



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, R_{sig} , 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, R_{IF} , 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]:

$$R_{LO} = R_s/t \tag{10}$$

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 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

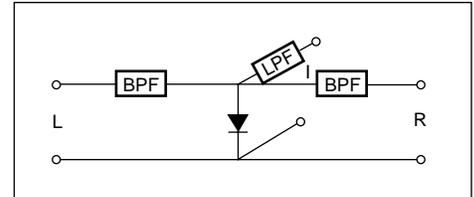


Figure 1. Single-ended mixer.

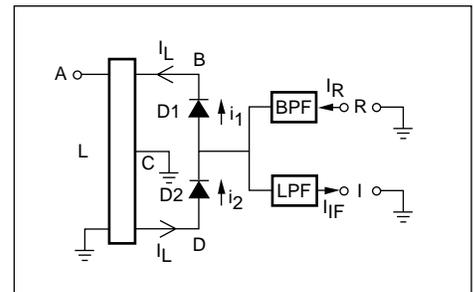


Figure 2. Single-balanced mixer.

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

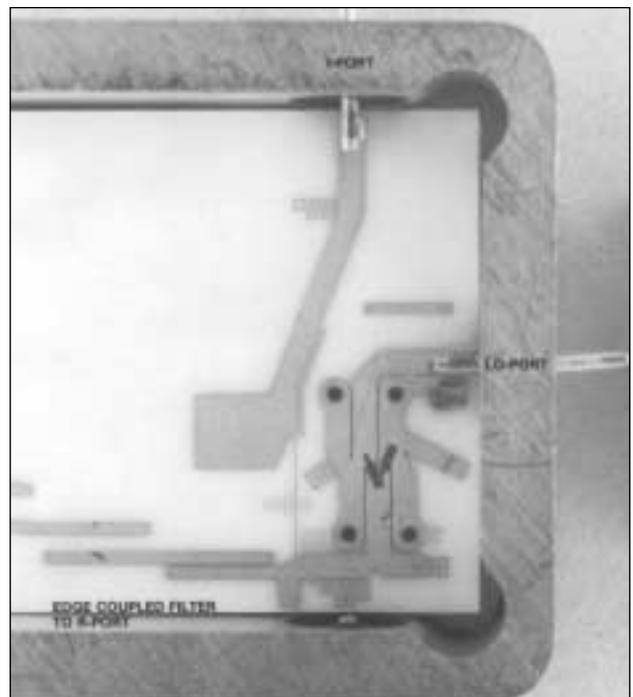


Figure 3. Thin-film single-balanced mixer.



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].

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

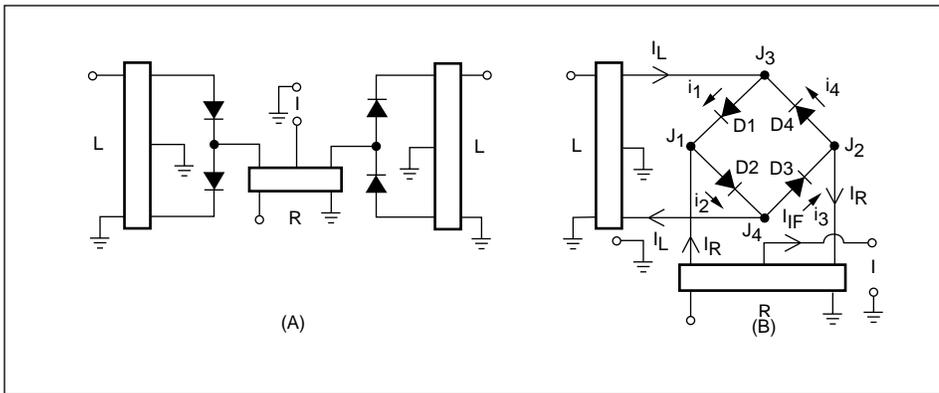


Figure 4. The ring double-balanced mixer is formed by combining two single-balanced mixers.

