most manufacturers specify intercept point as explained in this discussion, some manufacturers, in order to be able to publish a seemingly high value for the intercept point of their mixers, have a different interpretation. Their technique is to specify input intercept point as the power level at which the input RF and output intermodulation power levels are equal. Figures 3 and 4 show that if the input RF power level is increased from +13 dBm to +16 dBm, the power level of the intermodulation products theoretically increases 9 dB, to become +16 dBm also. Some mixer manufacturers would specify +16 dBm as the input intercept point for this mixer, allowing the customer to think he or she is buying a better mixer than an identical one specified correctly at +13 dBm. This method generates a value for input intercept point that is higher by half the mixer conversion loss than the true input intercept point. It also generates values for input and output intercept points that are equal.

When specifying intercept point for a mixer, it is advisable to:

1. Distinguish between input and output intercept point.
2. Specify the order of the intermodulation product, and number of input tones it has.
3. When measuring two-tone, third-order intercept point, keep both RF input power levels no greater than:
   (a) -20 dBm for a Class 1 mixer
   (b) -10 dBm for a Class 2 mixer
   (c) 0 dBm for a Class 3 mixer
4. Check that input IP and output IP are not equal; if they are, the input IP value given is misleadingly higher than the correct one by half the mixer conversion loss.
5, Specify individual test frequencies instead of a test bandwidth, and specify all input power levels because intercept point changes as a function of frequency and input power.

SSB NOISE FIGURE

Mixer SSB noise figure is measured in dB, and is the amount of noise added by the mixer to the converted signal plus the SSB conversion loss, Noise figure is the difference in dB between the input RF signal-to-noise ratio and the output IF signal-to-noise ratio (IF power out includes either the up- or down-converted IF product).

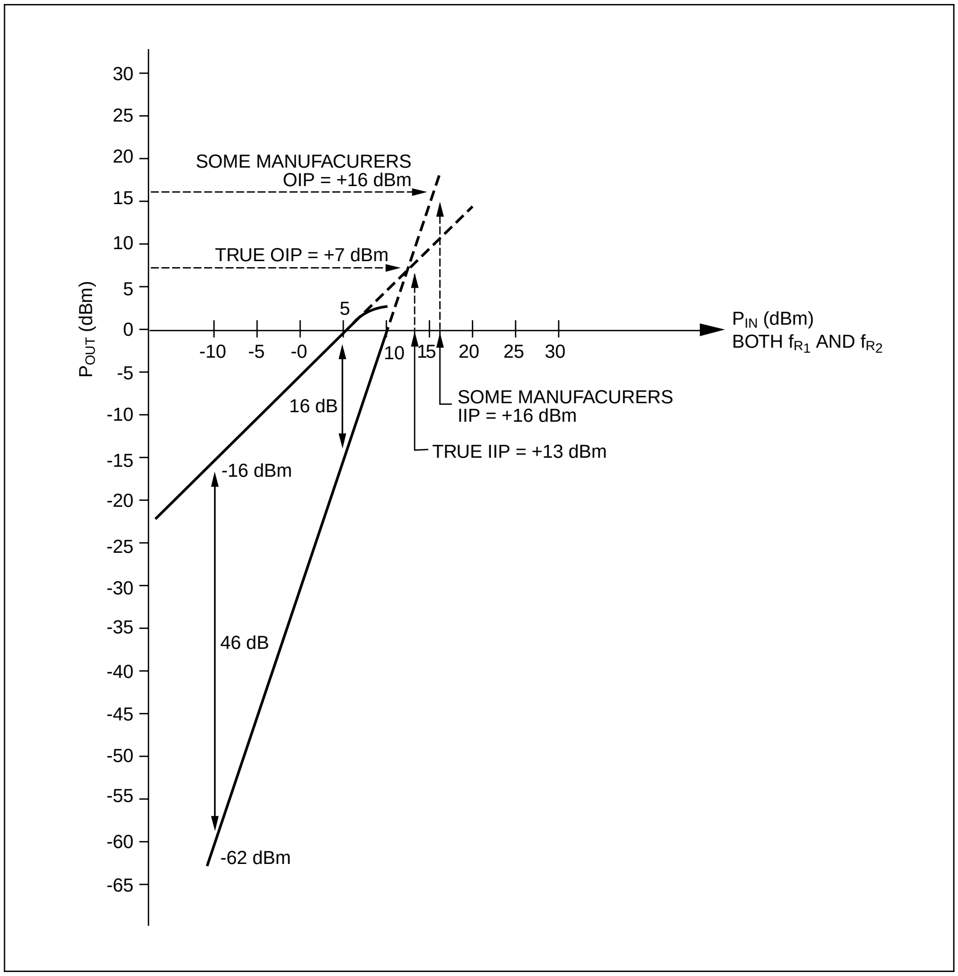

Figure 4. Output power of IF and intermodulation products as a function of input RF power.

$$\text{SSB NF (dB)} = 10\log\frac{\text{RF PWR In}}{\text{Noise RWR Out}} - 10\log\frac{\text{IF PWR In}}{\text{Noise PWR In}}$$

$$= [\text{RF Power In (dBm)} - \text{IF Power Out (dBm)}] + [\text{Noise Power Out (dBm)} - \text{Noise Power In (dBm)}] \quad (3)$$

$$\text{SSB NF (dB)} = [\text{SSB Conversion Loss (dB)}] + [\text{Output-to-Input Noise Ratio (dB)}] \quad (4)$$

Like SSB conversion loss, SSB noise figure is normally specified instead of DSB (Double Sideband) noise figure, because the mixing process produces both up- and down-converted IF products, and normally only one of these products is desired, so the other product is discarded. This causes half the input power to be lost, making the SSB noise figure 3 dB higher than the DSB noise figure. This is why IF output power in Equation (3) includes either the up- or down-converted IF product, and not both. Simply adding 3 dB to the DSB noise figure assumes that the mixer generates both sidebands with equal conversion loss. This assumption is routinely made in specifying mixer SSB noise figure because DSB noise figure is sometimes easier to measure.

