

Mixers and Modulators

MIXER AND MODULATOR OVERVIEW

An idealized mixer is shown in Figure 1. An RF (or IF) mixer (not to be confused with video and audio mixers) is an active or passive device that converts a signal from one frequency to another. It can either modulate or demodulate a signal. It has three signal connections, which are called *ports* in the language of radio engineers. These three ports are the radio frequency (RF) input, the local oscillator (LO) input, and the intermediate frequency (IF) output.

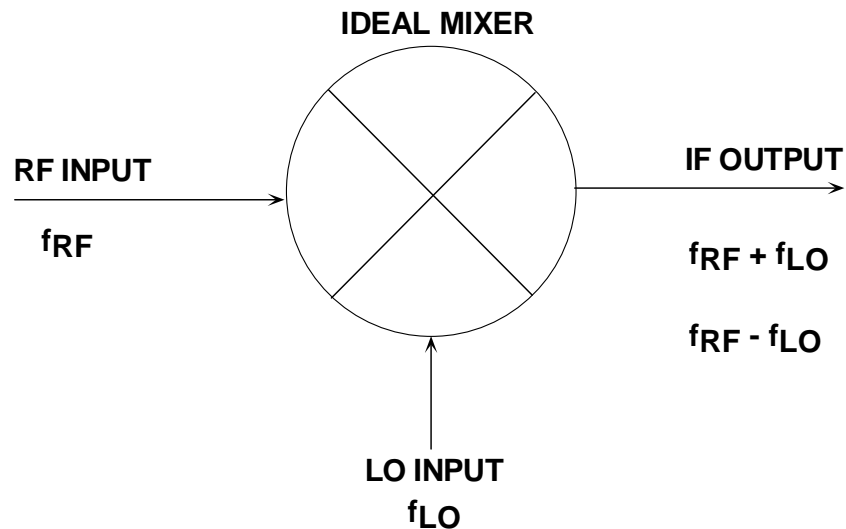


Figure 1: The Mixing Process

A mixer takes an RF input signal at a frequency f_{RF} , mixes it with a LO signal at a frequency f_{LO} , and produces an IF output signal that consists of the sum and difference frequencies, $f_{RF} \pm f_{LO}$. The user provides a bandpass filter that follows the mixer and selects the sum ($f_{RF} + f_{LO}$) or difference ($f_{RF} - f_{LO}$) frequency.

Some points to note about mixers and their terminology:

- When the sum frequency is used as the IF, the mixer is called an *upconverter*; when the difference is used, the mixer is called a *downconverter*. The former is often used in a transmit channel, the latter in a receive channel.
- In a receiver, when the LO frequency is below the RF, it is called *low-side injection* and the mixer a *low-side downconverter*; when the LO is above the RF, it is called *high-side injection*, and the mixer a *high-side downconverter*.

- Each of the outputs is only half the amplitude (one-quarter the power) of the individual inputs; thus, there is a loss of 6 dB in this ideal linear mixer. (In a practical multiplier, the conversion loss may be greater than 6 dB, depending on the scaling parameters of the device. Here, we assume a *mathematical* multiplier, having no dimensional attributes.

A mixer can be implemented in several ways, using active or passive techniques.

A brief review of the various classes of nonlinear elements that can be used for frequency translation may be helpful in setting the context. We can identify three subclasses of circuits, sharing certain similarities. All are in the class of signal multipliers, producing at their output a signal which is, in one way or another, the product of its two inputs. They are *multipliers*, *modulators*, and *mixers*.

An *analog multiplier* generally has two signal input ports, which can be called X and Y, and generates an output W that is the linear product of the voltages applied to these two ports. To retain dimensional consistency, the analog linear multiplication function must invoke the use of a reference voltage, which we can call U, thus $W=XY/U$. In some cases, U is actually a third input that can be used to implement analog division.

There are three functional categories of multipliers: In *single-quadrant* multipliers, X and Y must be unipolar; in *two-quadrant* multipliers, one of the inputs may be bipolar; in *four-quadrant* multipliers, both X and Y may be bipolar. Analog Devices produces a wide range of "linear" multipliers, including the [AD534](#), [AD538](#), [AD539](#), [AD633](#), [AD734](#), [AD834](#) and [AD835](#), providing the highest available accuracy ($\pm 0.02\%$ for the AD734) to the highest speed (more than 500 MHz for the AD834).