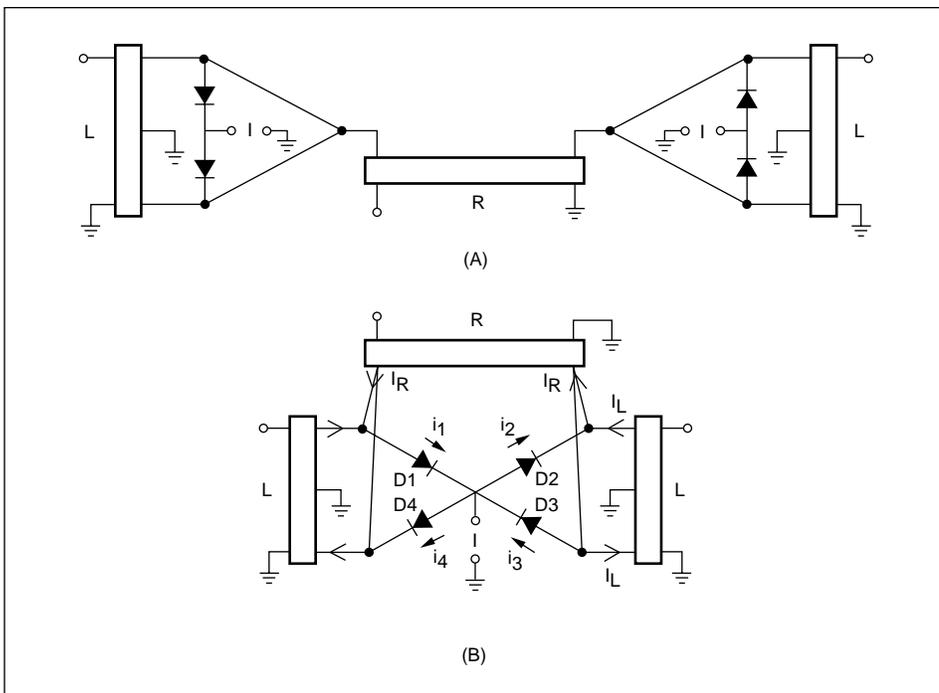


Figure 5. The star double-balanced mixer is formed by combining two single-balanced mixers.

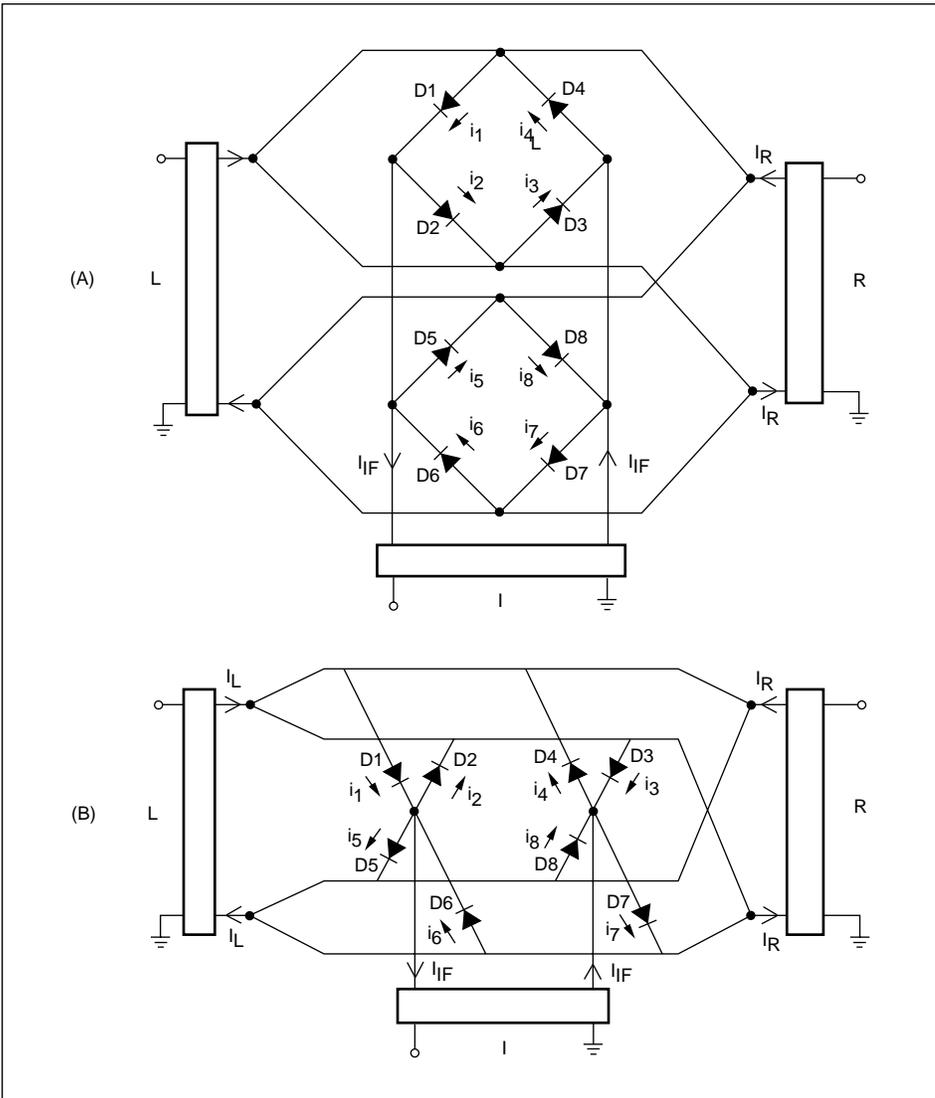


Figure 6. A triple-balanced mixer is formed by combining two double-balanced ring or star mixer.

