CHAPTER 7

Mixer Design

Mixers are three port active or passive devices, are designed to yield both a sum and a difference frequency at a single output port when two distinct input frequencies are inserted into the other two ports. This process, called *frequency conversion* (or *heterodyning*), is found in most communication's gear, and is used so that we may increase or decrease a signal's frequency. One of the two input frequencies will normally be a CW wave, produced within the radio by a local oscillator (LO), while the other input will be the RF signal received from the antenna.

If we would like to produce an output frequency within the mixer circuit that is lower than the input RF signal, then this is called *down conversion*; if we would like to produce an output signal that is at a higher frequency than the input signal, it is referred to as *up conversion*. Indeed, most AM, SSB, and digital transmitters require mixers to convert up to a higher frequency for transmission into space, while superheterodyne receivers require a mixer to convert a received signal to a much lower frequency. This lower received frequency available at the mixer's output port is called the *intermediate frequency* (IF). Receivers use this lower-frequency IF signal because it is much easier to efficiently amplify and filter with all the IF stages tuned and optimized for a single, low band of frequencies, which increases the receiver's gain and selectivity.

Again, the frequency conversion process within the nonlinear mixer stage produces the intermediate frequency by the RF input signal heterodyning, or beating, with the receiver's own internal LO. This heterodyning mixer circuit will consist of either a diode, BJT, or FET that is overdriven, or biased to run within the nonlinear area of its operation. However, the beating of the mixer's RF and LO input signals yields not only the RF, the LO, and the sum and difference frequencies of these two primary signals, but also many spurious frequencies at the mixer's output port. Most of these undesired frequencies will be filtered out within the receiver's IF stages, resulting in the new desired signal frequency, consisting of the converted carrier and any sidebands, now at the *difference* frequency. This new, lower difference frequency will then be amplified and further filtered as it passes through the fixed-tuned IF strip.

There are three basic classifications for both active and passive mixers: *Unbalanced* mixers have an IF output consisting of f_S, f_{LO}, $f_S - f_{\text{LO}}$, $f_S + f_{\text{LO}}$, and other spurious outputs. They will also exhibit little isolation between each of the mixer's three ports, resulting in undesired signal interactions and feedthroughs to another port. *Single-balanced* mixers will at least strongly attenuate either the original input signal *or* the LO (but not both), while sending less of the above mixing products on to its output than the unbalanced type. A *double-balanced* mixer, or *DBM* for short, supplies superior IF-RF-LO inter-port isolation, while outputting only the sum and difference frequencies of the input signal and the local oscillator, while attenuating both the LO and RF signals, and significantly attenuating three quarters of the possible mixer spurs at the output of the IF port. This makes the job of filtering and selecting a frequency plan a much easier task.

7.1 Passive Mixers

7.1.1 Introduction

Passive mixers permit a much higher amplitude RF input signal level than active mixers before severe distortion products within the output IF becomes unacceptable. These distortion products are in the form of *intermodulation distortion* (IMD), along with *compression distortion*. The IMDs may fall in band, or cause other signals to fall in band, possibly swamping out or creating interference to the baseband signal. This causes additional noise, which will degrade system performance and BER.

Most passive mixers also possess a lower noise figure than active mixers, which is very important for any stage within the front end of a low-noise receiver. But instead of an insertion gain as many active mixers will enjoy, passive mixers will have an insertion loss of around 7 dB.

The passive mixer conversion losses are caused by the mixing diode's internal resistance, port impedance mismatches, mixer product generation, and the inevitable 3 dB that is wasted in the undesired sum or difference frequency. (This sum or difference frequency is removed by filtering, cutting the mixer's final output power in half.)

Figure 7.1 shows a common double-balanced mixer, which utilizes a *diode ring* to achieve frequency conversion of the RF input signal. The mixer's diodes are being constantly switched *on* and *off* within the ring by the high-powered LO stage, while the RF signal is alternately sent through the diodes, mixing the two signals in a nonlinear manner, producing the IF output frequency. DBMs commonly function up to 8 GHz and beyond by using *hot-carrier* (*Schottky*) diodes, which possess low-noise and high-conversion efficiency.

DBMs made of lumped components and placed on the wireless devices' PC board as a discrete circuit are seldom utilized today. Instead, double-balanced mixers are available in a module, with the diodes and transformers already balanced and placed within a surface-mount package.

Lower performing passive mixers that are not double balanced are available that employ either a single diode or double diodes (Fig. 7.2). Unlike DBMs, they are cheap, require few components, and are relatively easy to design.

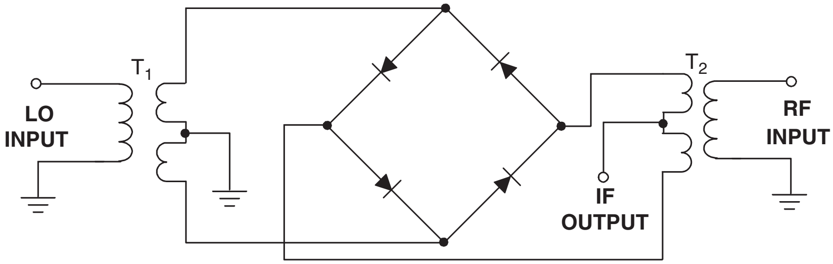


Figure 7.1 A double-balanced mixer stage.

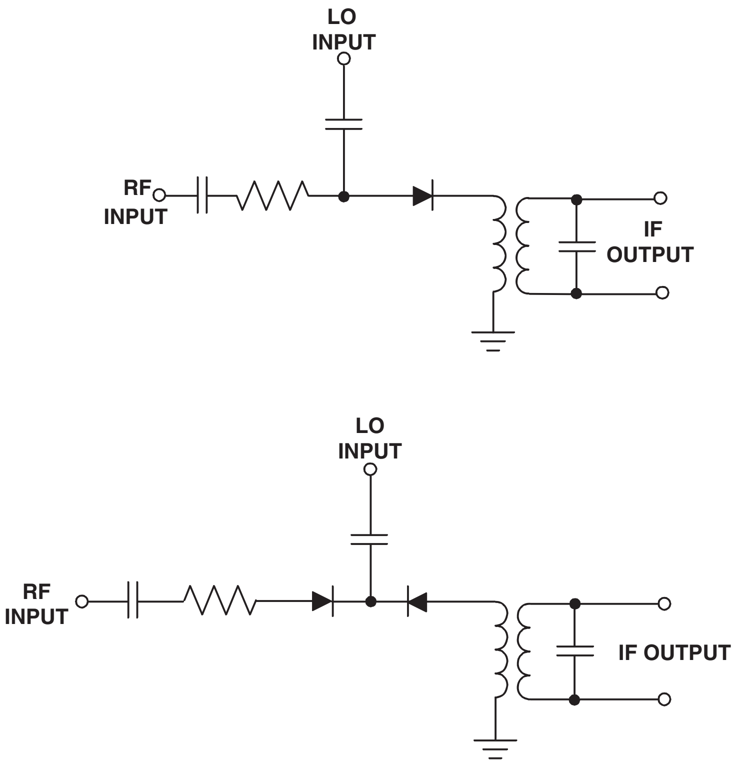


Figure 7.2 A single-diode mixer and a double-diode mixer stage.

7.1.2 Passive Mixers Types

There are several types of passive mixer designs available, depending on cost and performance levels required. Some of these passive diode mixers have already been introduced above, but will be further investigated in this section.

Figure 7.3 shows a one diode, *single-ended* mixer. This circuit is only found in very low-cost circuits, with the isolation between ports being supplied by bandpass and lowpass filters that are separated in frequency. Some of these single-ended mixer can also take advantage of a somewhat lower level of LO power needed to drive the single-diode mixing element, as compared to the often times higher drive levels required of a high-performance DBM stage. The single-ended mixer, however, has a relatively narrow

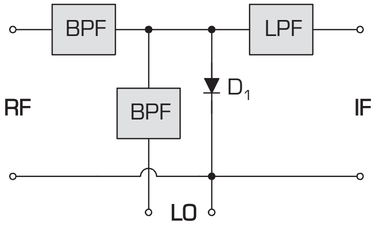


Figure 7.3 A basic single-diode mixer circuit with filtering.