Modulators (sometimes called *balanced-modulators*, *doubly-balanced modulators* or even on occasions *high level mixers*) can be viewed as *sign-changers*. The two inputs, X and Y, generate an output W, which is simply one of these inputs (say, Y) multiplied by just the sign of the other (say, X), that is $W = Y\text{sign}(X)$. Therefore, no reference voltage is required. A good modulator exhibits very high linearity in its signal path, with precisely equal gain for positive and negative values of Y, and precisely equal gain for positive and negative values of X. Ideally, the amplitude of the X input needed to fully switch the output sign is very small, that is, the X-input exhibits a comparator-like behavior. In some cases, where this input may be a logic signal, a simpler X-channel can be used. A highly-linear mixer such as the [AD831](#) is well-suited as a modulator.

A *mixer* is a modulator optimized for frequency-translation. Its place in the signal path is usually close to the antenna, where both the wanted and (often large) unwanted signals coexist at its signal input, usually called the *RF port*. Thus, the mixer must exhibit excellent linearity in the sense that its output (at the IF port) is expected to increase by the same number of dB as a test signal applied to the RF port, up to as high as level as possible. This attribute is defined both by the 1 dB gain-compression and the 3rd-order intercept. The conversion process is driven by an input applied to the LO port.

Noise and matching characteristics are crucial to achieving acceptable levels of performance in a receiver's mixer. It is desirable to keep the LO power to a minimum to minimize cross-talk between the three ports, but this often conflicts with other requirements. The gain from the RF port to its IF port at specified RF and LO frequencies is called the *conversion gain* and in classical diode-bridge mixers is less than -4 dB. *Active mixers* provide higher conversion gain, and better port-port isolation, but often at the expense of noise and linearity. It is not usually possible (nor even desirable) to describe mixer behavior using equations relating the instantaneous values of inputs and outputs; instead, we generally seek to characterize mixers in terms of their non-ideal cross-product terms at the output.

Thus far, we have seen that multipliers are linear in their response to the instantaneous value of both of their input voltages; modulators are linear in their response to one input, the other merely flipping the sign of this signal at regular intervals, with virtually zero transition time, and beyond that having ideally no other effect on the signal; mixers are a sort of RF half-breed, ideally being very linear on the RF input, and 'binary' in their switching function in response to the LO input, but in reality being non-ideal in both respects; they are optimized for very low noise and minimal intermodulation distortion.

MIXING USING AN IDEAL ANALOG MULTIPLIER

Figure 2 shows a greatly simplified RF mixer by assuming the use of an analog multiplier.

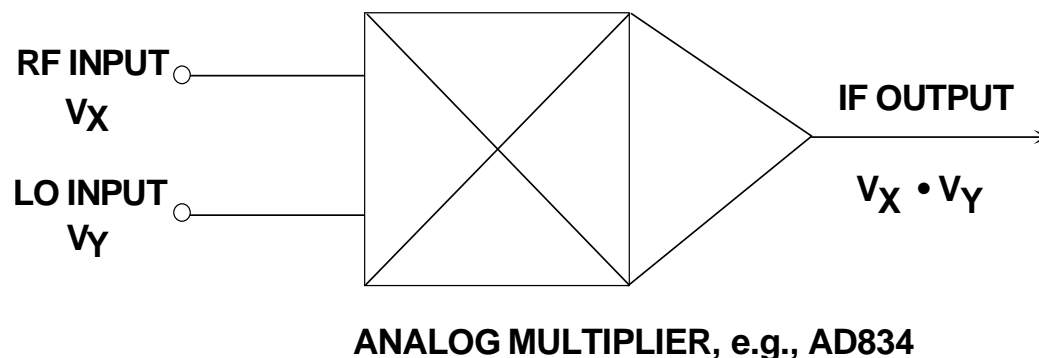


Figure 2: Mixing Using an Analog Multiplier

Ideally, the multiplier has no noise, no limit to the maximum signal amplitude, and no intermodulation between the various RF signals (that is, no spurious nonlinearities). Figure 3 shows the result of *mixing* (= multiplying) an RF input of $\sin\omega_{RF}t$ with (= by) a LO input of $\sin\omega_{LO}t$, where $\omega_{RF} = 2\pi \times 11\text{MHz}$ and $\omega_{LO} = 2\pi \times 10\text{MHz}$.