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Additive noise has three main components: Johnson (thermal), shot, and flicker noise. Johnson noise is generated by Brownian motion of electrons in the series bulk resistance of the diode, causing random voltage fluctuations to appear across it. As diode temperature increases, the electrons move faster and over a longer distance, increasing the amplitude of the noise power generated. Another source of noise is the shot effect. This noise contribution is generated by random fluctuations in diode current. Both shot and thermal noise are generated randomly, and produce relatively constant noise power (white noise) over a given bandwidth. When calculating the amount of noise added by these two sources, it is important to specify the bandwidth over which the noise power is measured, since the noise power is proportional to bandwidth. Flicker noise is also generated in diodes. Its rms power is proportional to 1/frequency, so it becomes appreciable at lower frequencies. When diodes are operated at much below 400 kHz, flicker noise may become a problem. Thermal, shot, and flicker noise are always generated, and combine with SSB conversion loss to yield the overall mixer SSB noise figure. The SSB noise figure is usually about 0.5 dB higher than SSB conversion loss.

This discussion has presented the basics of mixer characteristics and performance. Part 2 of this Tech-notes series will go on to discuss mixer theory.

Vol. 8 No. 2 March/April 1981

References

Mixers, Part 1:

1] RF Signal Processing Components Catalog, Watkins-Johnson Company, 1980/81: Effect of Attenuating Pads on VSWR, p. 569

2] "High Dynamic Range Receiver Parameters", Rodney McDowell, WJ Tech Notes

3] "Selecting Mixers for Best Intermod Performance", Dan Cheadle, Microwaves, Nov/Dec 1973

4] Introduction to Communication Systems, Ferrel Stremler, Addison-Wesley 1977, p. 21-22, 199

5] "Consider a Single Diode to Study Mixer Intermod", Dan Cheadle, Microwaves, Dec 1977

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Mixers in Microwave Systems (Part 2)

The frequency-conversion function of a mixer plays a critical role in RF and microwave systems. Part 1 of this article deals with mixer theory, analysis of frequency conversions, conversion loss, noise figure, and intermodulation. Part 2 will discuss impedance matching, diode-mixer design, mixer realization, and use of mixers in microwave system environments.

IMPEDANCE MATCHING

RF and IF port mismatch is a major contributor to conversion loss. Three main cases exist: RF and image frequencies having the same termination, image short-circuited, and image open-circuited. For the RF and image equally terminated, theoretical minimum conversion loss is 3.0 dB, with IF VSWR equal to 1:1, but with RF VSWR equal to 3:1. This means that minimum conversion loss is obtained at the expense of poor RF port impedance match [3]. A single-balanced (two-diode) mixer design example using computer numerical analysis shows the real part of RF impedance, Rsig, to be about 150 ohms for signal and image equally terminated. For short-circuited image, R_{sig} = 100 ohms, and for open-circuited image, R_{sig} = 120 ohms [24]. Tucker has tabulated input resistance for various modulator configurations [1], and Maas has given specific impedance values for a diode operated at 10 GHz [6]. Also, Saleh has given RF and IF impedances for the above three cases [4].

IF impedance is real only when the image is terminated in an open or short circuit [5]. For a single diode with the three cases given above, the real part of IF impedance, RIF, is approximately 200 ohms, 150 to 350 ohms and 200 to 2000 ohms, respectively.

The real part of LO impedance has been approximated as [11]:

$$R_{LO} = R_s/t \qquad (10)$$

where R_s is the diode series resistance and t is the conductance-pulse duty ratio.

DIODE MIXER DESIGN AND REALIZATION

Many types of mixer circuits and realizations exist. A given mixer circuit may be realized in various ways to cover different frequency ranges; for example, different mixers can employ the same basic balun circuit, but can be realized in bifilar-core, semi-rigid coax or balanced microstrip. Many types of mixer circuits exist: single-ended, single-balanced, double-balanced, triple-balanced, Class IV, and image-reject. RF, LO, and IF ports may be interchanged in any passive mixer due to the linear relationship between small-signal RF, IF, and image signals.

A single-ended mixer, shown in Figure 1, comprises a single diode with triplexed RF, LO, and IF ports. This circuit is rarely used because it does not provide the extra intermodulation suppression given by balanced mixers.

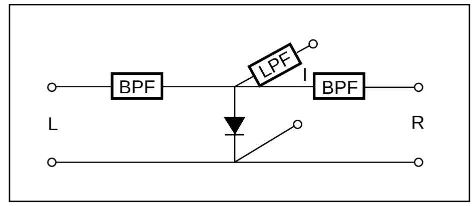

Figure 1. Single-ended mixer.

