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Mixers: Part 2
Theory and Technology

This article presents the practical aspects of mixer theory and technology. It discusses mixer circuits, the mixing process, baluns, diodes, and one typical mixer design. An understanding of the material in parts 1 and 2 of this Tech-notes series will provide the foundation necessary to discuss and specify mixers.

MIXER CIRCUITS

There are basically four types of mixer circuits. single-ended (SE), single-balanced (SB), double-balanced (DB), and double double-balanced (DDB). Each has its own set of performance tradeoffs that must be considered to optimize system performance.

Single-ended mixers are the simplest type, since they use only one diode. Figure 1 shows that the L-, R- and I-ports are electrically the same, being only separated by filters that provide interport isolation. The bandwidths of the filters must not overlap if high isolation is required. Part 1 of this Tech-notes series outlined some of the important benefits of having good interport isolation. In addition, good isolation in SE mixers forces the LO and input RF currents into the diode, and the IF current out the I-port. All the possible intermodulation products $f_{I_{m,n}}$ exit the I-port of SE mixers.

$$f_{I_{m,n}} = \pm m\, f_R \pm n\, f_L \qquad (1)$$

$$m,n = 0, 1, 2, 3, \ldots$$

Coefficients m and n are integers and can assume any value. SE mixers can operate with very low LO power because only one diode is used. This is beneficial in systems that can deliver only a small LO power level. However, low LO power also means a small dynamic range because the 1-dB compression point, which is usually taken to be the top of the dynamic range, is typically 5 to 10 dB below the LO power level. If a greater dynamic range is required, two or more diodes can be placed in series to allow for more LO power. Other solutions for allowing more LO power to bias the diode are presented later in the section on Classes of Mixers. If the system is narrow-band and does not require great dynamic range, good IM suppression, or high isolation, an SE mixer may be the best choice, since it can be very inexpensive if the filter arrangements are simple. However, if a more broadband mixer that has better IM suppression is required, a balanced mixer is the better choice.

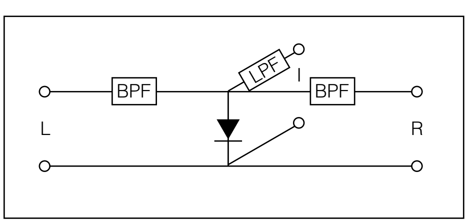

Figure 1. Single-ended mixer.

Single-balanced mixers are composed of two single-ended mixers (see Figure 2). Figure 3 shows two of the forms that SB mixers can take. The L-port balun balances the diodes and interfaces them with the unbalanced LO input. The most important characteristic about a balun is its ability to maintain phase angles with respect to ground, of ±90° at B, ∓90° at D, and 0° at C (if it has a center tap). When these angles are maintained, the balun is said to be well-balanced. Insertion loss, and output-to-input impedance ratios of baluns are also important. Many versions exist, some of which are discussed later.

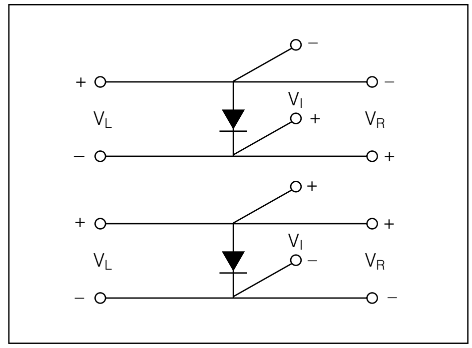

Figure 2. Single-balanced mixer is composed of two single-ended mixers

Single-balanced mixers have good L- to-I and L-to-R isolation due to the balance of the balun and diode match. If the i-v (current-voltage) curves match with each other, and the parasitic reactances of all the diodes match, the diodes form a voltage divider, causing a virtual ground to appear at the junction between D1 and D2 in Figure 3. A virtual ground is a node having a 0° phase angle with respect to ground. The effect of the virtual ground is to null out the LO voltage to keep it from appearing at the R- and I-ports, thus isolating the L-port from

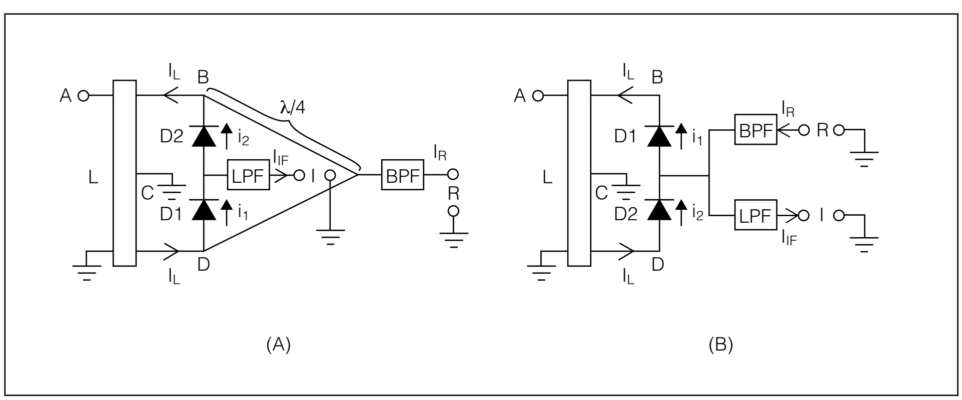

Figure 3. Two versions of a single-balanced mixer.

the R- and I-ports. This is a broadband means of causing isolation, because balun balance and diode match are inherently less susceptible to frequency change than are filters. Actual baluns are never perfectly balanced, and actual diodes are never perfectly matched, so a finite amount of LO power becomes incident at the R- and I-port filters.