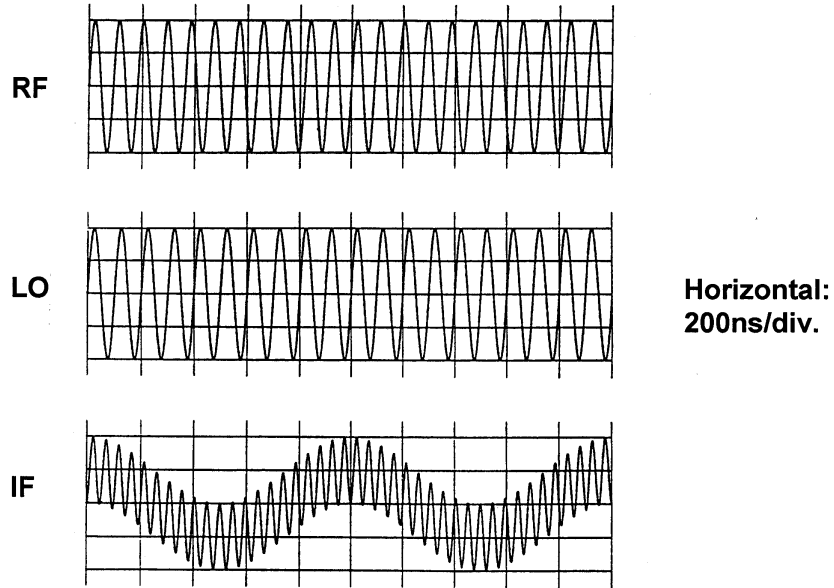


Figure 3: Inputs and Output for Multiplying Mixer for $f_{RF} = 11\text{MHz}$, $f_{LO} = 10\text{MHz}$

Clearly, to better understand mixer behavior, we will need to consider not only the time-domain waveforms, as shown here, but also the spectrum of the IF output. Figure 4 shows the output spectrum corresponding to the above IF waveform.

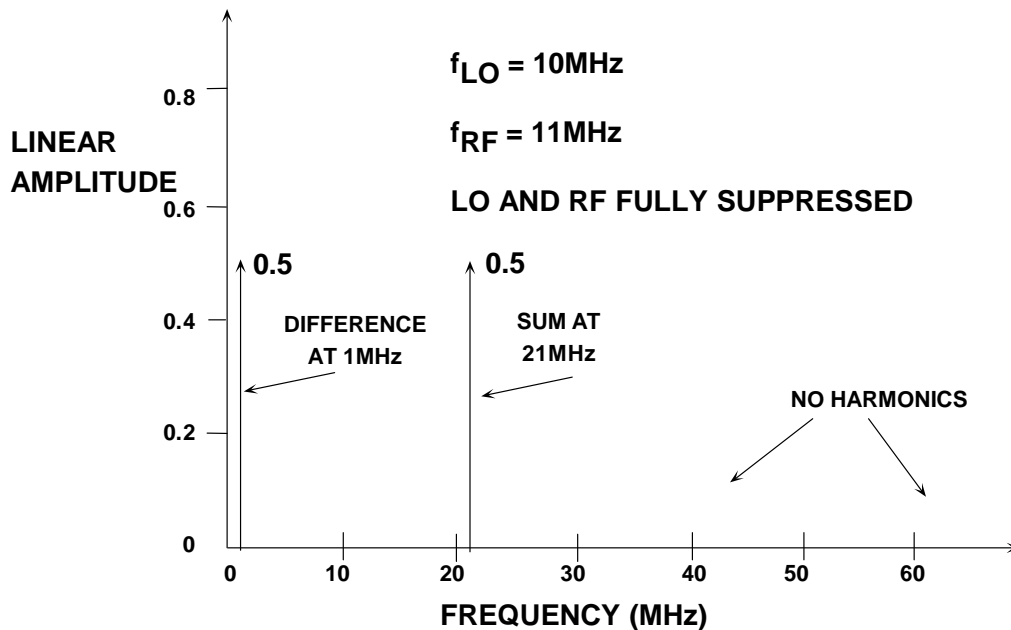


Figure 4: Output Spectrum for Multiplying Mixer for $f_{RF} = 11\text{MHz}$, $f_{LO} = 10\text{MHz}$

Neglecting scaling issues (real signals are voltages; thus a practical multiplier needs an embedded voltage reference, ignored here) the relationship is:

$$\sin\omega_{RF}t \sin\omega_{LO}t = 1/2 \{ \cos(\omega_{RF} + \omega_{LO})t + \cos(\omega_{RF} - \omega_{LO})t \} \quad \text{Eq. 1}$$

The multiplier has thus transformed the RF input into two, equal-amplitude cosinusoidal components at its output (the IF port), one at the sum frequency, $\omega_{RF} + \omega_{LO}$, and the other at the difference frequency, $\omega_{RF} - \omega_{LO}$. In practice, an analog multiplier would be a poor choice for a mixer because the two linear inputs bring with them a serious noise penalty.