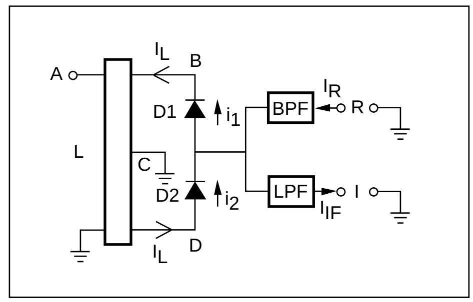

Figure 2. Single-balanced mixer.

Figure 2 shows a single-balanced mixer composed of two single-ended mixers and a balun. A balun interfaces a single-ended input port with two output ports having voltages that are equal in magnitude but opposite in phase. The balun isolates the LO from the IF port, and suppresses even-order intermodulation products. (Even though the balun is at the LO port, it causes IM products with even RF harmonics to be suppressed.) Single-balanced mixers are most often found in image-reject mixers. Figure 3 shows a uni-planar single-balanced, image-reject mixer designed at Watkins-Johnson Company.

Double-balanced mixers, shown in Figures 4 and 5 as ring and star circuits comprise four

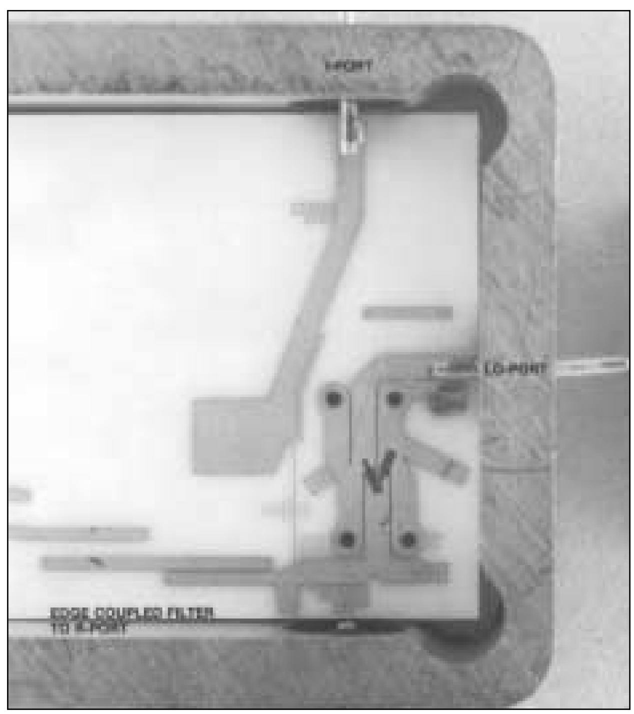

Figure 3. Thin-film single-balanced mixer.

diodes and two baluns [25]. RF, LO, and IF ports are all isolated by means of circuit balance. In Figure 4B, LO voltages at J3 and J4 are equal and opposite, assuming a perfect LO balun and identical diode impedances, so that J1 and J2 are virtual grounds with respect to LO voltage. RF and IF output voltages, respectively, are proportional to the difference and sum of the residual LO voltages present at J1 and J2. The RF and IF ports are isolated through the R-port balun alone. IF bandwidth in microwave double-balanced mixers are generally limited to frequencies below approximately 3 GHz, due to inductance present in the physical realization of the single-ended IF-port. Theoretically, assuming identical diodes and perfect baluns, all IM products are balanced out at the IF-port, except those having odd RF and LO harmonic coefficients, m and n.

In all passive mixer designs, current return paths for RF, LO, and IF circuits must exist. For example, in the mixer of Figure 4B, the LO current path alternates between diodes D1-D2 and D3-D4. The center-tapped LO balun provides the IF ground return path. RF current returns through the time-averaged conductances of D1-D4 in parallel with D2-D3. This seems paradoxical since D1, D4, and D2, D3 are never on at the same time during a given LO cycle. However, the periodic conductance waveform for each diode has a non-varying Fourier component, approximately equal to 1/2 of the peak conductance. This average conductance provides the RF current path. Triple-balanced (also known as double-double-balanced) mixers are shown in Figure 6 as ring and star circuits, which comprise two diode ring-quads and three baluns. The major benefit of using a triple-balanced mixer is very broadband IF port response. Triple-balanced mixers with RF and LO ports operating over 2 to 26 GHz, and the IF port operating over 1 to 15 GHz, have been constructed [26].

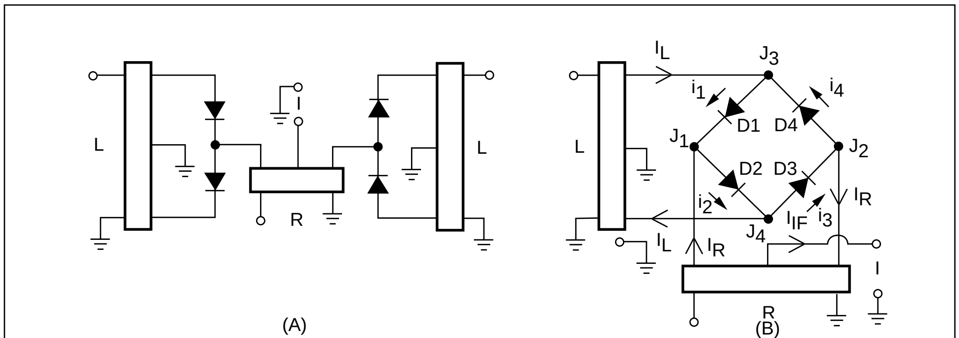

Figure 4. The ring double-balanced mixer is formed by combining two single-balanced mixers.