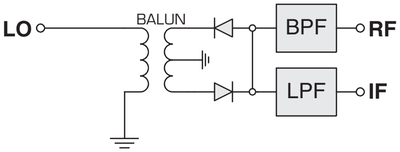


FIGURE 7.4 A single-balanced two-diode mixer.

bandwidth, poor port-to-port isolation, a low intercept point, and inferior intermodulation distortion suppression (their $IP3_{OUT}$ value will normally equal their LO input drive level). If we would like to increase the specifications and overall quality of this device, we will need to increase the number of diodes. This will permit a higher amplitude LO drive level input, which automatically forces an increase in the mixer's P1dB compression point. (The P1dB is normally specified at about 10 dB below the LO for all diode mixers. So, the higher the LO drive that can be inserted into a mixer, the higher the P1dB.) As we are demanding a more powerful LO for increased mixer performance, this will unfortunately not only cost more, but also radiate a higher level of EMI.

Single-balanced mixers, as shown in Fig. 7.4, are comprised of two matching diodes, a balun, and generally two filters. The balun converts the unbalanced LO output to a balanced mixer input, matches the diodes to the port's impedance, helps in port-to-port isolation, and balances the diodes. The filters, one at each of the RF and IF ports, are to improve mixer isolation.

This particular mixer type will balance out (cancel) and filter the LO power, preventing excessive LO feedthrough at the RF and IF ports. In fact, single-*balanced* mixers are superior to single-ended mixers in this LO-to-IF and LO-to-RF isolation, as well as in their wider bandwidth operation. Furthermore, intermodulation distortion suppression is increased over the single-ended type. This is because any distortion products that are made up of even harmonics will be suppressed by the balanced-circuit action and, since twice as many diodes are typically used with this circuit, along with higher LO power, the same RF amplitude levels that are inserted into the single-balanced mixer's input will create less IMDs to be generated in the first place. As compared to a single-ended mixer, the negative attributes of a single-balanced mixer would be that the LO power must often be somewhat higher (which necessitates a more expensive and power hungry oscillator), and the part's count is increased (since a perfectly balanced balun and one more matched diode must be used).

Single-balanced mixers are so named due to their single-balanced balun, while double-balanced mixers are so named for the same reason; they employ two baluns. To any significant extent, quality double-balanced mixers will output only IMD products that are constructed of both odd RF and odd LO harmonics. This action decreases the DBM's total output of mixer products to a quarter of the amount generated within any simple mixer. However, mixer products are suppressed to varying levels, strongly dependent on the quality of the diode match and the accuracy of the balun balance. So, while a DBM often may require twice the LO power as a single-balanced mixer, as well as double the number of internal-balanced diodes and baluns, a DBM will have much better IMD suppression, a wider bandwidth, and a higher intercept point.

Triple-balanced mixers (TBM, or DDM for *double double-balanced mixers*) have baluns located at all three ports, along with two complete diode rings. They have increased intercept points for decreased mixer product generation and two-tone intermodulation distortion levels, as well as better port-to-port isolation and a wider possible IF bandwidth output. However, TBMs need higher LO power, another matched diode ring, and one more balanced balun above that demanded by the DBM type. The price will be higher.

7.1.3 Passive Mixer Design

This section provides several methods to design straightforward, but highly useful and effective, RF mixers for many low-cost high-frequency consumer wireless products.

As with any practical design calculation at these frequencies, parasitic capacitance and inductance, as well as component and PCB pad/trace length and distributed reactances, will modify ideal circuit behavior, sometimes extremely, so accurately modeling and tuning the mixer will always be necessary.

For both cost and performance reasons, design and construction of DBMs themselves is generally best left to the specialized mixer manufacturing companies. Therefore, when utilizing DBMs in a wireless design, it is easier and faster to simply purchase a completed, off-the-shelf device.

A Passive RF Diode Single-Ended Mixer (Fig. 7.5)

A huge limitation of unbalanced mixers in general is excessive LO radiation from the RF ports, limited only by any possible RF filtering. Another issue is the close-in RF feedthrough into the IF, with the stronger, but typically more distant, LO feedthrough being more easily filtered out from the IF. In fact, we could add further filtering to all mixer ports, but this would substantially add to cost and complexity, which is exactly what we are trying to avoid with the use of a single-ended mixer in the first place.

To Design

1. Select an appropriate diode for the frequencies of interest. This will normally be a silicon, low-barrier Schottky type for RF use.
2. Design L_4 and C_5 for series resonance at the IF frequency, and with a high L to C ratio for a narrow passband.
3. Design L_5 and C_6 for parallel resonance at the IF frequency, and with a high C to L ratio for a narrow passband.
4. Design a 50-Ω lowpass RF filter to attenuate the high level of LO radiation from the mixer's RF port (to decrease this LO radiation even further, additional front-end system-level RF filtering is assumed).

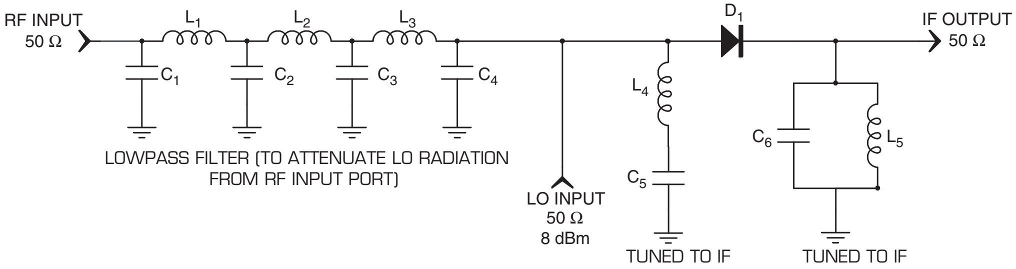


Figure 7.5 A practical single-ended diode mixer circuit.

5. In such low-cost applications, mixer port matching to the diode is rarely used. In fact, for the high LO power levels that are commonly used for this topology, the impedance will be close enough to 50 Ω to supply a decent match for the input LPF. (Increasing the LO drive level would further decrease the mixer diode's input impedance, while decreasing the drive level will increase the input impedance.)
6. Insert an 8-dBm LO signal, which will supply the mixer with an RF-to-IF conversion loss of 10-dB.

A Quick Example Design a Passive Single-Ended RF Diode Mixer (Fig. 7.6)

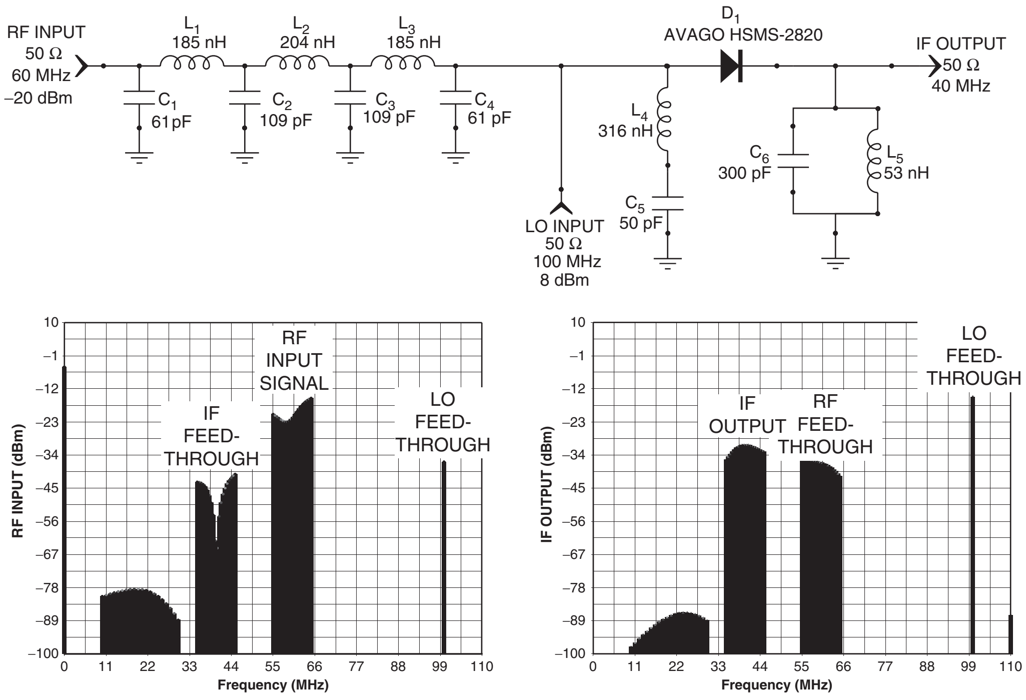
Goal: Create a single-diode RF mixer. The specifications and parameters for the circuit are:

$f_{RF} = 60$ MHz

$f_{IF} = 40$ MHz

$f_{LO} = 100$ MHz

$P_{LO} = +8$ dBm



a. b.