RF current in Figure 3 flows from cathode to anode in D2. A forward biased diode can be modeled as a switch that is either open or closed: a closed switch allows current flow in both directions. If the RF current through D2 is much smaller than the LO current biasing it on, D2 will appear to the RF current as a closed switch. The small-signal RF current flowing in D2 cancels a small part of the large-signal LO current, shifting the average operating point of D2 to a lower voltage. Similarly, the RF current flowing in Dl adds to the LO current, causing the average operating point of D1 to have a higher voltage. This is illustrated in Figure 4. If the RF and LO amplitudes are different by less than about 10 dB, alternate cycles of the RF signal cause one diode to almost completely bias off, and the other diode to bias on even harder, causing the mixer to become unbalanced, degrading isolation and IM suppression. Conversion loss degrades as well because the IF and RF current paths have higher time-averaged impedances due to the diodes biasing off on alternate RF cycles. Also, the diodes are forced to operate in the very nonlinear region of their i-v curve, increasing the potential for two-tone IM products to appear, should a second RF signal be incident at the R-port. R-to-L isolation in SB mixers is caused by the RF currents from Dl and D2 canceling each other in the L-port balun. Recall that SB mixers also have good L-to-R isolation due to mixer balance. In general, such reciprocity (good L-to-R isolation and good R-to-L isolation) holds for interport isolation caused by mixer balance, but not necessarily for isolation resulting from filters, as R-to-I and I-to-R isolation is in SB mixers. Removal of the R-port filter degrades I-to-R isolation without affecting R-to-I isolation, because the I-port filter keeps RF current from exiting through the I-port.

Besides having better L-to-R and L-to-I isolation than SE mixers, SB mixers have better IM suppression. Half the possible IM products exiting the I-port are suppressed because those with even harmonics of the RF are cancelled due to circuit balance and diode match. Of course, cancellation is never perfect, so IM products with even harmonics of f_R do appear, but they are suppressed. Single-balanced mixers have twice as many diodes as SE mixers, so they require more LO power. More diodes allow SB mixers to have better IM suppression and isolation than SE mixers with the same amount of input RF power, because the RF voltage is dispersed across two diodes instead of one, thus causing half the deviation from average diode operating point than that of an SE mixer.

If the system requires suppression of IM products with even harmonics of f_R, high L-to-R and L-to-I isolation over a broad bandwidth, and non-overlapping R- and I-port bandwidths, an SB mixer is a better choice than an SE mixer. If the filter arrangements are simple, and the diodes are inexpensive, an SB mixer can be very cost effective.

Double-balanced mixers are composed of two SB mixers. Figures 5 and 6 show that combining two SB mixers results in either a ring or a star (cross) DB mixer, depending on which type of SB mixers are used. DB mixers are so termed because they use two baluns, whereas SB mixers use only one.

L-to-R and L-to-I isolation in DB mixers is achieved in the same way as it is in SB mixers, except that the R-port balun causes the LO-generated voltage appearing at the R-port to equal the difference between the small voltages appearing at junctions J_1 and J_2 in Figure 5. Ideally, these small LO-generated voltages are nulled out as virtual grounds, but nonidealities in balun balance and diode match allow them to appear. The LO-generated voltage appearing at the I-port is the sum of the small voltages at J_1 and J_2.

The I-port could be placed at the current return of the L-port balun instead of at the R-port balun (as shown in Figure 5), but L-to-I isolation would degrade. Diode match is not used to help isolate the L- and I-ports; the L-port is not balanced as well, due to the loss of its ground return; and the I-port is more susceptible to receiving LO power radiated from the L-port if the two are nearer to each other.

R-to-I isolation in DB mixers is caused by the balance of the R-port balun. In both ring and star DB mixers, the I-port is a virtual ground with respect to the R-port input voltage. This voltage nulling effect is mainly dependent on the balance of the R-port balun in ring mixers, whereas in star mixers, it may also depend on the diode match if the I-port is taken to be the junction of the four diodes (as in Figure 6) and

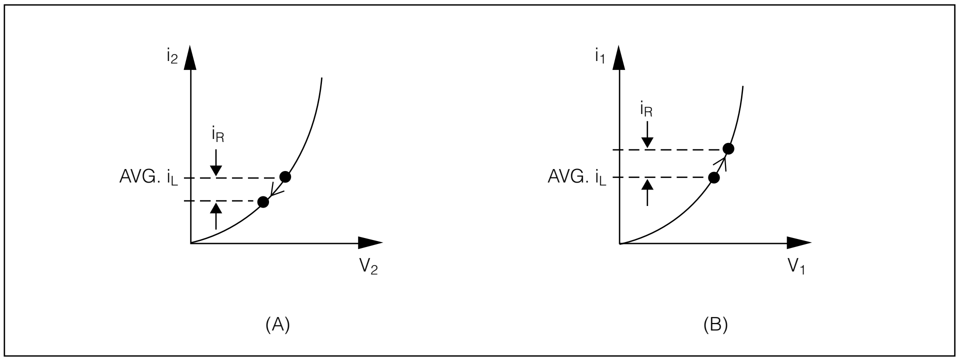

Figure 4. The average operating point of Dl (A) is slightly lowered and of D2 (B) is slightly raised by RF input curren i_R.

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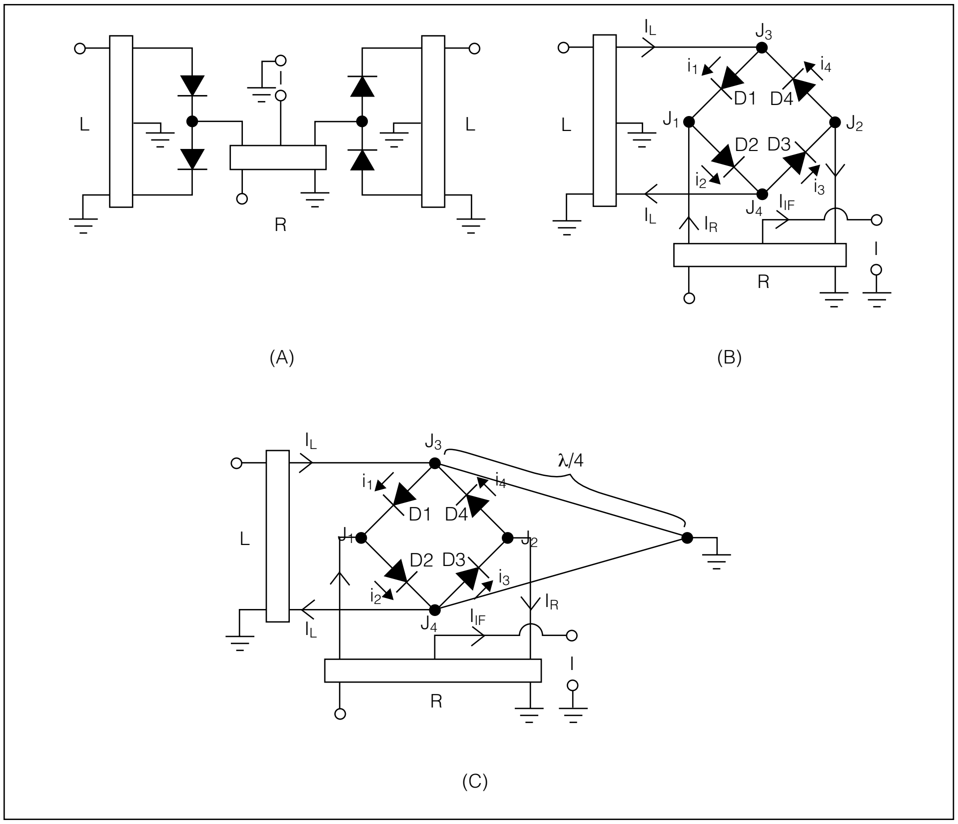