IMAGE RESPONSE

A receiver using even this mathematically perfect mixer suffers a basic problem, that of *image response*. Consider the use of a low-side downconverter. The wanted output is found at the frequency $\omega_{IF} = \omega_{RF} - \omega_{LO}$. So we might suppose that the only component of the RF spectrum that finds its way through the mixer “sieve” to the narrow IF passband is the wanted component at ω_{RF} . But we could have just as easily written Eq. 1 as

$$\sin\omega_{RF}t \sin\omega_{LO}t = 1/2 \{ \cos(\omega_{RF} + \omega_{LO})t + \cos(\omega_{LO} - \omega_{RF})t \} \quad \text{Eq. 1a}$$

because the cosine function is symmetric about $t = 0$. So there is another spectral component at the RF input that falls in the IF passband, namely the one for which $\omega_{IF} = \omega_{LO} - \omega_{RF}$, in this case, the *image* frequency.

Consider the above example, where $f_{LO} = 10$ MHz and $f_{IF} = 1$ MHz; the wanted response is at the IF frequency, $f_{IF} = 1$ MHz for $f_{RF} = 11$ MHz. However, the mixer produces the same IF in response to the *image frequency*, $f_{IMAGE} = 9$ MHz (see Figure 5).

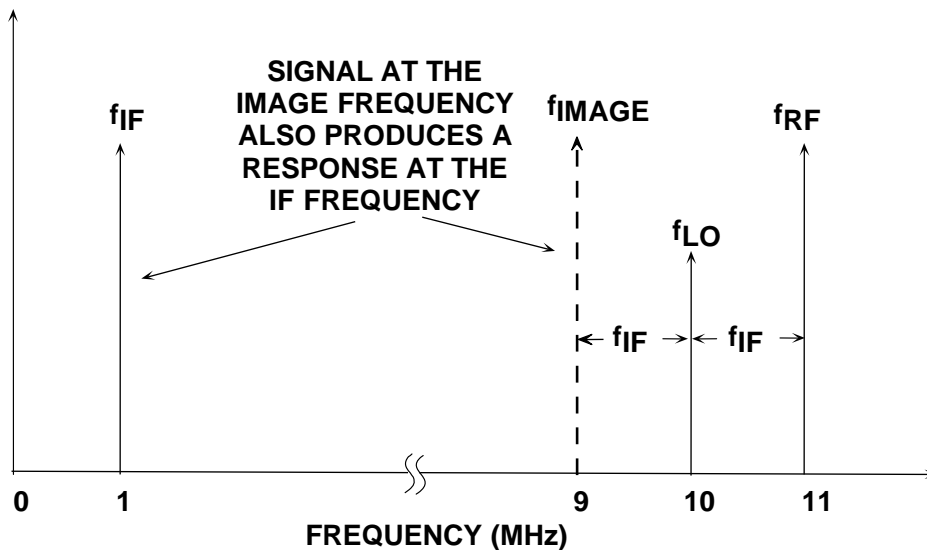


Figure 5: Image Response

The most practical solution to this dilemma is to carefully choose the IF frequency to minimize the likelihood of image sensitivity and also include an image-reject filter at the RF input, just ahead of the mixer. Another approach is to use a special type of mixer circuit that does not respond to the image frequency. This approach requires circuitry which is considerably more complex, and for this reason has generally been unpopular, but it is becoming more practical in a modern IC implementation. It has the further disadvantage of higher power consumption, since two mixer cells operating in quadrature are required.

THE IDEAL MIXER

Ideally, to meet the low-noise, high-linearity objectives of a mixer we need some circuit that implements a polarity-switching function in response to the LO input. Thus, the mixer can be reduced to Figure 6, which shows the RF signal being split into in-phase (0°) and anti-phase (180°) components; a changeover switch, driven by the local oscillator (LO) signal, alternately selects the in-phase and antiphase signals. Thus reduced to essentials, the ideal mixer can be modeled as a sign-switcher.