Figure 7.6 The example single-ended diode mixer circuit with part's values, along with harmonic balance frequency sweep results: (*a*) All the signals present at the RF input port; (*b*) All the signals present at the IF output port.

$P_{OUT} = -5$ dBm

Conversion loss = 10 dB

Diode = Avago HSMS-2820 (Schottky type, appropriate for frequency of interest)

Solution:

1. $L_4 = 316$ nH, $C_5 = 50$ pF
2. $L_5 = 53$ nH, $C_6 = 300$ pF
3. LPF component values as shown for a seven-pole Chebyshev with a $f_{r(3\ \mathrm{dB})}$ of 62 MHz

Distributed Diode Single-Balanced Narrowband Hybrid Mixer for Microwave Frequencies (Fig. 7.7)

This mixer structure will have decent dynamic range, and requires approximately 8 to 10-dBm LO power, with satisfactory RF/LO-to-IF and LO-to-RF isolation for most applications. It enjoys very good IMD performance, with fair cancellation of even harmonic signals. However, the IF must be no higher in frequency than 50 MHz or so, since the difference between the LO and RF frequencies must be relatively small due to the mixer's resonant distributed design, which has to be able to effectively react to *both* the RF and the LO frequencies.

For maximum LO rejection, design each microstrip section for the LO's output frequency, or for midway between the LO and RF frequency values. The mixer's conversion loss will be approximately −6 dBm.

To Design

1. $A = 90°$ long at LO frequency or at $(f_{RF} + f_{LO})/2$, using 50-Ω microstrip.
2. $B = 90°$ long at LO frequency or at $(f_{RF} + f_{LO})/2$, using 35.5-Ω microstrip.
3. $C = 90°$ long at RF frequency, using 50-Ω microstrip. (C shorts RF to ground. Bends do not affect actual length, but are used for compactness.)
4. $D = 90°$ long at LO frequency, using 50-Ω microstrip. (D shorts LO to ground. Bends do not affect actual length, but are used for compactness.)
5. E = 50-Ω microstrip, with the two traces before the D_1 and D_2 diodes being of equal length.
6. RFC = 90° long at LO frequency, using 100-Ω microstrip.
7. D_1 and D_2 = select the appropriate Schottky diodes for the frequency of operation and the application.

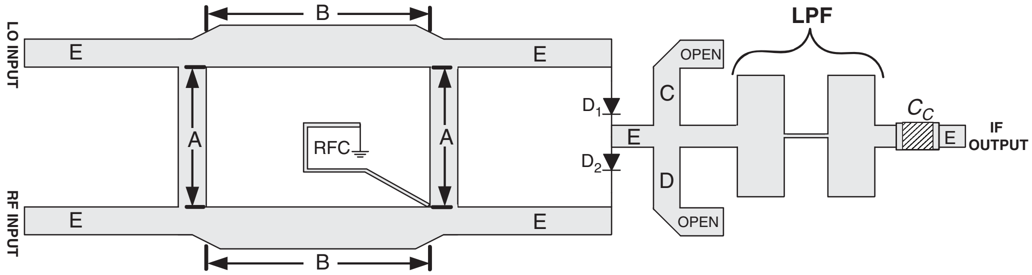


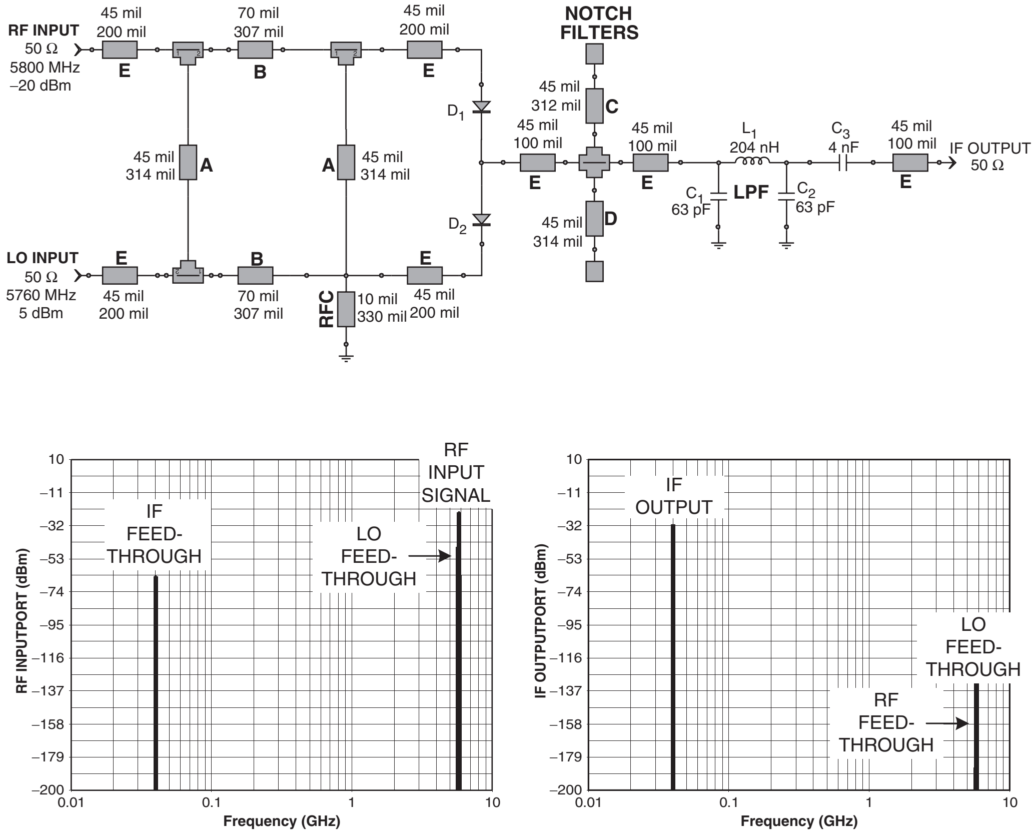
FIGURE 7.7 A narrowband microwave mixer for UHF and above applications.

NOTE: *The* B *section is extremely sensitive to exact dimensions for LO suppression at RF port. The LPF is used to attenuate all frequencies above the IF.*

A Quick Example Design a Passive Single-Balanced RF Diode Mixer (Fig. 7.8)

Goal: Create a single-balanced diode RF mixer. The specifications and parameters for the circuit are:

$f_{\mathrm{RF}} = 5.8$ GHz
$f_{\mathrm{IF}} = 40$ MHz
$f_{\mathrm{LO}} = 5.76$ GHz
$P_{\mathrm{LO}} = +5$ dBm
$P_{\mathrm{OUT}} = -5$ dBm
Conversion loss = −6 dB



a. b.

FIGURE 7.8 The example single-balanced diode mixer circuit with calculated part's values, along with harmonic balance frequency sweep results (log scale): (*a*) All the signals present at the RF input port; (*b*) All the signals present at the IF output port.