Figure 5. The two versions of a double-balanced mixer in (B) and (C) are formed in (A) by combining the two single-balanced mixers of Figure 3(B).

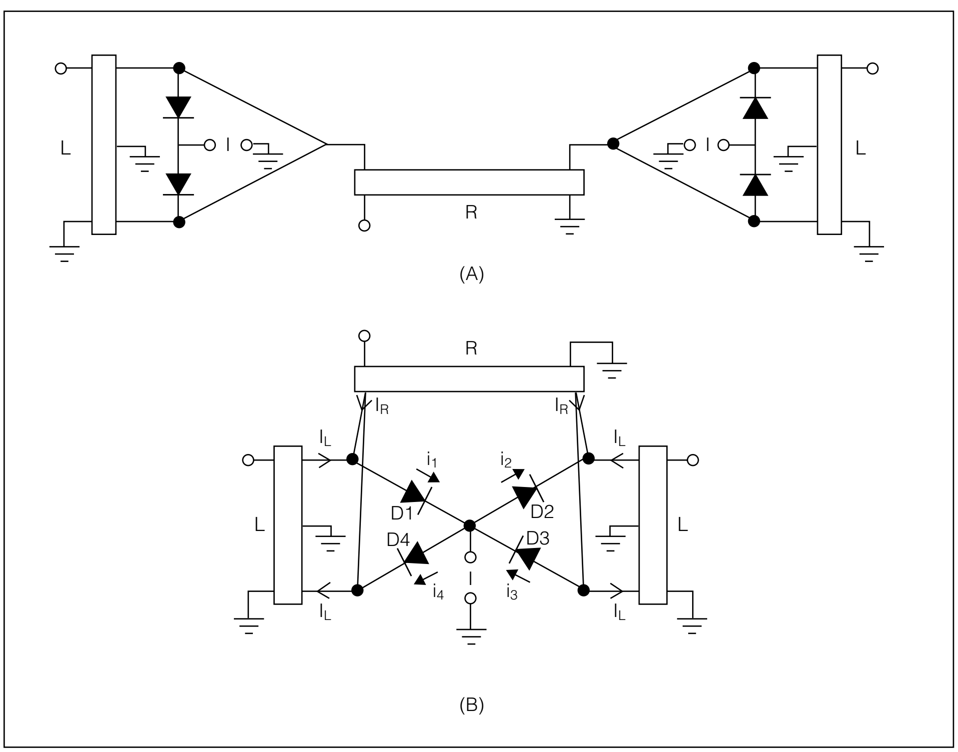

Figure 6. The star double-balanced mixer (B) is formed in (A) by combining the two single-balanced mixers of Figure 3(A).

not the center tap of the R-port balun.

Double-balanced mixers theoretically generate only one quarter of the possible IM products; these have odd f_R and odd f_L harmonies. The other IM products are suppressed, the degree of which is a function of balun balance and diode match. Even-by-even IM products which have even fR and even fL harmonics are usually suppressed more than even-by-odd, or odd-by-even products.

LO power for DB mixers is typically 3 dB higher than that for SB mixers because DB mixers use twice as many diodes as SB mixers. Hence, the 1-dB compression point of a DB mixer is higher than that of an SB mixer, causing correspondingly greater dynamic range and IM suppression.

Ring DB mixers using soft-dielectric (PTFE) [1] technology (as opposed to thin-film) are generally more popular than star DB mixers using the same technology, because the state-of-the-art with soft-dielectric mixers is to use a ring quad, which has four Schottky-barrier diodes arranged in a ring. Ring quads have four leads, each of which is bonded to one of the four junctions between diodes. DB star mixers with ring quads use two quads, utilizing only half of each, and, hence, are less cost effective than ring mixers, which fully utilize one quad. Ring quads are quite small, being typically 0.100 to .045 inches square or in diameter [2]. Quads are preferred over individual glass-encapsulated diodes because parasitics in the latter limit the maximum operating frequency to about 5 GHz, whereas ring quads have been successfully operated at frequencies up to 26 GHz, and show promise of going even higher in frequency. Individual beam-lead Schottky-barrier diodes do not have extreme parasitics, as do individual glass-encapsulated diodes.

For most applications, double-balanced mixers, which are the industry standard, are usually by far the best choice over SB and SE mixers. However, an understanding of SB and SE mixers is important because they are the building blocks of which DB mixers are composed. The superior performance of DB mixers over SB mixers almost always far outweighs the minimal increase in price for the two extra diodes and balun. DB mixers have superior IM suppression and dynamic range, as well as low VSWR, low conversion loss, and low noise figure. These characteristics have been achieved over multiple-octave bandwidths.

Ground return paths for RF and IF currents must be present in any mixer. The RF current return in DB mixers exists due to the time-averaged conductance of the diodes, which is mainly controlled by the LO, but also by the input RF if its power level is close to that of the LO. RF current in the mixers of Figure 5 splits: half of it passes through D2 and D3 and half passes through D1 and D4 to complete the RF circuit. The IF currents leave junctions J_3 and J_4 to return to ground through either the L-port balun center tap to ground as in Figure 5B, or through the quarter wave-length lines as in Figure 5C. IF ground return currents usually pass through the mixer case; increasing conversion loss by as much as 1 dB. Triple-balanced mixers, which have a balanced I-port, do not require IF currents to return to ground through the case, eliminating the effect of path losses through the case.