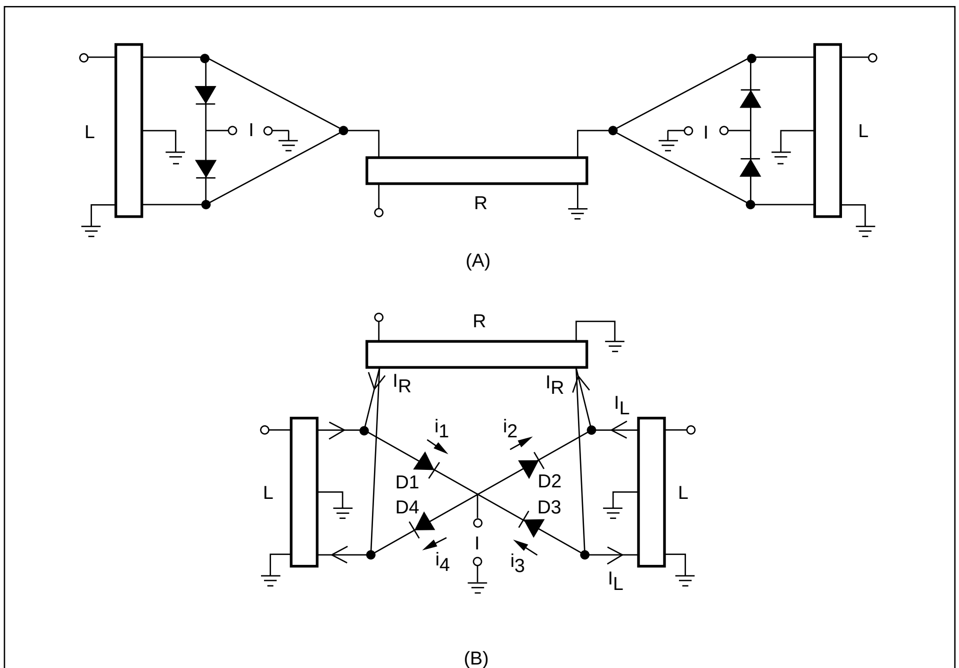

Figure 5. The star double-balanced mixer is formed by combining two single-balanced mixers.

Class IV mixers, commonly known as termination (or load) insensitive [27], comprise two diode bridge quads and two 100-ohm chip resistors that are embedded in a network of 100-ohm transmission line baluns [28]. Diode currents for IM products with frequency $f = \pm nf_L \pm mf_R$, where m and n are both even integers, are dissipated in the two resistors. In double-balanced mixers using ring quads, these currents circulate around the diode ring, causing further intermodulation of out-of-band signals reflected back into the mixer. Class IV mixers suppress the even-by-even products, and so tend to have more constant conversion loss and IM suppression as RF and IF load impedances are varied.

Image-reject mixers (IRM) are used to suppress unwanted image noise and signals. They are also commonly used as SSB upconverters [29]. Image rejection is achieved through phase cancellation or filtering, and is defined as the ratio of available IF power to available downconverted image power at the IF output port. As

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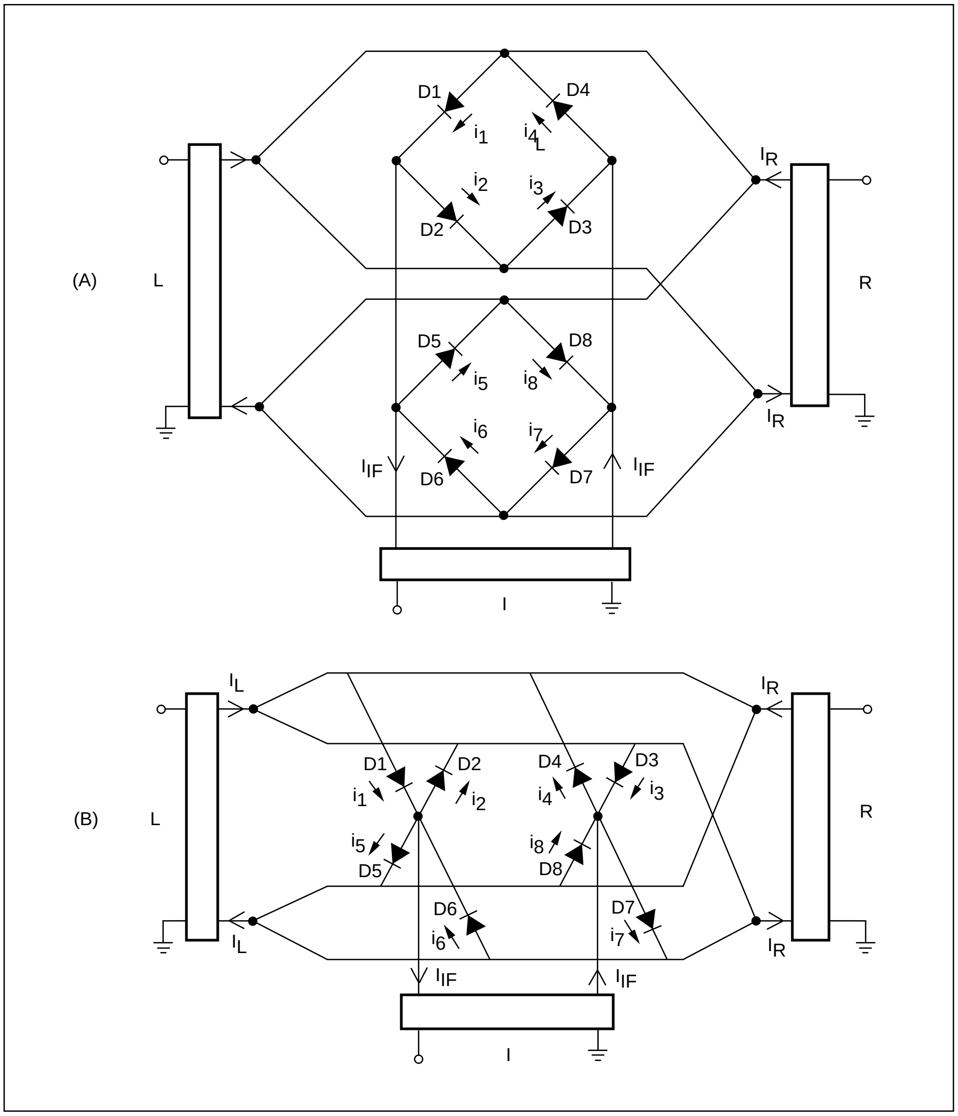