Diodes = Avago HSMS-2820 (Schottky type, appropriate for frequency of interest)
Substrate = Roger's RO-4003, 20-mils thick

Solution:

1. A = 45-mils wide by 314-mils long
2. B = 76-mils wide by 306-mils long (to decrease LO feedthrough to RF port, B section optimized in simulator slightly to 70-mils wide by 307-mils long)
3. C = 45-mils wide by 312-mils long
4. D = 45-mils wide by 314-mils long
5. E = 45-mils wide by variable length
6. RFC = 10-mils wide by 330-mils long
7. LPF = C_1, C_2 = 63 pF; L_1 = 204 nH (cutoff frequency = 42 MHz)
8. C_3 = 4 nF (coupling capacitor for 40 MHz IF)

Microwave Circular Rat Race Single-Balanced Diode Mixer (Fig. 7.9)

Very similar to the above mixer, this low-cost, distributed microwave diode mixer, when used with Schottky diodes, is an excellent choice for very high frequencies. It requires an 8-dBm LO drive level, has decent intermodulation performance, good RF/LO-to-IF and LO-to-RF port isolation and, as with all diode mixers, will have a conversion loss (in this case, −6 dB).

The IF must be no higher in frequency than 50 MHz or so, since the difference between the LO and RF frequencies must be relatively small due to the mixer's resonant distributed design; which has to be able to effectively react to *both* the RF and the LO frequencies.

To Design

1. $f_m = \dfrac{f_{\mathrm{RF}} + f_{\mathrm{LO}}}{2}$ (for midway between the RF and LO frequencies)
2. $A = 90°$ long at f_m, using 70.7-Ω microstrip
3. $B = 270°$ long at f_m, using 70.7-Ω microstrip
4. $C = 10°$ long at f_m, using 50-Ω microstrip
5. D_1 and D_2 = select the appropriate Schottky diodes for the frequency of operation and the application

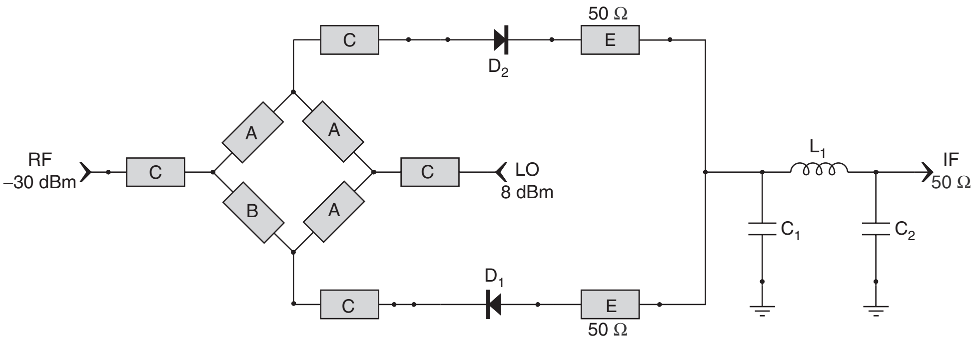


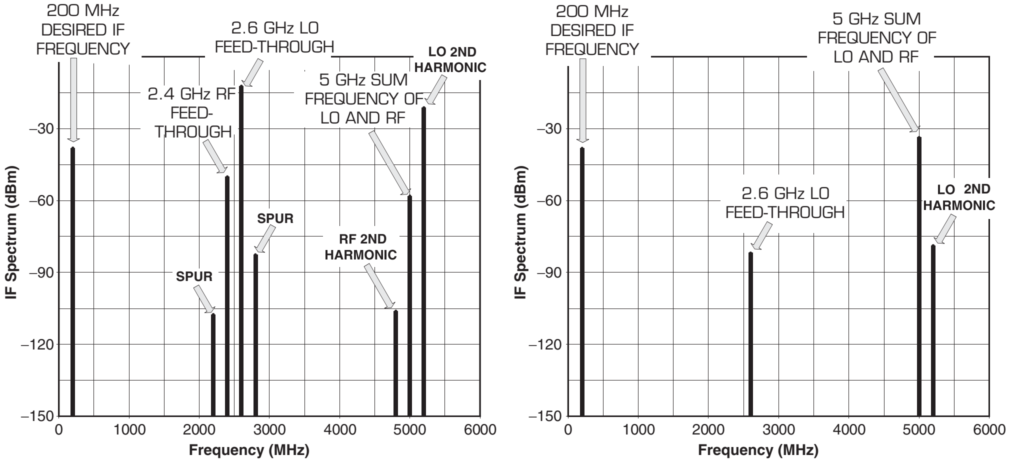
Figure 7.9 The rat race distributed diode mixer circuit.

6. LPF = in the included *AADE Filter Designer* software, design a 50-Ω lumped lowpass filter with 1.5 × IF frequency cutoff (a shunt capacitor must begin the filter for the LO and RF currents). The LPF may also be designed as a distributed network, or by using a small multilayer ceramic filter.
7. *E* = short 50-Ω microstrip

7.1.4 Passive Mixer Distortion

The undesired mixer product frequency generation, and its suppression, is important in the entire heterodyning process. Output mixer products (Fig. 7.10) are formed by the mixing in the nonlinear diode elements of the incoming single-tone RF (and its own resultant harmonics), with the single-tone LO (and its resultant harmonics). This creates high-order distortion products that are higher and lower in frequency than the desired product, with this desired product normally being the difference frequency of the LO and RF in a receiver, or the sum of the LO and IF in a transmitter.

Two-tone intermodulation products are created when two tones (f_1 and f_2) are placed at the RF input port of the receiver's mixer and, when mixed with each other and the LO, give birth to high-order in-band spurious responses at the IF output port of the mixer. While keeping in mind that the higher the possible LO oscillator power, the lower the distortion products, Fig. 7.11 demonstrates this point with three different level mixers, a *Level 7*, *Level 17*, and a *Level 23*), with each using its recommended LO input power of either 7, 17, or 23 dBm. The Level 7 mixer's IF output shows high third-, fifth-, and seventh-order two-tone IMD products for a 0-dBm RF input. The Level 17 mixer decreases these IMD products for the same 0-dBm RF input amplitude. The Level 23 mixer shows IMD products much further down than even the Level 17 mixer, at approximately 65 dBc.



R = 2.4 GHz (−30 dBm); LO = 2.6 GHz (+13 dBm); IF = 200 MHz RF = 2.4 GHz (−30 dBm); LO = 2.6 GHz (+8 dBm); IF = 200 MHz

FIGURE 7.10 Various single-tone mixer spurs generated by the single-ended mixing of the RF (2.4 GHz at −30 dBm) and the LO (2.6 GHz at +13 dBm), and their harmonics in an unbalanced mixer, with light one-pole filtering (left); a DBM diode mixer's IF output spectrum in a well-balanced circuit (right).

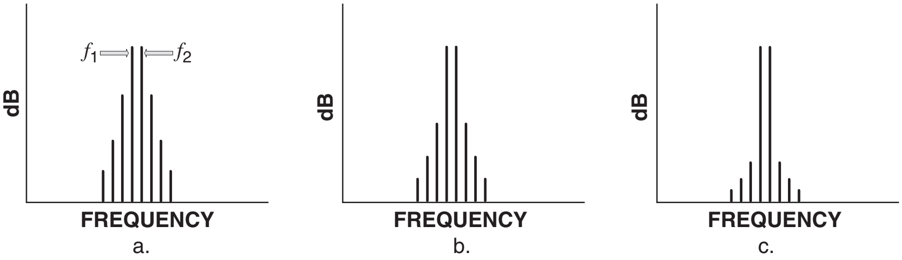


Figure 7.11 Different level mixers and their two-tone output spectra for a DBM: (*a*) Level 7, (*b*) Level 17, (*c*) Level 23.