Triple-balanced mixers are so termed because the I-port, as well as the L-and R-ports are balanced as shown in Figure 7. Twice the number of diodes are present in TB mixers as in DB mixers, so more LO power is required, and the RF voltage is dispersed across twice as many diodes. These factors increase dynamic range and IM suppression. LO power required is typically in the +10 dBm to +13 dBm range for TB mixers with medium-barrier Schottky-barrier diodes, but some TB mixers can handle as much as +24 dBm of LO power, allowing for very high intercept points for both single- and two-tone IM products, much greater dynamic range, and good operation as upconverters because the mixer can handle more input power before compressing. This is significant because amplification is less expensive at the lower frequency before the signal is upconverted.

TB mixers are formed by combining two-star or two-ring DB mixers. A careful study of Figure 7 reveals that these two methods yield identical circuits, suggesting that a duality exists between ring and star DB mixers. They are, in fact, electrically identical.

Triple-balanced mixers usually offer greater dynamic range, better IM suppression and interport isolation, and broader I-port bandwidth than DB mixers. But, the disadvantages are the higher LO power requirement, and greater cost for the extra four diodes and the labor necessary to match eight diodes instead of only four.

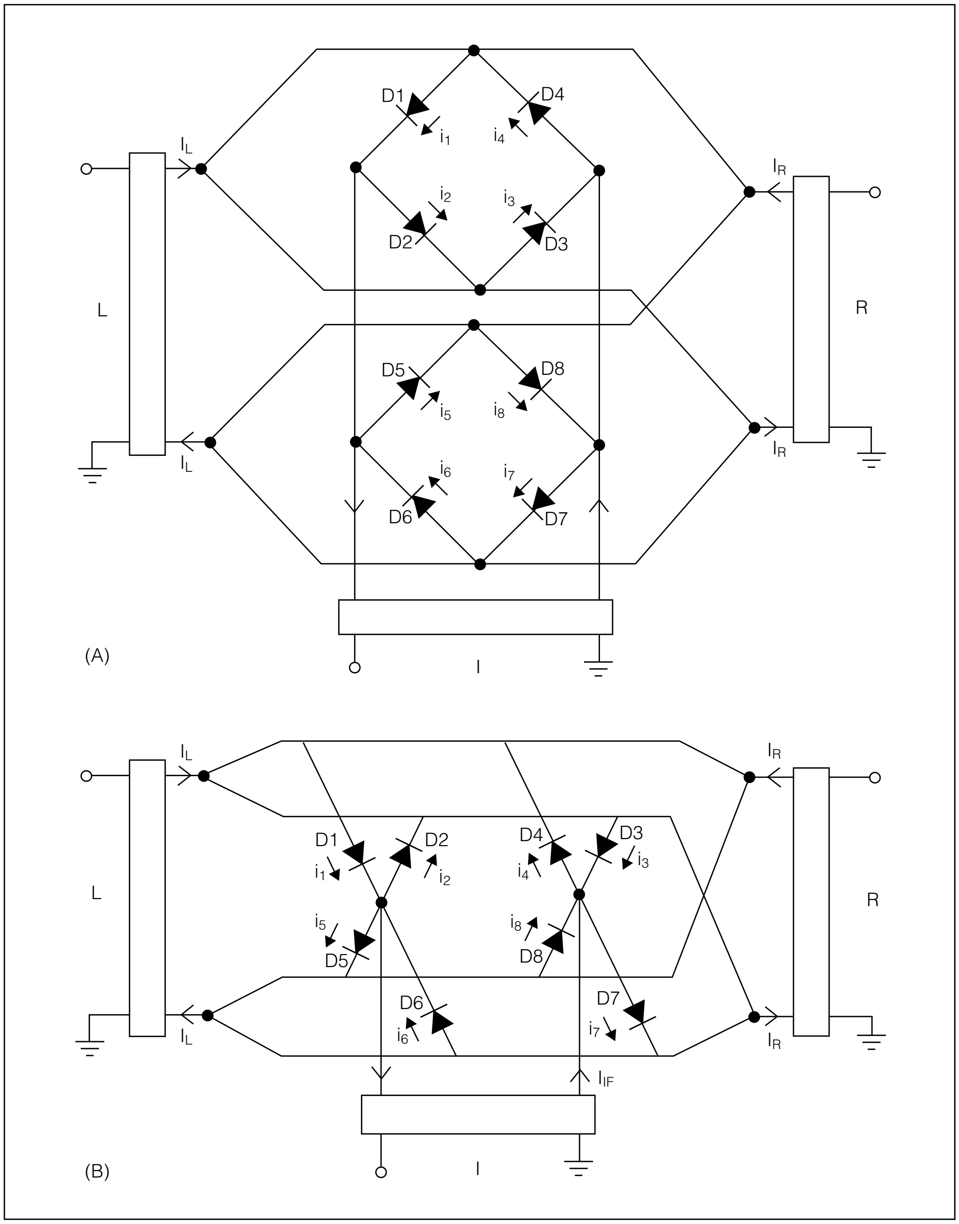

Figure 7. A DDB mixer is formed by combining two ring DB mixers (a) or two star DB mixers (B). (A) and (B) are the same circuit.

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Any of the three ports in SB, DB and TB mixers can be the R-, L- or I-port because these mixers are all composed of SE mixers, which have electrically identical L-, R- and I-ports (ignoring filters), which all appear in parallel across the SE diode.

Port selection is largely based on frequency requirements for f_I , f_R and f_L Essentially, port usage is that which optimizes system performance. This is why even though the R-, L- and I-ports may be designated for a given mixer, the system sometimes performs better with reversed R- and L-ports. Care must be taken, however, when reversing R- and L-ports because L-to-I isolation is typically better than R-to-I isolation in most DB mixers.