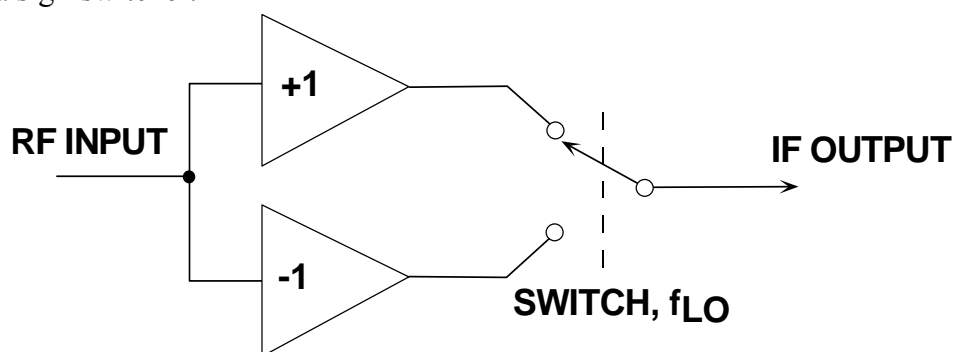


Figure 6: An Ideal Switching Mixer

In a perfect embodiment, this mixer would have no noise (the switch would have zero resistance), no limit to the maximum signal amplitude, and would develop no intermodulation between the various RF signals. Although simple in concept, the waveform at the intermediate frequency (IF) output can be very complex for even a small number of signals in the input spectrum. Figure 7 shows the result of *mixing* just a single input at 11 MHz with an LO of 10 MHz.

The *wanted* IF at the difference frequency of 1 MHz is still visible in this waveform, and the 21 MHz sum is also apparent. But the spectrum of this waveform is clearly more complex than that obtained using the analog multiplier. How are we to analyze this?

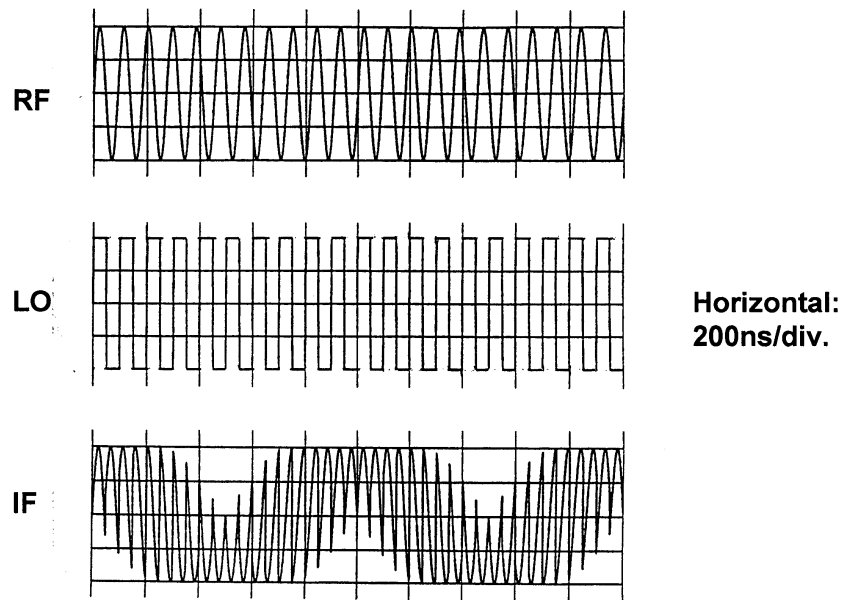


Figure 7: Inputs and Output for Ideal Switching Mixer for $f_{RF} = 11\text{MHz}$, $f_{LO} = 10\text{MHz}$

We still have a product, but now it is that of a sinusoid (the RF input) at ω_{RF} and a variable that can only have the values +1 or -1, that is, a unit square wave at ω_{LO} . The latter can be expressed as a Fourier series

$$S_{LO} = \frac{4}{\pi} \{ \sin\omega_{LO}t - \frac{1}{3} \sin 3\omega_{LO}t + \frac{1}{5} \sin 5\omega_{LO}t - \dots \} \quad \text{Eq. 2}$$

Thus, the output of the switching mixer is its RF input, which we can simplify as $\sin\omega_{RF}t$, multiplied by the above expansion for the square wave, producing

$$S_{IF} = \frac{4}{\pi} \{ \sin\omega_{RF}t \sin\omega_{LO}t - \frac{1}{3} \sin\omega_{RF}t \sin 3\omega_{LO}t + \frac{1}{5} \sin\omega_{RF}t \sin 5\omega_{LO}t - \dots \} \quad \text{Eq. 3}$$

Now expanding each of the products, we obtain

$$S_{IF} = \frac{2}{\pi} \{ \sin(\omega_{RF} + \omega_{LO})t + \sin(\omega_{RF} - \omega_{LO})t - \frac{1}{3} \sin(\omega_{RF} + 3\omega_{LO})t - \frac{1}{3} \sin(\omega_{RF} - 3\omega_{LO})t + \frac{1}{5} \sin(\omega_{RF} + 5\omega_{LO})t + \frac{1}{5} \sin(\omega_{RF} - 5\omega_{LO})t - \dots \} \quad \text{Eq. 4}$$

or simply

$$S_{IF} = \frac{2}{\pi} \{ \sin(\omega_{RF} + \omega_{LO})t + \sin(\omega_{RF} - \omega_{LO})t + \text{harmonics} \} \quad \text{Eq. 5}$$

The most important of these harmonic components are sketched in Figure 8 for the particular case used to generate the waveform shown in Figure 7, that is, $f_{RF} = 11\text{MHz}$ and $f_{LO} = 10\text{MHz}$.