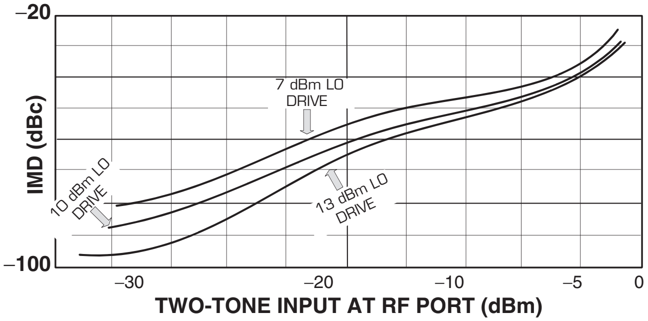


Figure 7.12 A Level 7 DBM mixer's IMD generation at various LO levels and two-tone input powers.

A further subject in mixer design is demonstrated in Fig. 7.12: Boosting a Level 7 DBM's LO drive does not in itself drastically improve the IMD product suppression. This can only be accomplished, in any significant way, by increasing the number of diodes in each mixer leg from one to two in series (as well as other techniques), and then increasing the LO drive, with the then resultant improvement in IMD suppression.

The intercept point indicates the mixer's capability to suppress intermodulation distortion, typically referring to two-tone third-order intermodulation products. A high intercept point decreases the undesirable generation of these IMDs. But in the world of DBMs, the intercept point and the 1-dB compression point do not directly correlate to each other; so choosing a mixer simply for its high 1-dB compression point as a guarantee of increased two-tone suppression could prove a poor choice.

As stated above, two-tone third-order products can be reduced by increasing the *level* of the mixer (and therefore the LO drive level itself), and/or by decreasing the power of the input two-tone RF signal. But since we will generally use the manufacturer's recommended LO drive for our chosen level of mixer, which will be selected in consideration of the maximum LO power available within our own wireless design, as well as cost constraints, then decreasing the input RF level is normally the easiest and cheapest solution for two-tone third-order product improvement.

By decreasing the input two-tone RF signal by 1 dB, we will decrease the output two-tone third-order products by 3 dB. However, the inverse is also true: increasing the RF two-tone input by 1 dB will increase the output two-tone third-order products by

3 dB. As stated, because they can fall in band at the mixer's IF port, these third-order products are the most dangerous spurious signals, and must be attenuated to the lowest level the system requires.

To assure ourselves of decent intermodulation distortion performance and conversion-loss variations, a Level 7 mixer should never be run with an RF input higher than −3 dBm (with the LO drive at the rated power level), while a Level 10 mixer should never go above a 0-dBm RF, and a Level 13 mixer never above +3 dBm, or a Level 17 mixer never higher than +7 dBm. In fact, decreasing these RF input levels to 20 dB below the LO drive is commonly adopted to reduce IMD generation to extremely low amplitudes. (This will, unfortunately, also increase the *relative* LO feedthrough level.)

Within a mixer, it is possible to calculate the highest in amplitude two-tone third-order spur level that is down from our desired RF signal by:

$$\mathrm{TOIM_{SUP}} = 2(\mathrm{TOIP} - \mathrm{RF_{IN}})$$

where $\mathrm{TOIM_{SUP}}$ = third-order intermodulation suppression down from the signal of interest at the mixer's output port, dBc
TOIP = third-order (input) intercept point of the mixer, dBm
$\mathrm{RF_{IN}}$ = power of the RF signal at the input to the mixer, dBm

When viewing the mixer's *third-order intercept point* at its input port (TOIP or TOIP_I) specification on a data sheet, we may sometimes be required to convert from this input intercept to an output intercept (TOIP_O). This can be accomplished by:

$$\mathrm{TOIP}_O = \mathrm{TOIP}_I - \mathrm{CL}$$

where TOIP_O = mixer output intercept point, dBm
TOIP_I = mixer input intercept point, dBm
CL = mixer conversion loss (usually 6 to 9 dB, as a positive number), +dB

7.1.5 Passive Mixer Issues

No software or mathematical calculation can design (or *synthesize*) a microwave circuit with 100% accuracy—especially nonlinear mixer networks—due to the practical inability for the program or the formula itself to take the PCB's trace/pad lengths and parasitics, the lumped component's distributed effects, and the nonlinear active models all into account. This limits the accuracy of the synthesized RF design that is possible within the calculated results. Thus, without the proper microwave design knowledge *and* the correct use of PCB traces, circuit elements, and device models within the appropriate RF circuit simulator, then no microwave design, no matter how simple or how complex, will operate as expected. Therefore, only RF software tuning, or "tweaking," of the calculated synthesized design within such a simulator will ever obtain even ballpark results, which may still require further bench optimization to complete.

During the system's frequency planning stage, an appropriate LO and IF frequency should be selected that will minimize the number and strength of mixer products present within the IF bandpass of the mixer. This is most conveniently performed by employing the appropriate software, such as Blattenberger's *RF Workbench*, or The Engineer's Club *MixerSpur*. Both of these programs will graphically indicate if there are any dangerous mixer's spurs within the IF's passband.

As all mixers have not only a nominal, but also a minimum and a maximum, LO drive level (as recommended by the mixer's manufacturer), we may sometimes want to select the minimum LO level for two reasons: one, sufficient LO power may not be readily available; and two, LO feedthrough from the RF port must be minimized. However, if we select a decreased level, then the mixer's two-tone IMD suppression, conversion losses, and return losses will all suffer as a result. Conversely, by slightly increasing the drive level above the nominal value, we will obtain a higher mixer noise figure and LO feedthrough, but will somewhat improve the mixer's two-tone IMD performance, mixer product suppression, and conversion losses across the band. Therefore, running the mixer at the recommended LO drive level will be the best compromise for superior overall system performance.

A wideband conjugate match (a good VSWR) at the RF and IF mixer ports is important for the conversion gain and intermodulation performance levels of many DBM type mixers. Therefore, nonreflective filtering is necessary since the undesired signals and products will be reflected back into the IF port of the mixer stage by the reflective stopbands inherent in a common IF bandpass filter, causing two-tone IMD performance to suffer, sometimes by as much as 25 dB. With passive mixers, there are several ways we can combat this effect. We can use a *diplexer* at the IF port of a downconverting mixer stage, which will filter and pass the desired IF but, unlike other filters, will stop the LO harmonics, the sum of the RF and LO, and the IMD products from entering the IF stages. It accomplishes this by the diplexer's ability to *absorb* rather than *reflect* certain undesired frequencies, since the reflection of such undesired frequencies could unbalance the mixer's diode ring, adversely upsetting its dynamic range and conversion loss if high enough in amplitude.

Instead of a diplexer, we may also simply pad the IF output of the mixer so that these reflections are attenuated not only as they enter the pad, but also as they are reflected back into the mixer's IF port. Attenuator pads improve the input/output VSWR by supplying the mixer with an almost pure, and extremely wideband, $50 + j0$ termination. Or we could use a wideband, high-isolation IF amplifier. This will permit all of the mixing products to pass through this amplifier and, after filtering from a normally reflective IF filter, which will bounce much of the undesired signals back toward the sensitive IF port of the mixer, these reflected signals will have been significantly attenuated by the reverse isolation of the buffer amplifier itself. And because the less the power coming from the mixer's IF output the lower in amplitude these reflections will be, and thus the less the requirement will be for their suppression, the exact choice of which of the above methods to use will depend to a certain degree on the output port power.

There may occasionally be a requirement for an *upconverting* superheterodyne receiver when working with HF radios. When designing such receivers, the incoming RF signal should be placed at the passive mixer's IF port, while the now higher frequency IF output signal should be sent out of the mixer's RF port. This is also equally valid for transmitter design, since the mixer will also be performing up conversion.

The selection of the proper double-balanced mixer for a particular receiver or transmitter application will depend on the required P1dB compression point, LO power, port isolation, device cost, and two-tone intermodulation and mixer generated product suppression. Therefore, it is important to study a part's data sheet well before making any final mixer selections.

7.1.6 Passive Mixer Terminology

Some common terminology used to specify a mixer:

Conversion compression—Specification that indicates the maximum value of the input RF signal level that will obtain a linear increase in IF output power. For example, Level 7 DBM mixers will usually have a conversion compression of +2 dBm.