THE MIXING PROCESS

Mixing can only be caused by devices which have current-voltage relationships that are non-linear or that change as a function of time (time-variant), or both [4]. Switches are time-variant because they form either a short or an open circuit as a function of time. Mixers require very fast switching (at the LO frequency), making mechanical switches impractical. Schottky-barrier diodes are usually used in mixers as switches because of their low noise figure and fast switching speed [5]. Diodes are nonlinear, so both their time-variant and non-linear properties are used to cause mixing.

Because diodes are nonlinear, they cause two or more signals applied simultaneously across them to mix, producing single and multiple-tone IM products. Two voltages applied in series across a diode cause the current through it to contain the IF and higher-order IM products of the two voltage inputs. This is shown by expanding the exponential diode i-v relationship into a power series for a forward biased diode:

$$I_D \cong I_O\, e^{(V_L+V_R)/V_T}$$

$$= I_O \sum_{n=0}^{\infty} \frac{(V_L + V_R)^n}{V_T^n\, n!}$$

where:

V_L and V_R are sinusoidal.
I_O is the reverse bias saturation current.
V_T is the $(q/NKT)^{-1}$ term.
I_D is the diode current.

The n = 0 term yields a dc current. The n = 1 term yields the fundamentals.

The n = 2 term yields the second harmonics of f_L and f_R, plus the up- and down-converted IF products. The n = 3 term yields the fundamentals, the third harmonics of f_L and f_R, and the $2f_L \pm f_R$ and $\pm f_L + 2f_R$ intermodulation products. If all n terms were calculated, all the IF and higher-order intermodulation products would show up. Higher-order intermodulation products are caused by higher values of n, so they are severely attenuated by the term,

$$\frac{1}{n!}$$

This agrees with empirical observation, because higher-order IM products are suppressed more than lower-order ones are.

Besides being caused by nonlinear devices, mixing is caused by devices that are time-variant. Switches are time-variant because their two possible states, open or closed, change over time. Figures 8 and 9 illustrate how switching causes LO and RF signals to multiply each other to generate IF and intermodulation products.

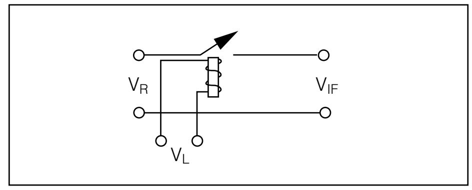

Figure 8. Series switch controlled by V_L gates V_R to produce V_{IF}.

When V_L is high, V_{IF} equals V_R, and when V_L is low, V_{IF} equals zero. The high and low states of V_L cause the switching waveform of the relay to, S_L, be one and zero, respectively. V_{IF} is the product of S_L and V_R: when V_L is high, $V_{IF} = (1) \cdot (V_R) = V_R$ and when V_L is low, $V_{IF} = (0) \cdot (V_R) = 0$. Since S_L is an odd square wave, it contains the odd harmonics of its base frequency, weighted by their individual Fourier coefficients. V_L and S_L have the same waveform, so their Fourier series are identical; however, their dimensions are different. All the harmonics of f_L in S_L multiply with V_R, generating intermodulation products containing odd harmonics of f_L as illustrated by the following trigonometric identity:

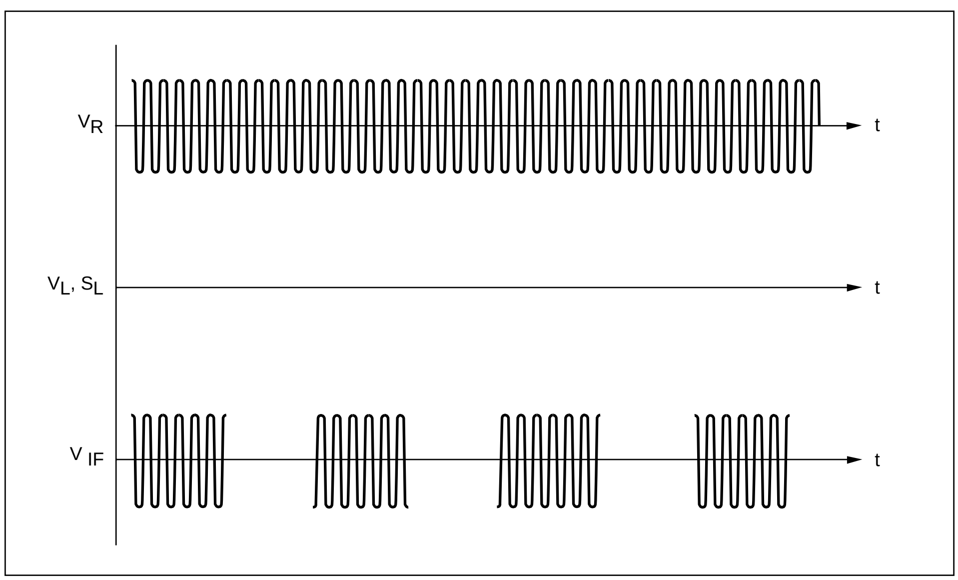

Figure 9. Waveforms Of V_R, V_L and V_{IF}.

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$\cos(n\omega_L t)\cos(\omega_R t) =$
$1/2\,[\cos(n\omega_L + \omega_R)t + \cos(n\omega_L - \omega_R)t]$

where,

$n = 1, 3, 5, 7, \ldots$

Figure 10 shows a simplified SE mixer, which is the basic building block in balanced mixers. It is identical to Figure 8 in that the large-signal V_L periodically switches the diode on and off to gate V_R, but different in that the diode passes through a very nonlinear conduction region between its fully-on and fully-off states. V_L, which controls diode conductance, G_L (analogous to S_L), causes current I_L to flow through the diode. I_L contains harmonics of f_L due to the diode nonlinearity. G_L equals I_L divided by V_L; hence, G_L also contains harmonics of f_L. These harmonics are especially prevalent in G_L if the level of V_L is high enough to make the diode clip, causing I_L to approximate a squarewave. V_R, being a small signal, does not cause the diode to clip; hence, IM products, $\pm mf_R \pm f_L$ are usually suppressed more than $\pm f_R \pm nf_L$ where m and n are integers. V_R causes current I_R to flow through the diode. I_R contains harmonics of f_R because of diode nonlinearity, and generates V_R across the diode series bulk and dynamic resistance. Since I_R contains harmonics of f_R, V_R does also. V_R and G_L are each expanded into a Fourier series to represent their respective harmonic content, as in equations 2 and 3. Multiplying the two expansions produces a double Fourier series expansion for I_{IF}, as shown in equation 4, that contains all the IM products generated when f_L mixes with f_R [6].