Figure 6. A triple-balanced mixer is formed by combining two double-balanced ring or star mixer.

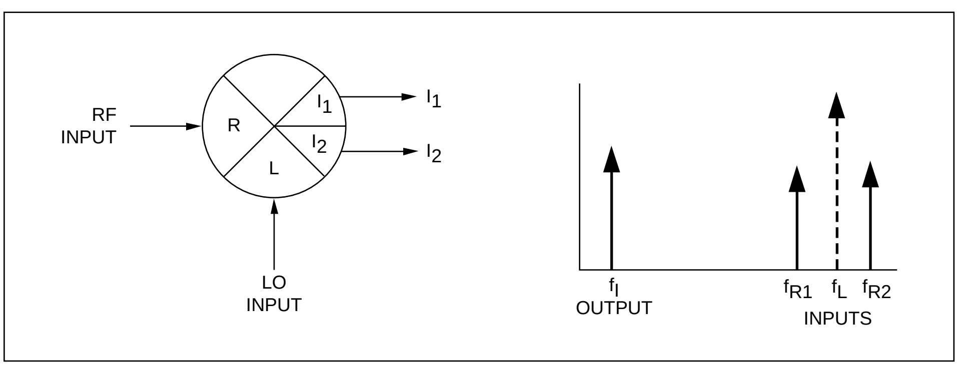

Figure 7. Image-reject mixer configuration, and corresponding frequencies.

shown in Figure 7, the RF and image frequencies, referenced to the LO frequency, are the mirror images of each other. If the RF frequency is defined as f_{R1}, then the image is f_{R2}. The image frequency is, $f_{IM} = 2f_L - f_R$, regardless of whether f_{IM} equals f_{R1} or f_{R2}.

The image signal is normally thought of as a mixer-generated IM product that exits the mixer, and which is related to image enhancement. However, for an IRM, the image refers to signals and noise power at the image frequency that enter the mixer along with the desired RF signal. Image noise that is higher than the thermal noise floor level (such as that generated by a broadband amplifier placed ahead of the mixer) will increase the system noise figure by up to 3 dB above the expected SSB noise figure level, because it downconverts to the IF along with the noise associated with the desired RF signal. The contribution of image noise to the overall noise figure can be reduced by using an image-reject mixer. Equation 10 and Table 1 show that with only 10 dB of image rejection, the image noise contribution is reduced from 3.0 to 0.41 dB. Equation 10 is based on the definition of noise figure as being the input S/N ratio divided by the output S/N ratio. Downconverted image noise causes the output noise power to be multiplied by the factor, (1 + IR), where $IR = 10^{[-IR(dB)/10]}$ thus increasing overall noise figure.

$$\text{Change in NF} = 10 \log (1 + IR) \qquad (10)$$

Figure 8 shows that phase-cancellation IRMs consist of two mixers, two quadrature hybrids and one in-phase power divider. Mixers M1 and M2 are identical and have IF output currents I'_1 and I'_2, which are equal in magnitude but are in phase quadrature. The presence of the RF harmonic coef-

Image Rejection (dB)	Change in NF (dB)
0	3.0103
10	0.4140
20	0.0430
30	0.0043

Table 1. Image-noise contribution to noise figure as a function of image rejection.

ficient, m, in the phase angle of the mixing products, I_1 and I_2, is a result of the power series expansion for the diode current-voltage characteristic.