Conversion loss—The rated signal level difference between the input and the output of a mixer at the rated LO input power. For instance, a Level 7 (+7 dBm LO drive) DBM mixer may have a loss in power from the input to the output of 8 dB at midband.

Cross modulation—Describes the undesired transfer of the modulation between a modulated and a CW signal within the mixer stage.

High-side injection—When the LO frequency is higher than the RF frequency in a mixer stage.

Intercept point—Superior two-tone third-order product suppression demands a high mixer intercept point. This value is approximately 10 dB higher at the mixer's input than the *conversion compression* rating discussed above. The *cross modulation* distortion and desensitization are also reduced with a high intercept point.

Interport isolation—The rating of the feedthrough between the mixer's LO, RF, and IF ports. This is the value, in dB, that one port's signal is attenuated at another port's input or output. The most important of these isolation specifications is the LO attenuation at the IF and RF ports, since LO feedthrough is a major problem in receiver and transmitter system's design, and the RF to LO isolation is normally of little concern due to the RF's low input levels. Typical mixer LO to IF isolation will range from 0 to 50 dB, depending on topology and port filtering.

Low-side injection—When the LO frequency is lower than the incoming RF frequency in a mixer stage.

Noise figure (NF)—The noise added by the mixer itself, and equals the difference between the noise at the input of the mixer and the output of the mixer, in dB. When the mixer is driven with the proper LO drive level, the NF will equal the conversion loss.

7.2 Active Mixers

7.2.1 Introduction

Active mixers vary from the passive-type diode mixers described above. Active mixers can supply a conversion gain instead of a loss, they require far less LO drive power, are much less sensitive to port terminations, have better ultimate LO-to-IF isolation, and produce less mixer spurs. However, wider adoption of certain active mixers, such as the *Gilbert cell* type, has been somewhat hindered by a poor IP3, high NF (around 15 dB), and the need for a DC supply voltage. In many high-end wireless applications, the first two problems have limited the active mixer's role to the later stages of a receiver, where the dynamic range of the signal is more under control by the AGC, and the NF matters little.

Many active mixers work by exploiting the high-level signal that is produced by the radio's LO to force the mixer's transistor to operate within its nonlinear region, functioning only during a 180° of its conduction cycle (similar to a Class C amplifier), while the much smaller in amplitude RF signal operates within the active device's linear region. And even though the mixer is built for nonlinearity, it still acts as a far from perfect, but nondistorting, linear frequency shifter (when not overdriven by the RF input signal), and thus will produce a relatively small amount of IMD products.

7.2.2 Active Mixers Types

As with passive mixers, there are different types of active mixers. The *single-ended FET* mixer of Fig. 7.13 is comprised of a JFET, some biasing components, and two tuned tanks. The RF input signal is dropped across the first tuned input tank and sent to the JFET's gate. An LO signal is inserted into the source lead, with the resultant converted signal removed from the JFET's drain and placed across the tuned output tank. This second tank is tuned to the desired IF output frequency, with most of the mixing, RF signal, and LO frequencies being severely attenuated by this circuit. The secondary circuit of the output transformer takes this signal, reduces the high-output impedance, and places it into the IF amplifiers.

A *dual-gate MOSFET* mixer of the type shown in Fig. 7.14 employs a MOSFET, some biasing components, and a single tuned tank. The RF signal is sent through the coupling capacitor into the second gate while the LO is inserted into the first gate, with the sum and difference frequency, along with the mixer products, being sent on to the tuned circuit. Since this output tank is tuned to exactly the desired IF frequency, all other frequencies are attenuated, while the IF frequency itself is dropped across the

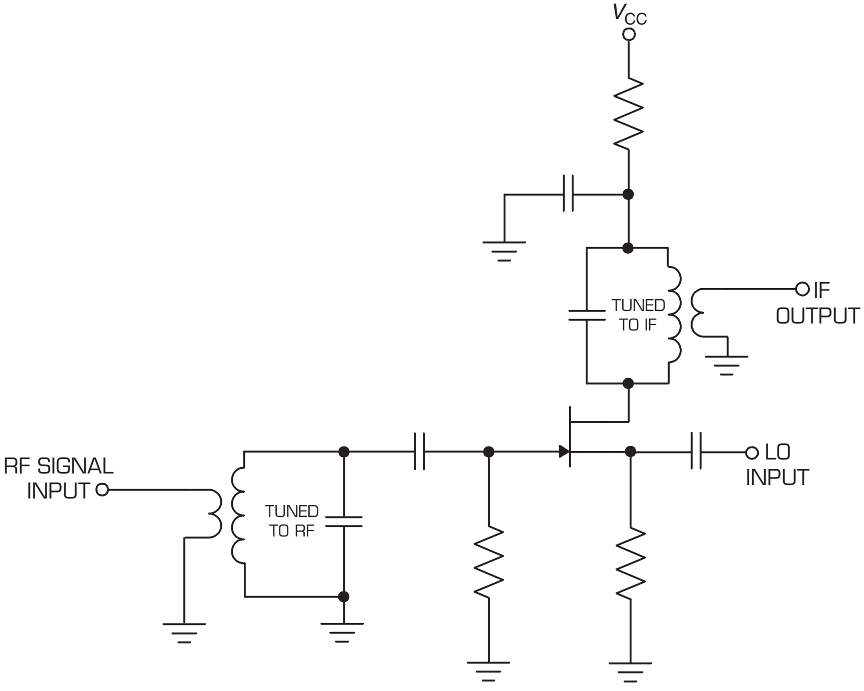


FIGURE 7.13 A single-ended active JFET mixer circuit.

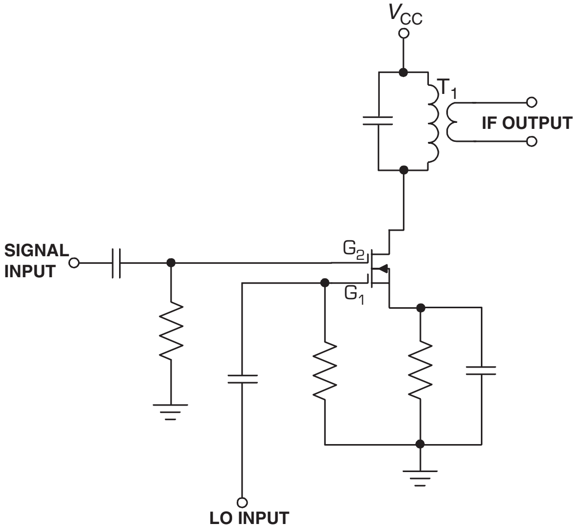


FIGURE 7.14 A dual-gate MOSFET mixer circuit.

transformer's primary. The IF is then removed from the transformer's secondary and sent on to the IF strip for further amplification and filtering.

Another low-cost active mixer is the *single-ended transistor* type of Fig. 7.15. Both the signal and the LO are inserted into the base and mixed together by the nonlinear Class AB biased transistor. Obviously, unless a diplexer is placed at the input, the RF and LO have no real isolation between their ports. The original RF signal and the LO frequency, as well as all mixing products, are present at the transistor's collector but, due to the

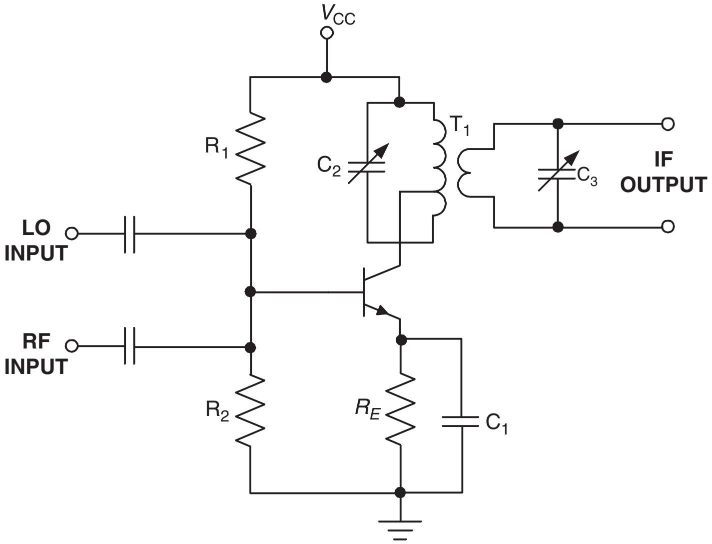


FIGURE 7.15 One method of using a transistor as a nonlinear mixer stage.