$$G_L = \sum_{n=-\infty}^{\infty} g_n e^{jn\omega_L t} \qquad (2)$$

$$V_{R'} = \sum_{m=-\infty}^{\infty} v_m e^{jn\omega_R t} \qquad (3)$$

$$I_{IF} = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} g_n v_m e^{j(\pm n\omega_R \pm n\omega_R)t} \qquad (9)$$

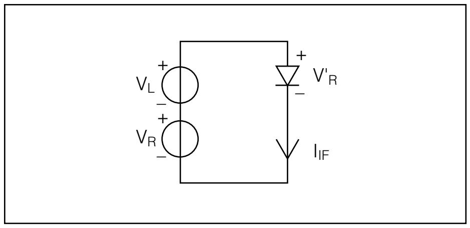

Figure 10. Simplified single-ended mixer.

IF power, which is transferred from the mixer to the IF load by current I_{IF} , contains these IM products. Multiple-tone IM products result when two or more input RF signals mix with the LO to produce the following frequencies.

$$f_{IM} = (\pm\, m_1 f_{R_1} \pm m_2 f_{R_2} \pm \ldots) \pm n\, f_L$$

Coefficients m and n are integers and can assume any value. The IM products, f_{IM}, are generated by two means: diode nonlinearity acting alone, and acting together with the diode switching property to remix products reflected back into the mixer. The multiple-tone IM products of most interest are the two-tone third-order products, f_{IM}, which are generated by two products, f_{IM_1} and f_{IM_2}. These are generated by the n = 4 and n = 6 (as well as higher-order) terms of the power series expansion for diode current [7]

$$f_{IM_1} = (\pm 2f_{R_1} \pm f_{R_2}) \pm f_L$$
$$f_{IM_2} = (\pm f_{R_1} \pm 2f_{R_2}) \pm f_L$$

Two-tone third-order IM products are also generated when the following IM products reflect back into the mixer to remix. This effect can change the intercept point by as much as 3 dB or so.

Single-Tone

$$f = \pm 2f_{R_{1,2}} \pm f_L$$
$$f = \pm f_{R_{1,2}} \pm 2f_{R_{2,1}}$$

Two-Tone

$$f = \pm f_{R_1} \pm f_{R_2} \pm f_L$$

This method of generating multiple-tone IM products requires poor mismatch at the mixer ports, so its effect can be minimized by properly matching the ports. Operating the diodes in the more linear part of their current-voltage curve by applying relatively high LO power and low input RF power will minimize multiple-tone IM products generated by diode nonlinearity. High-level mixers of the Class-2 and Class-3 variety require more LO power than Class-1 mixers, thus allowing for increased IM suppression.

CLASSES OF MIXERS

Various classes of mixers have been defined that require increased LO power levels and have superior IM suppression [8]. A normal DB mixer which has a single diode in each leg of the ring is a Class-1 mixer. Class-2, type-l mixers have a second series diode in each leg of the ring, for a total of eight diodes. This type of ring is now available in a small package, similar to ring quads, and is called an octal. Class-2, type-2 mixers have an added series resistor in each leg. Class-3, type-l mixers have a series diode in series with a shunt RC combination in each leg of the ring. Class-3, type-2 and type-3 mixers are identical to Class 3, type-1 mixers except that they have two series diodes or two shunt diodes, respectively, in place of the single diode in the type-1 mixer. These classes are outlined in Table 1. Class-4 mixers have a network of hybrids that drive two sets of diodes, and two resistors that absorb certain IM products [9]. Adding more elements to the ring allows more input RF power to be applied to the mixer before the average operating points of the diodes in adjacent legs change enough to significantly unbalance the mixer, and also enter the more nonlinear region of the diode i-v curve. Such unbalancing degrades cancellation of IM products with even f_L or f_R harmonics. IM products with odd f_R and odd f_L harmonics theoretically are not affected by mixer balance. When unbalancing occurs, conversion loss increases because power that would otherwise help generate IF products, instead partially contributes to help generate the IM products that begin to appear. This, combined with the higher time averaged imped-

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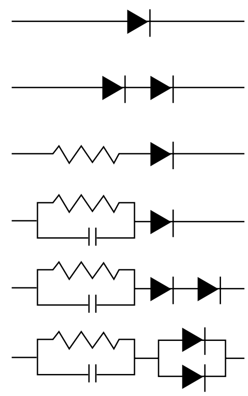
ance in the IF and RF current paths, and generation of heat, cause conversion compression as input RF power increases.

Class-2 mixers have better IM suppression than Class-1 mixers because input RF voltage is dispersed across twice as many elements. Class-3 mixers, in turn, have better IM suppression than Class-2 mixers because the shunt RC combination self-biases the diode by charging up during the positive LO cycle and discharging slowly enough to keep input RF power from dominating the operating point when LO voltage goes through its zero crossing. Conversion-loss in Class-3 mixers does not significantly increase due to the extra RC combination because the capacitor skirts RF current around the resistor.



MIXER CLASS	CIRCUIT	LO POWER FOR DB MIXERS (dBm)
Class 1		+7 to +13
Class 2, Type 1		+13 to +24
Class 2, Type 2		+13 to +24
Class 3, Type 1		+20 to +30
Class 3, Type 2		+20 to +30
Class 3, Type 3		+20 to +30

Table 1. The various classes of mixers with their approximate LO power ranges.

BALUNS

Balanced mixers are composed of baluns and diodes. The balun balances the diodes and interfaces them with the unbalanced system. It also matches system and diode impedance, and helps provide interport isolation. If the balun is at the L-port, it must provide the IF current return path to ground. Currents in the two balanced leads of a balun are 180° apart in phase and -90° and + 90° out of phase with respect to ground.