Since $I'_2 = j^m I'_1$

and setting:

$$|I'_1| = |I'_2| = I,$$

the currents exiting the IF quadrature coupler are:

$$\begin{aligned} I_1 &= (I/2)\,(1 + j^{(m+1)}) \\ &= I \text{ for } m = -1 \quad (f_L - f_{R1}) \\ &= 0 \text{ for } m = +1 \quad (f_{R2} - f_L) \end{aligned} \tag{11a}$$

$$\begin{aligned} I_2 &= (I/2)\,(j + j^m) \\ &= 0 \text{ for } m = -1 \quad (f_L - f_{R1}) \\ &= jI \text{ for } m = +1 \quad (f_{R2} - f_L) \end{aligned} \tag{11b}$$

I'_1 and I'_2 combine in the output quadrature coupler so as to channelize the $(f_L - f_{R1})$ product into port I_1, and the $(f_{R2} - f_L)$ product into port I_2.

Image rejection is a function of the cumulative amplitude and phase imbalance of the hybrids and mixers, and is given as,

$$IR\ [dB] = -10 \log \frac{(1 + A^2 - 2A \cos \phi)}{(1 + A^2 + 2A \cos \phi)} \tag{12}$$

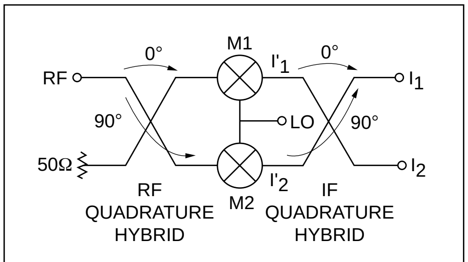

Figure 8. Block diagram of an image-reject mixer. A single sideband mixer is formed by reversing RF and IF ports.

Figure 9 gives image rejection as a function of total phase and amplitude imbalance. It shows, for example, that to achieve 20 dB of image rejection, amplitude imbalance must be less than about 1.6 dB, and phase imbalance must be less than about 12 degrees.

MIXER REALIZATION

Balanced mixers are generally realized with passive balun structures composed of various types of transmission lines. Recently, however, active-balun mixers have been designed for MMIC circuits, with the goal of reducing the amount of GaAs surface area required. Diode and FET mixers also have been built using passive and active baluns.

Balanced mixers operating in the frequency range of 1 to 3000 MHz generally use transmission line baluns composed of bi-, tri-, or quadfilar wire wrapped on ferrite cores. These structures are multioctave, employing magnetic coupling up to about 200 MHz, and electric coupling up to frequencies of about 3000 MHz.

Microwave mixers operating above approximately 2 GHz are realized using various combinations of micro-strip, coplanar waveguide (CPW) and slotline. Most microwave mixers are built using soft dielectric balanced microstrip with soldered-in diode ring-quad packages. The major challenges to these designs include the crossover of the RF and LO lines shown schematically in Figure 4B, and the dual-sided nature of most broadband microwave balun structures. A number of catalog mixer designs exist that provide various tradeoffs among conversion-loss, bandwidth and intermodulation performance. Mixers realized using CPW and slotline [30,31] have increased in popularity due to small size, ease of fabrication and low conversion-loss. [32].

A number of MMIC mixer circuits have been described recently that use multioctave distributed active baluns [33, 34]. Passive baluns are also used in MMIC mixers. One approach, requiring a minimum of GaAs space, consists of printed spiral transformers [35]. These have bandwidths of 4:1 with about 1 dB of insertion loss, compared with the 6 dB of added noise figure typically found in distributed active baluns [36]. Various bipolar Gilbert-cell mixers have been described, which offer conversion gain and small size, but at the expense of higher noise figure [37].

MIXERS AND SYSTEM SPECS

Various tradeoffs exist between gain, noise figure, compression, and intercept point when cascading mixers with other devices in systems. For example, if an amplifier and

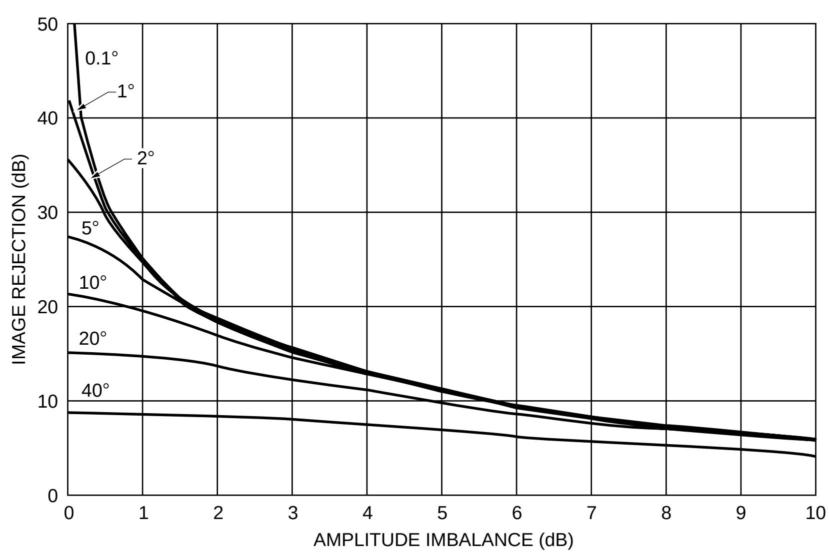

Figure 9. Image-rejection versus amplitude and phase imbalance.

mixer are cascaded, the amplifier should precede the mixer to minimize overall noise figure, but the opposite arrangement would be required to maximize overall intercept point. Cascaded third-order output intercept point for two stages has been given as [38]:

$$\text{OIP3 (dBm)} = -10\log\left(\frac{1}{\text{OIP3}_1 \times G_2} + \frac{1}{\text{OIP3}_2}\right)$$

where OIP3_n and G_n are the algebraic third-order output intercept and gain of the nth stage. This formula assumes linear IM suppression relative to the IF product, and cascaded voltages all adding at (worst-case) phase maximums. The cascaded third-order output intercept point is maximum when g_2 is large, indicating the amplifier should follow the mixer to optimize intercept point.