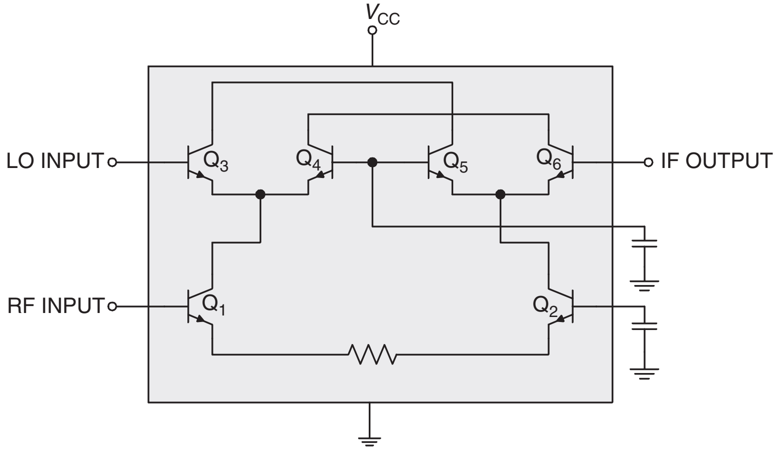


FIGURE 7.16 A simplified depiction of a Gilbert cell–integrated mixer.

primary and secondary tuned tank circuits, only the desired IF frequency will be of any significant amplitude.

Gilbert cell mixers, the most advanced of the active types, are commonly available up to RF frequencies of 5.8 GHz, with IF frequencies of 2 GHz, and are double balanced. A popular Gilbert cell mixer is shown in Fig. 7.16. The RF signal is inserted into the base of Q_1 of the modified emitter-coupled amplifier (comprised of Q_1 and Q_2), while the square wave LO is input into the base of Q_3. The LO causes Q_3 and Q_6 to be *on*, while next Q_4 and Q_5 transistors are turned *on*, causing mixing of the LO and the RF, creating the IF signal. When Gilbert cell IC mixers are operated at low frequencies, a square wave local oscillator must be used to decrease the steadily rising NF of the mixer, caused by the longer off times of the quad transistor's (Q_3, Q_4, Q_5, and Q_6). A square wave minimizes these off times.

Many active mixers can be operated past their maximum rated frequency, but there may then be a conversion loss instead of a conversion gain. Depending on design, these mixers are also available for both balanced and unbalanced operation, and can be found in low-cost surface-mount packages.

7.2.3 Active Mixer Design

Presented below are some low-cost discrete active mixer designs for consumer applications. However, the use of modern Gilbert cell–integrated mixers is sometimes the quickest and easiest route to take in today's fast-paced wireless market.

Dual-Gate Single-Ended Narrowband MOSFET Mixer for up to 250 MHz (Fig. 7.17)

This is a simple, inexpensive mixer that is a good choice for lower frequency RF applications in consumer wireless equipment. If the RF frequency is not exceptionally high, this MOSFET mixer will supply conversion gain. It does not require the high levels of LO drive that the passive mixers do, but has much lower intermodulation performance. The output port should be diplexed or padded to decrease IMD products. Stage gain will vary with LO amplitude and terminating impedances.

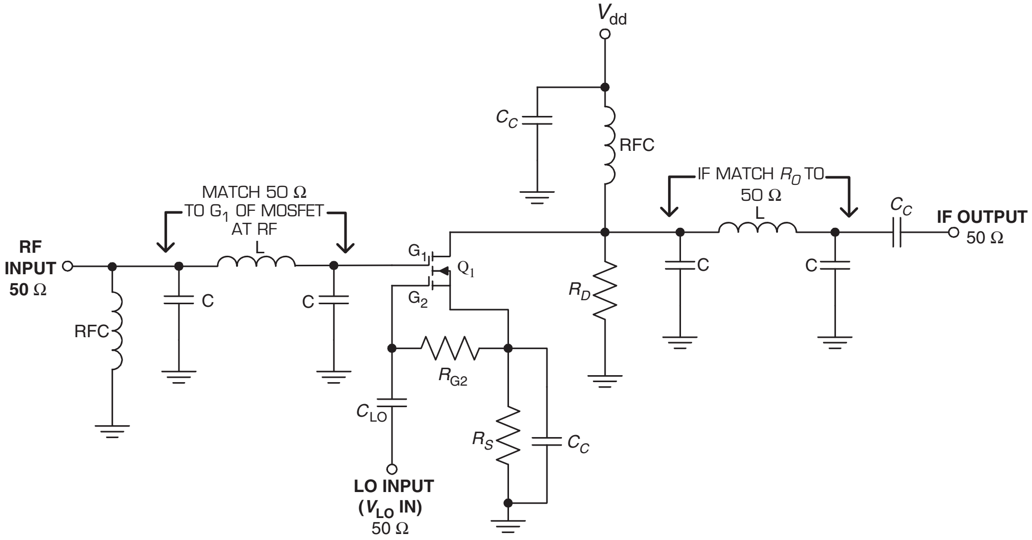


Figure 7.17 A narrowband active dual-gate MOSFET single-ended mixer design.

To Design

1. Select an RF dual-gate *N*-channel E-MOSFET that has plenty of gain at and significantly above the highest RF frequencies of interest.
2. $C_{LO} = C_C/10$ (if LO not buffered)
3. $R_{G2} = 100\ \text{k}\Omega$
4. $R_S = 560\ \Omega$
5. $C_C = < 1\ \Omega$
6. $V_{LO} \approx 6$ Vpp
7. $V_{dd} = 12$ V
8. $R_D = 2\ \text{k}\Omega$ to $5.6\ \text{k}\Omega$ (R_D pulls the MOSFET's drain down to the value of R_D, rather than to that of the MOSFET's low-frequency high-output impedance. This use of R_D helps IMD levels, but since Z_{OUT} drops as the frequency increases, R_D is not required at the higher frequencies.)
9. Match the input and output of the MOSFET to 50 Ω using *S*-parameters.

This MOSFET mixer should exhibit the following specifications:

$V_{G2} = 1$ V (supplied by self bias to MOSFET)

$P_{1dB} \approx 1$ dBm (output)

TOIP ≈ 17 dBm (output)

$RF_{IN} < -12$ dBm (for decreased IMD levels)

GAIN ≈ 12 dB – MAG (≈ +10 dB)

LO-to-RF isolation ≈ 30 dB

NF ≈ 8 to 10 dB

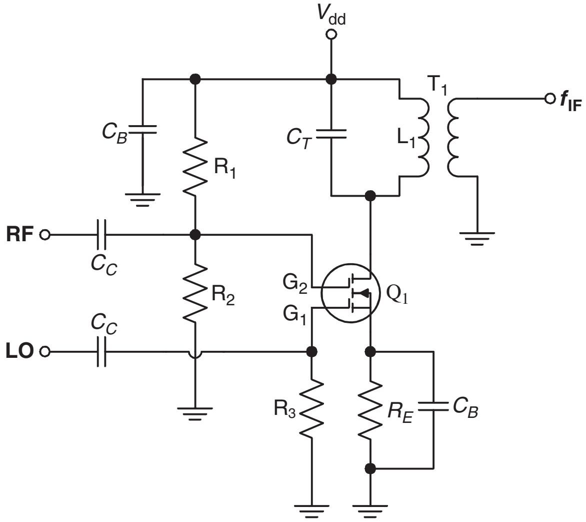


FIGURE 7.18 A dual-gate MOSFET mixer design.

Dual-Gate MOSFET Single-Ended Mixer for up to 400 MHz (Fig. 7.18)

This mixer is useful for undemanding consumer applications. The mixer's output should be diplexed or padded to decrease IMD's. Voltage gain of this mixer varies with LO amplitude and terminating impedances, but should be around a value of 10.