Baluns are also used for applications other than mixers; in fact, many baluns used in mixers were borrowed from antenna applications [10]. Much has been written about baluns, and many clever versions have been developed [11], [12]. Mixers can be constructed using any type of balun, but certain ones are consistently used in most mixer designs. Most balun circuits can be realized using various technologies such as: waveguide, thin-film and soft dielectric MIC (microwave integrated circuit), coaxial cable, or bifilar and core. These technologies are generally associated with specific frequency ranges [13]. Generally, MIC and waveguide baluns are used in the 0.5- to 100-GHz frequency range, coaxial and bifilar baluns are used in the dc to 8-GHz frequency range, and bifilar-core baluns are used in the dc to 4-GHz frequency range. Figure 11 shows a center-tapped transformer which is used in virtually all dc to 4-GHz balanced mixers. Broadband transformers of this type, having very good balance and various impedance ratios, are realized using bi-, tri- and quad-filar transmission lines wrapped around various shapes and types of ferrite cores [14]. The centertap-to-ground allows for good balance over a fairly broad bandwidth. The frequency dependence of the core permeability limits the bandwidth over which the balun is well balanced because electrical lengths of the windings change as frequency changes, causing a corresponding change in phase. Conversion loss in mixers using these baluns is typically 6.5 dB to 8 dB. Figure 11 is also used to represent baluns, as depicted in most mixer schematics, even though they may be realized completely differently than this figure suggests.

The balun in Figure 12, using a transmission line and quarter-wave line to ground, has been realized using thin film technology in the so-called coplanar balun of many microwave mixers. When L is a quarter wavelength long, points B and D are ±90° and ∓90°, respectively, out of phase with respect to ground. A fairly broadband balun can be realized by adjusting the lengths of L and the quarter-wave line so that they are a quarter-wave long at different frequencies. The impedance ratio of this balun is 1:1. When this balun is used on the L-port of a DB mixer, the quarter-wave line to ground provides the ground return path for the IF current.

Another version using transmission lines is shown in Figure 13. Node C is used as the

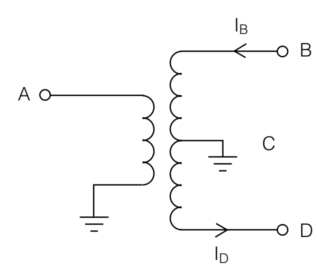


Figure 11. Transformer with a grounded center tap is a balun.

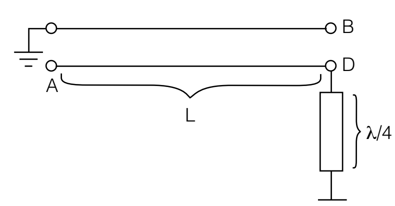


Figure 12. Transmission line with quarterwave line to ground is a balun.

I-port in mixers using this balun.

Figure 14 shows another transmission line balun that uses a shorting transformer (I_1 and I_2) to provide the ground return path for IF current. This balun is usually realized using two lengths of bifilar: one for L, and one for L_1 and L_2. I_B and I_D do not short to ground through L_1 and L_2 because I_B and I_D force equal currents through L_1 and L_2 that oppose each other if L_1 and L_2 are long, compared to the wavelength in use. When L_1 and L_2 are too short, I_B and I_D do short to ground; this limits the low frequency end of the balun bandwidth. The high frequency limit is determined by the series inductance of bifilar L.

DIODES

Almost all mixers currently available use Schottky-barrier diodes to cause mixing. Other devices, such as transistors and FETs, have been used in active mixers [15], [16] that provide conversion gain and high intercept point. Schottky-barrier diodes are relatively inexpensive, have low NF, and can be operated up to millimeter-wave frequencies [3], [5]. They usually require no dc power supply for normal operation because LO power is sufficient to switch them on and off.

The forward-biased properties of Schottky-barrier diodes are controlled by majority carriers, so these diodes can be switched quickly because minority carrier storage effects are not present. When the forward voltage drops to zero, the current stops almost instantly, and the reverse voltage can be established in a few picoseconds [2], [5].

Schottky-barrier quads are made by bonding four diodes arranged in a ring onto a. ceramic, fiberglass, or plastic substrate. A monolithic ring quad is preferred over one with individual diodes because the diodes in the monolithic quad match each other and track together over temperature much better than individual diodes. Rings with eight (octal) and twelve (duo-decca) diodes have recently become available for high-level mixer applications.

GaAs Schottky-barrier diodes typically have cutoff frequencies in the 400- to 1000-GHz frequency range, whereas silicon diodes cutoff in the 80- to 200-GHz frequency range. GaAs diodes have higher forward voltage, V_f, resulting in a higher LO power requirement. They are more expensive than silicon diodes and have higher flicker noise. V_f for GaAs diodes with 1 mA of series current is typically .70 volts, compared to .30 volts for a medium-barrier silicon diode.

In order to optimize the noise figure of Schottky-barrier diodes, the following LO power levels should be applied per diode [5]:

Barrier	LO Power Per Diode
High	+3 dBm or more
Medium	-3 dBm to +3 dBm
Low	-3 dBm or less

ANALYSIS OF INTERMODULATION PRODUCTS

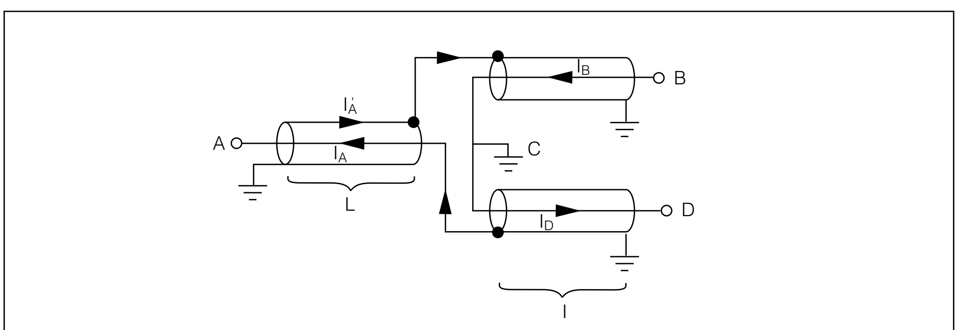


Figure 13. Transmission line balun.