Cascaded 1-dB power compression can be approximated for amplifiers using the same formula as for cascaded intercept point [39]. This relationship is based on the fact that for amplifiers, output power at 1-dB compression is generally 10 dB below the two-tone third-order output intercept point. The output 1-dB compression and third-order output intercept points in mixers are generally less than 10 dB apart and are less predictable, so this relationship should be used carefully for mixers cascaded with amplifiers and other devices.

GROUP DELAY

Group delay for RF and microwave mixers is in the range of 0.350 to 0.500 ns. There is no inherent group delay increase in a passive mixer, except that which is caused by the transmission line lengths and reactive elements that are present in the mixer circuit. Group delay of broadband mixers can be measured by pulsing the RF input signal and measuring delay using a fast oscilloscope with and without the mixer present. The difference in delay equals the group delay. This method requires the oscilloscope to be fast enough to display both the IF and RF signals. When this is impractical, group delay can be approximated by placing two mixers in an up-down configuration and halving the resulting delay to get group delay for one mixer alone.

MAKE OR BUY DECISION

Whether to build or buy a mixer involves trading off such factors as cost, performance, availability, packaging, testing and screening. The cost of designing and building a high-performance mixer may indeed be higher than that of buying an existing catalog model. When catalog mixers do not meet the required performance, they can generally be modified by the manufacturer. For example, to achieve higher levels of compression and IM suppression, the diode can generally be replaced with one having a higher barrier level. Testing for phase and gain, match and track, is routinely done by mixer manufacturers who have large quantities of mixers to select from and automated test stations set-up specifically for this purpose [40]. Also, QPL (Qualified Products List) mixers are increasingly being used to reduce cost and delivery times [41].

CONCLUSION

This article has summarized the topics of mixer theory, design, realization, and usage. It was shown that image enhancement techniques must be used to minimize conversion loss, and that the image termination should be a short circuit, rather than an open circuit, in order to minimize noise figure and third-order intermodulation. Conversion-loss ripple of up to 5 dB peak-to-peak can result when filters are placed adjacently to broadband mixer ports. Theoretical limits for conversion-loss are 3.92 dB for conjugately matched broadband mixers, 3.0 dB for mixers with conjugately matched IF and equally matched signal and image, but with reactively terminated idlers; 0 dB optimally matched signal and IF, and for reactively terminated image and idlers. A broad array of mixer circuits exist, which are commonly realized using soft dielectric balanced microstrip and other transmission-line structures. Present areas of design include using uni-planar thin-film balun structures to minimize device cost and size, usage of MESFETs to achieve wider dynamic range than possible with Schottky diodes, and designing compact broadband balun structures for MMIC mixers.

ACKNOWLEDGEMENT

The author wishes to thank SE. Avery, Dr. R.K. Froehlich, and Dr. R.G. Ranson for their thoughtful review of this paper, MA. O'Mahoney, and T.G. Skala for their non-linear CAD evaluations, R.W. Bruce for the usage of his extensive bibliography, and R.Y.S. Parsons for preparing the draft.