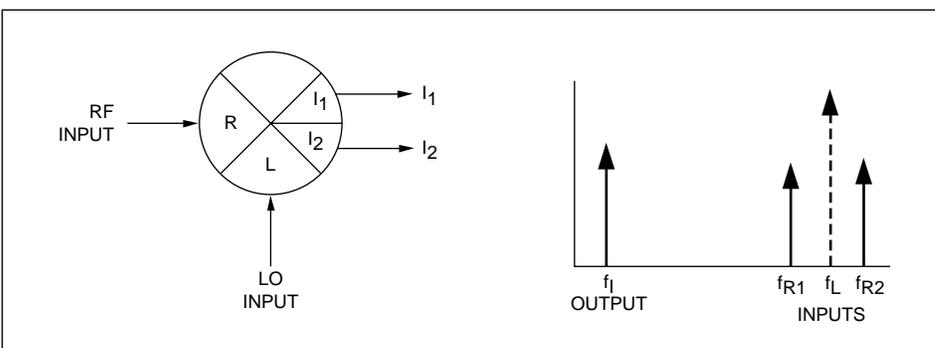


Figure 7. Image-reject mixer configuration, and corresponding frequencies.

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.

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

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.



efficient, 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.

$$\text{Since } I_2 = j^m I_1$$

and setting:

$$|I_1| = |I_2| = I,$$

the currents exiting the IF quadrature coupler are:

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

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

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,

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

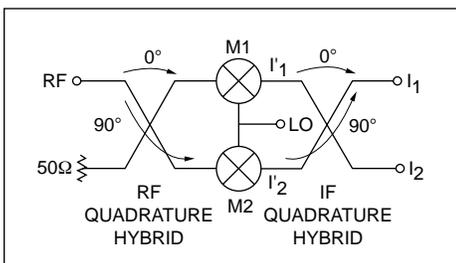


Figure 8. Block diagram of an image-reject mixer. A single sideband mixer is formed by reversing RF and IF ports.

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 quadfilair 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 slot-line [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

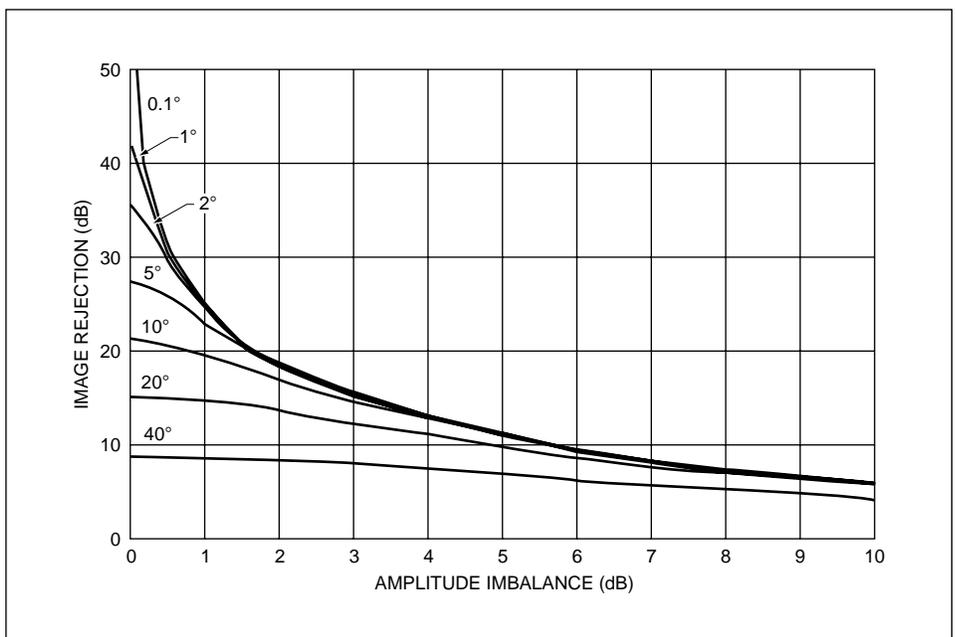


Figure 9. Image-rejection versus amplitude and phase imbalance.



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]:

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

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 sig-

nals. 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.

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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.