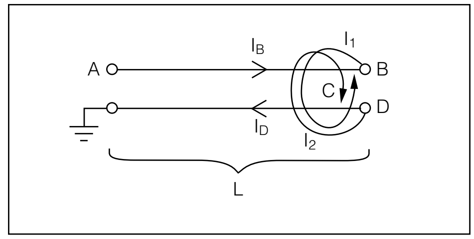


Figure 14. Shorting transformer balun.

The IM products present in the IF output of an SE mixer are derived by using Equation (4). When SE mixers are combined to form a balanced mixer, some of these IM products are eliminated through cancellation. This is illustrated in the following analyses for SE, DE, and TE mixers. The analysis procedure used assumes diode conductance G_L is influenced exclusively by harmonics of large-signal V_L; because V_R is a small-signal voltage, its effect on diode conductance can be ignored. It also assumes the diodes are identical, and the baluns are perfectly balanced. Diode currents i_1 and i_2 in the SE mixer of Figure 3A combine to give IF current, I_{IF}.

$$i_1 = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} v_m g_n e^{j(\pm n \omega_L \pm m \omega_R)t} = K$$

$$I_2 = K e^{\pm jm\pi} = K(-1)^m$$

$$I_{IF} = i_1 - i_2 = K[1-(-1)^m]$$

The $e^{\pm jm\pi}$ term in i_2, which equals $(-1)^m$, is present because I_R opposes i_2. K represents the double Fourier series, the coefficients of which give the relative amplitudes of the IM products. Since the goal is to determine which IM products exit the I-port and not their relative amplitudes, the double Fourier series is dropped. This allows for quick determination of which IM products will exit the I-port of a given mixer circuit, because the cumbersome Fourier series expansions need not be written.

When m is even (m = 0, 2, 4,...) $I_{IF} = 0$; when m is odd (m = 1, 3, 5,...) $I_{IF} \neq 0$, showing that IM products containing even harmonics of f_R are suppressed in SB mixers and that all others exit the I-port.

Analysis of the ring DB mixer in Figure 5 is

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similar. Diode currents i_1, i_2, i_3 and i_4 combine to produce IF current, I_{IF}. Current i_1 has the $(-1)^m$ term because it opposes I_R; i_3 opposes I_L, and i_4 opposes both I_L and I_R.

$$i_l = K(-1)^m$$
$$i_2 = K$$
$$i_3 = K(-1)^n$$
$$i_4 = K(-1)^{n+m}$$

$$I_{IF} = i_1 - i_2 + i_3 - i_4$$
$$= K[(-1)^m - 1 + (-1)^n - (-1)^{n+m}]$$
$$= K[(-1)^n - 1]\,[1 - (-1)^m]$$

$I_{IF} = 0$ if either n or m are even, so only the IM products with odd f_L and odd f_R harmonics exit the I-port.

The star DB mixer in Figure 6 has the same IF output as the ring DB mixer just analyzed. Its IF output current is calculated as follows:

$$I_{IF} = i_1 - i_2 + i_3 - i_4 = K[(-1)^n -1]\,[(-1)^m -1]$$

Again, the odd-by-odd IM products are the only ones exiting the I-port.

The two TB mixers in Figure 7 are identical circuits. An analysis of both versions shows that only the odd-by-odd IM products exit the I-port.

$$I_{IF} = i_1 - i_2 + i_6 - i_5 = i_7 - i_8 + i_4 - i_3$$
$$= K[(-1)^n -1]\,[(-1)^m -1]$$

Knowledge of which IM products exit the R- and L-ports is often required. Current leaving the R-port of the ring DB mixer in Figure 5 is Irout:

$$I_{Rout} = i_l - i_2 = K[(-1)^m -1]$$

IM products with odd f_R and even f_L harmonics exit the R-port. Current $I_{L_{out}}$ contains the IM products exiting the L-port:

$$I_{Lout} = i_4 - i_1 = K\,(-1)^m[(-1)^n -1]$$

IM products with even f_R and odd f_L harmonics exit the L-port. A similar analysis of currents leaving the R- and L-ports of the TB mixer of Figure 7 shows that the odd fR by even f_L IM products exit the R-port; the even f_R by odd f_L IM products exit the L-port. R- and L-ports must be well-matched to the system in order to keep these products from reflecting back into the mixer to remix and produce further IM products. Attenuators on the mixer ports enhance matching by attenuating unwanted products, thus lessening their effects on adjacent system components.

Harmonic mixers, as shown in Figure 15, use the second harmonic of the LO to generate the desired IF signal.

$$I_{IF} = -i_1 + i_2 - i_3 + i_4$$
$$= K\,[-(-1)^m + 1 - (-1)^{n+m} + (-1)^n]$$
$$= K\,[1 - (-1)^m]\,[1 + (-1)^n]$$

IF output occurs for IM products having

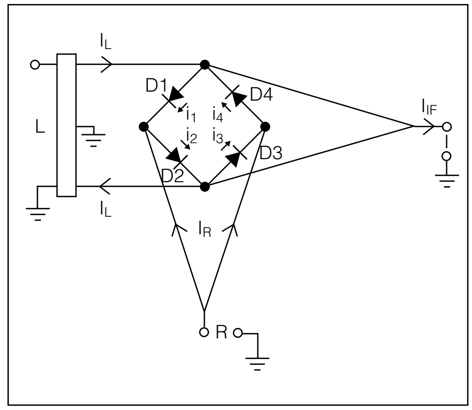

Figure 15. Harmonic mixer.

odd f_R and even f_L harmonics, which include the desired $\pm 2f_L \pm f_R$ products. Harmonic mixing allows the LO to operate with half the normally required frequency. These mixers have higher conversion loss and a more unstable IF output because frequency drift in the LO is doubled.

CONCLUSION

This Tech-notes series has presented the basics of mixer characteristics, performance, theory, and technology: Part 1 discussed SSB conversion loss, VSWR, isolation, dynamic range, IM products, intercept point and SSB noise figure. Part 2 discussed mixer circuits, the mixing process, classes of mixers, baluns, diodes and one example of how baluns and diodes are combined to form a mixer. This foundational material should pro-vide a good basis for the understanding of mixers.

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