REFERENCES

1. Tucker, D.G. “The Input Impedance of Rectifier Modulators,” lEE Proc., Vol. 107B, No. 1, pp. 273-284, January 1960.
2. Gardner, J.G., et al. “Distortion Performance of Single-Balanced Diode Modulators,” lEE Proc., Vol. 117, No. 8, August 1970.
3. Kelly, A.J. “Fundamental Limits on Conversion Loss of Double Sideband Resistive Mixers,” IEEE Trans. Microwave Theory Tech., Vol. M71’-25, No. 11, November 1977, pp. 867-869.
4. Saleh, A.A.M. Theory of Resistive Mixers, Cambridge, Massachusetts: MIT Press, 1971.
5. Torrey, H.C. and C.A. Whitmer. Crystal Rectifiers, New York: McGraw-Hill, 1948.
6. Maas, S.A. Microwave Mixers, Artech House, Dedham MA, 1986.
7. Held, D.N. and KR. Kerr. “Conversion Loss and Noise of Microwave and Millimeter-Wave Mixers: Part 1-Theory and Part 2-Experiment,” IEEE Trans. Microwave Theory Tech., Vol. MWI’-26, No.2, February 1978.
8. Burkley, C.J. and R.S. O’Brien. “Optimization of an 11 GHz Mixer Circuit Using Image Recovery,” mt. J. Electron, Vol. 38, pp. 777-787, June 1975.
9. Mass, S. ‘Two-Tone Intermodulation in Diode Mixers,” IEEE Trans. Microwave Theory and Tech., Vol. MTT-35, No. 3, March 1987, pp. 307-314.
10. Oxley, T.H. “Phasing Type Image Recovery Mixers,” IEEE MTT-S mt. Microwave Symposium Digest, pp. 270-273, 1980.
11. Dickens, LE. and D.W. Maki. “An Integrated-Circuit Balanced Mixer, Image and Sum Enhanced,” IEEE Trans. Microwave Theory Tech., Vol. MTT-23, No. 3, March 1975.
12. Pound, R.V. Microwave Mixers. Usington, Massachusetts: Boston Technical Publishers, Inc., pp. 81-87, 1964.
13. Shurmer, H.V. Microwave Semiconductor Devices. New York: Wiley Interscience, 1971.
14. Sze SM. Physics of Semiconductor Devices. New York: Wiley Inter-science, 1969, p. 459.
15. Sabin, WE. and E.O. Schoenike. Single-Sideband Systems and Circuits, New York: McGraw-Hill, 1987.
16. Steinbrecher, D.H. “Mixer Fundamentals,” Notes presented at 1989 RF Technology Expo, Santa Clara, CA.
17. Bain, R. “A Mixer Spurious Plotting Program,” RF Design, May 1989, pp. 32-43.
18. Weiner, S., D. Neuf and S. Spohrer. “2 to 8 GHz Double Balanced MES-FET Mixer with +30 dBm Input 3rd Order Interecept,” IEEE MTT-S Int. Microwave Symposium Digest, pp. 1097-1100, 1988.
19. Maas, SA. “A GaAs MESFET Mixer With Very Low Intermodulation,” IEEE Trans. Microwave Theory Tech., Vol. M’IT-35, No. 4, April 1987.
20. Oxner, E. “A Commutation Double-Balanced MOSFET Mixer of High Dynamic Range,” Proceedings 1986 RF Expo East, pp. 73-87.
21. Henderson, B.C. “Reliably Predict Mixer IM Suppression,” Microwaves and RF, Vol. 22, No. 12, Nov. 1983.
22. Cheadle, DL. “Consider a Single Diode to Study Mixer Intermod,” Microwaves, Dec. 1977.
23. Gretsch, W.R. “The Spectrum of Intermodulation Generated in a Semiconductor Diode Junction,” Proc. IEEE, Vol. 54, No. 11, November 1966.
24. Faber, MT. and W.K. Gwarek. “Nonlinear-Linear Analysis of Microwave Mixer With Any Number of Diodes”, IEEE Trans. Microwave Theory Tech., Vol. MYI’-28, No. 11, Nov. 1980.
25. Mouw, RB. “A Broad-Band Hybrid Junction and Application to the Star Modulator,” IEEE Trans. Microwave Theory Tech., Vol. MTI’-16, pp. 911-918, Nov. 1968.
26. Henderson, B. “Orthogonal Mixers: Punching Up Earth/Space Payload Performance,” MSN, January 1982, Vol. 12, No. 1.
27. Will, P. “Termination Insensitive Mixers,” Professional Program Session Record 24, WESCON, San Francisco, 1981.
28. Norton, D. “Three Decade Bandwidth Hybrid Circuits,” Microwave Journal, Vol. 31, No. 11, Nov. 1988, pp. 117-126.
29. Henderson, B. and J. Ceok. “Image Reject and Single Sideband Mixers,” MSN, Vol. 17, No. 9, August 1987.
30. Aikawa, M. and H. Ogawa “Double Sided MIC’s and Their Applications,” IEEE Trans. Microwave Theory Tech., Vol. 37, No. 2, February 1989.
31. Hirota, T., Y. Tarusawa and H. Ogawa. “Uni-planar MMIC Hybrids A Proposed New MMIC Structure,” IEEE Trans. Microwave Theory Tech., Vol. 37, No. 2, February 1989.
32. Izadian, J., et al. “A Uni-Planar Double-Balanced Mixer Using A New Miniature Beam Lead Crossover

Author: Bert C. Henderson

Quad," IEEE Int. Microwave Symposium Digest, pp. 691-694, 1988.

33. Pavio, AM., et al. "Double Balanced Mixers Using Active and Passive Techniques," IEEE Trans. Microwave Theory Tech., Vol. 36, No. 12, December 1988.

34. Titus, W., et al. "Distributed Monolothic Image Rejection Mixer," IEEE Int. GaAs IC Symposium, pp. 191-194, 1986.

35. Mi, F., S. Moghe and R. Ramachandran. "A Highly Integrated X-Ku Band Upconverter," IEEE GaAs IC Symposium Digest, pp. 157-160, 1988.

36. Private communication with AF. Podell.

37. Fotowat, A. and E. Murthi. "Gilbert Type Mixers vs. Diode Mixers," Proceedings RF Technology Expo 1989, pp. 409-413.

38. Wilson, SE. "Evaluate The Distortion of Modular Cascades," Microwaves, Vol. 20, March 1981.

39. Sorger, G.U. "The 1 dB Gain Compression Point for Cascaded Two Port Networks," Microwave Journal, July 1988.

40. Avery, SE. "Dual Mixers," Watkins-Johnson Company Tech-notes, Vol. 13, No. 4, July/August 1986.

41. Sehindler, SA. "MTL-Specification Mixers," Watkins Johnson Company Tech-notes, Vol. 15, No. 2, March/April 1988.

Note: Many of the referenced articles appear in the following volume of IEEE Press Selected Reprint Series: E.L Kollberg, "Microwave and Millimeter-Wave Mixers," IEEE Press, New York, N.Y., 1984.

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