Because of the $2/\pi$ term, a mixer has a minimum 3.92 dB insertion loss (and noise figure) in the absence of any gain.

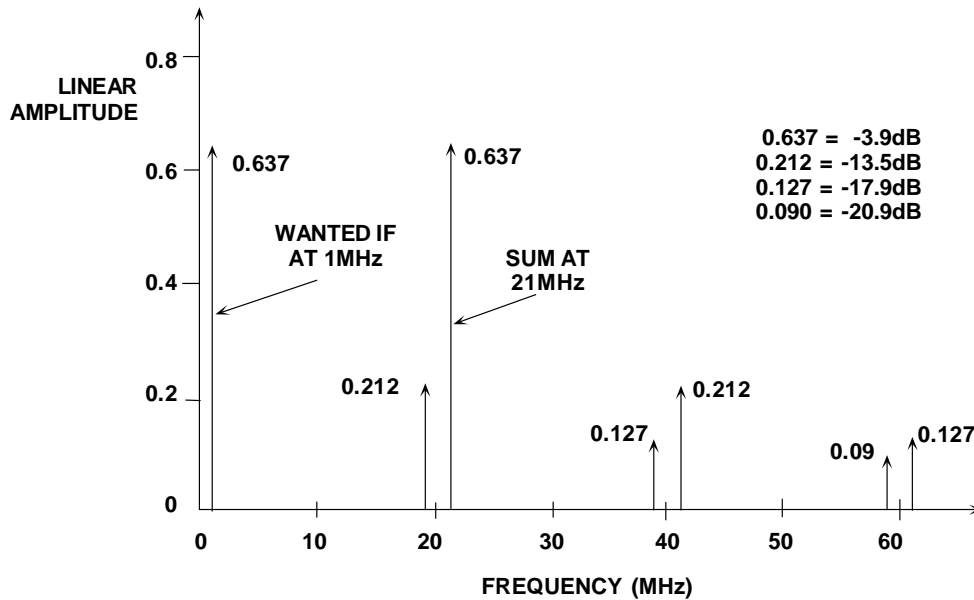


Figure 8: Output Spectrum for Switching Mixer for $f_{RF} = 11\text{MHz}$, $f_{LO} = 10\text{MHz}$

Note that the ideal (switching) mixer has exactly the same problem of image response to $\omega_{LO} - \omega_{RF}$ as the linear multiplying mixer. The image response is somewhat subtle, as it does not immediately show up in the output spectrum: it is a latent response, awaiting the occurrence of the "wrong" frequency in the input spectrum.

DIODE-RING MIXER

For many years, the most common mixer topology for high-performance applications has been the diode-ring mixer, one form of which is shown in Figure 9. The diodes, which may be silicon junction, silicon Schottky-barrier or gallium-arsenide types, provide the essential switching action. We do not need to analyze this circuit in great detail, but note in passing that the LO drive needs to be quite high—often a substantial fraction of one watt—in order to ensure that the diode conduction is strong enough to achieve low noise and to allow large signals to be converted without excessive spurious nonlinearity.

Because of the highly nonlinear nature of the diodes, the impedances at the three ports are poorly controlled, making matching difficult. Furthermore, there is considerable coupling between the three ports; this, and the high power needed at the LO port, make it very likely that there will be some component of the (highly-distorted) LO signal coupled back toward the antenna. Finally, it will be apparent that a passive mixer such as this cannot provide conversion gain; in the idealized scenario, there will be a conversion loss of $2/\pi$ [as Eq. 4 shows], or 3.92 dB. A practical mixer will have higher losses, due to the resistances of the diodes and the losses in the transformers.

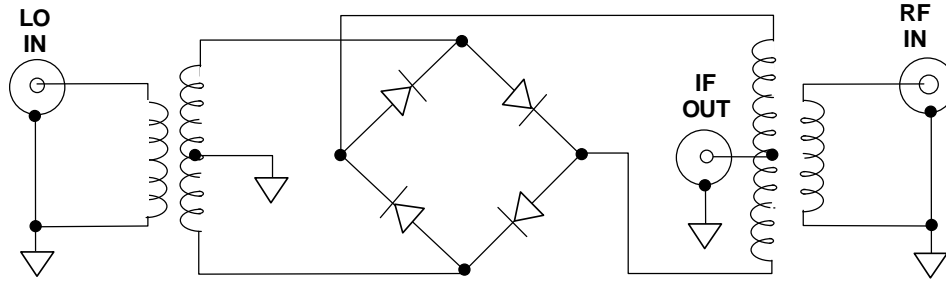


Figure 9: Diode Ring Mixer

Users of this type of mixer are accustomed to judging the signal handling capabilities by a “Level” rating. Thus, a Level-17 mixer needs +17 dBm (50 mW) of LO drive and can handle an RF input as high as +10 dBm (± 1 V). A typical mixer in this class would be the Mini-Circuits LRMS-1H, covering 2-500 MHz, having a nominal insertion loss of 6.25 dB (8.5 dB max), a worst-case LO-RF isolation of 20 dB and a worst-case LO-IF isolation of 22 dB (these figures for an LO frequency of 250-500 MHz). The price of this component is approximately \$10.00 in small quantities. Even the most expensive diode-ring mixers have similar drive power requirements, high losses and high coupling from the LO port.

CLASSIC ACTIVE MIXER

The diode-ring mixer not only has certain performance limitations, but it is also not amenable to fabrication using integrated circuit technologies, at least in the form shown in Figure 9. In the mid 1960's it was realized that the four diodes could be replaced by four transistors to perform essentially the same switching function. This formed the basis of the now-classical bipolar circuit shown in Figure 10, which is a minimal configuration for the fully-balanced version. Millions of such mixers have been made, including variants in CMOS and GaAs. We will limit our discussion to the BJT form, an example of which is the [AD831](#).

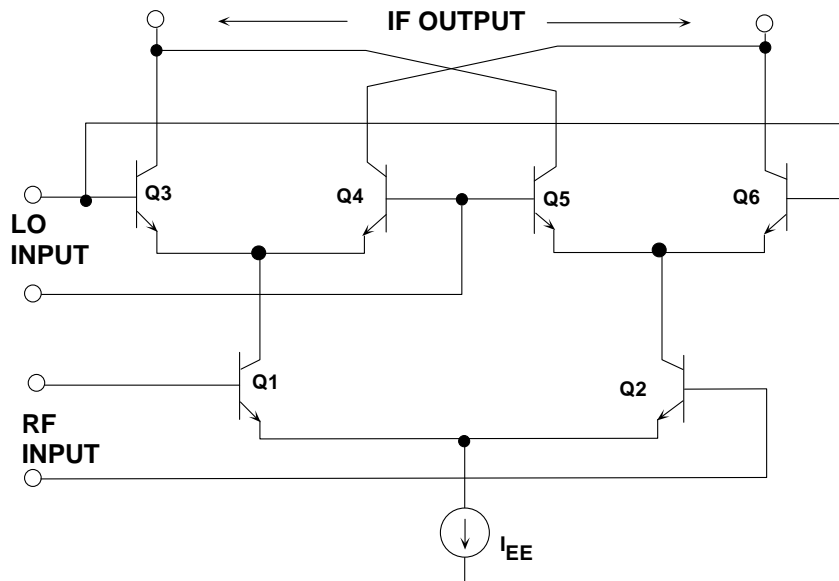


Figure 10: Classic Active Mixer

The *active mixer* is attractive for the following reasons:

- It can be monolithically integrated with other signal processing circuitry.
- It can provide conversion gain, whereas a diode-ring mixer always has an insertion loss. (Note: Active mixers may have gain. The analog Devices' AD831 active mixer, for example, amplifies the result in Eq. 5 by $\pi/2$ to provide unity gain from RF to IF.)
- It requires much less power to drive the LO port.
- It provides excellent isolation between the signal ports.
- Is far less sensitive to load-matching, requiring neither diplexer nor broadband termination.

Using appropriate design techniques it can provide trade-offs between third-order intercept (IP3) and the 1 dB gain-compression point (P_{1dB}), on the one hand, and total power consumption on the other. (That is, including the LO power, which in a passive mixer is "hidden" in the drive circuitry.)

BASIC OPERATION OF THE ACTIVE MIXER

Unlike the diode-ring mixer, which performs the polarity-reversing switching function in the voltage domain, the active mixer performs the switching function in the current domain. Thus the active mixer core (transistors Q3 through Q6 in Figure 10) must be driven by current-mode signals. The voltage-to-current converter formed by Q1 and Q2 receives the voltage-mode RF signal at their base terminals and transforms it into a differential pair of currents at the their collectors.

A second point of difference between the active mixer and diode ring mixer, therefore, is that the active mixer responds only to magnitude of the input voltage, not to the input power; that is, the active mixer is not matched to the source. (The concept of matching is that both the current and the voltage at some port are used by the circuitry which forms that port). By altering the bias current, I_{EE} , the transconductance of the input pair Q1-Q2 can be set over a wide range. Using this capability, an active mixer can provide variable gain.

A third point of difference is that the output (at the collectors of Q3-Q6) is in the form of a current, and can be converted back to a voltage at some other impedance level to that used at the input, hence, can provide further gain. By combining both output currents (typically, using a transformer) this voltage gain can be doubled. Finally, it will be apparent that the isolation between the various ports, in particular, from the LO port to the RF port, is inherently much lower than can be achieved in the diode ring mixer, due to the reversed-biased junctions that exist between the ports.

Briefly stated, though, the operation is as follows. In the absence of any voltage difference between the bases of Q1 and Q2, the collector currents of these two transistors are essentially equal. Thus, a voltage applied to the LO input results in no change of output current. Should a small DC offset voltage be present at the RF input (due typically to mismatch in the emitter areas of Q1 and Q2), this will only result in a small feedthrough of the LO signal to the IF output, which will be blocked by the first IF filter.

Conversely, if an RF signal is applied to the RF port, but no voltage difference is applied to the LO input, the output currents will again be balanced. A small offset voltage (due now to emitter mismatches in Q3-Q6) may cause some RF signal feedthrough to the IF output; as before, this will be rejected by the IF filters. It is only when a signal is applied to both the RF and LO ports that a signal appears at the output; hence, the term doubly-balanced mixer.

Active mixers can realize their gain in one other way: the matching networks used to transform a 50 Ω source to the (usually) high input impedance of the mixer provides an impedance transformation and thus voltage gain due to the impedance step up. Thus, an active mixer that has loss when the input is terminated in a broadband 50 Ω termination can have “gain” when an input matching network is used.

THE AD8345 QUADRATURE MODULATOR

Modulators (sometimes called *balanced-modulators*, *doubly-balanced modulators* or even on occasions *high level mixers*) can be viewed as *sign-changers*. The two inputs, X and Y, generate an output W, which is simply one of these inputs (say, Y) multiplied by just the sign of the other (say, X), that is $W = Y * \text{sign}(X)$. Therefore, no reference voltage is required. A good modulator exhibits very high linearity in its signal path, with precisely equal gain for positive and negative values of Y, and precisely equal gain for positive and negative values of X. Ideally, the amplitude of the X input needed to fully switch the output sign is very small, that is, the X-input exhibits a comparator-like behavior. In some cases, where this input may be a logic signal, a simpler X-channel can be used.

As an example, the [AD8345](#) is a silicon RFIC quadrature modulator, designed for use from 250 MHz to 1000 MHz (see Figure 11). Its excellent phase accuracy and amplitude balance enable the high performance direct modulation of an IF carrier.

The AD8345 accurately splits the external LO signal into two quadrature components through the polyphase phase-splitter network. The two I and Q LO components are mixed with the baseband I and Q differential input signals. Finally, the outputs of the two mixers are combined in the output stage to provide a single-ended 50 Ω drive at VOUT.

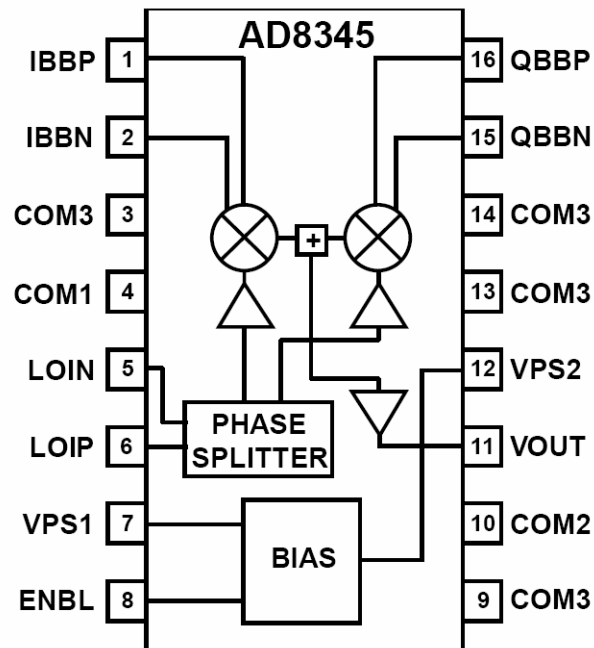


Figure 11: [AD8345](#) Quadrature Modulator Block Diagram

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1. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as [Linear Circuit Design Handbook](#), Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 2, 4.

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