To Design

1. Select an RF dual-gate *N*-channel E-MOSFET that has plenty of gain at and significantly above the highest RF frequencies of interest.
2. C_B and $C_C = 1/(6.28 \cdot f)$
3. $C_T = \dfrac{1}{4[f_{\mathrm{IF}}^2(\pi^2 \cdot L_1)]}$

   or
4. $L_1 = \dfrac{1}{4[f_{\mathrm{IF}}^2(\pi^2 \cdot C_T)]}$

   where f_{IF} = frequency of the IF, Hz, f = frequency of the RF or LO, Hz.
5. $R_1 = R_2 = R_3 = 100\ \mathrm{k\Omega}$
6. $R_E = 1.2\ \mathrm{k\Omega}$

Distributed Narrowband GaAs FET Mixer for Microwave Operation (Fig. 7.19)

Even though a mixer is always run in nonlinear fashion, this mixer circuit can be effectively simulated using *S*-parameters in any linear software simulation program (such as the included *Qucs*). In this way the input and output impedances, as well as the stability analysis, can be roughly performed on a computer. After the circuit is computer analyzed, and then physically constructed, the microwave mixer must be further tweaked on the bench in order to provide the highest stability, conversion gain, and port isolation, as well as the lowest LO input drive requirements.

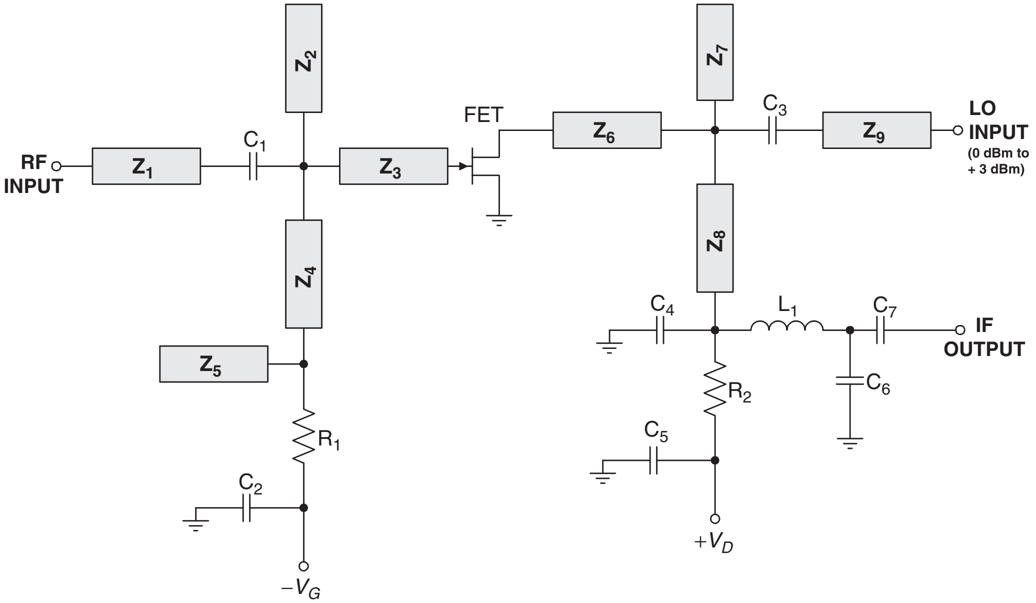


Figure 7.19 An active distributed mixer based on the JFET.

This active mixer design demands a good S_{11} match at the RF input of the FET at the RF frequency, with the FET's output being S_{22} matched at the LO frequency, along with the IF matched to the FET's output, which must form a diplexer. All of this permits the LO port to have a high return loss while rejecting the IF frequency, and allows the IF port to have a high return loss while rejecting both the RF and LO frequencies from being output, which enhances conversion gain, minimize LO drive power, and outputs a relatively clean signal from the mixer's IF port.

To Design

1. A GaAs JFET must be selected that can operate at a frequency far above the expected RF input frequency.
2. Z_1 and Z_9 are 50-Ω microstrip transmission lines.
3. C_1 will block DC, but pass the desired RF frequency with less than 1-Ω X_C.
4. Z_2 and Z_3 provide the proper input impedance match at the RF frequency for the JFET.
5. Z_4 acts as an distributed RFC to the desired RF frequency, while Z_5 functions as a capacitor. They form bias decoupling for the negative V_{CC} supply.
6. R_1 functions as a low-frequency termination to maintain mixer stability. Values of between 10 to 50 Ω should suffice.
7. C_2 is used to prevent the IF frequencies from exiting the RF port.
8. $-V_G$ should be adjusted from −5 to −1 V for best mixer operation.
9. Z_6 and Z_7 will match the S_{22} of the JFET at the LO frequency.

10. Z_8 functions as an RFC to attenuate the LO from entering the bias supply ($+V_D$) or the IF output port, but allows the DC and IF to pass unhindered. C_4 passes the LO to ground, and acts as the RF ground for Z_8.
11. C_5 bypasses the IF to ground to decouple from $+V_D$.
12. $+V_D$ should initially be set to +5 V, and then decreased for optimum performance.
13. L_1 and C_6 are chosen to match the IF frequency to the FET's output, while lowpass filtering the IF output for increased isolation.
14. C_7 is a DC block, but passes the IF with little attenuation. Could be parasitically series resonant to attenuate other frequencies besides the IF.
15. C_3 is a DC block, and should be chosen to operate at its series resonant frequency at the LO to assist in blocking the undesired IF frequency, while also increasing port isolation.
16. $R_2 = 50\ \Omega$

Integrated Circuit Double-Balanced Mixer for up to 5 GHz (Fig. 7.20)

Active mixers, such as the Agilent IAM-82028 and the IAM-82008, are useful in nonnoise sensitive applications that require a small LO input power (0 dBm). This IC mixer, unlike some active and many passive mixers, also possesses the very desirable trait of *load insensitive performance* due to its onboard buffer amplifier, and thus will have better IM suppression and conversion loss characteristics even if the RF and IF load impedances fluctuate. The IAM-82028 Gilbert cell–based mixer operates with a flat RF to IF conversion gain of 15 dB over a wide RF input range of 0.05 to 5 GHz, and enjoys an IF output capability of DC to 2 GHz. It has a maximum output P1dB value of 12 dBm, which is dependent on the V_{CC} voltage (7 V = 2 dBm, 12 V = 12 dBm), and will function with any V_{CC} between 7 to 13 V.

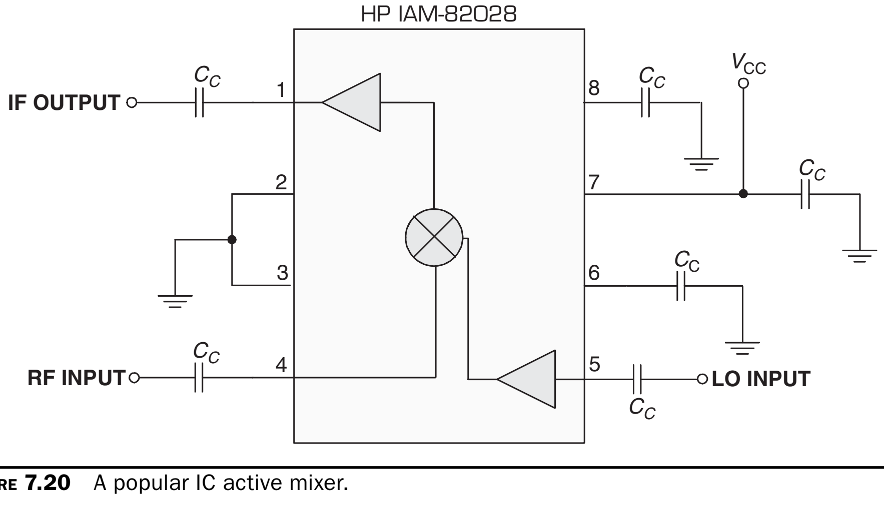


Figure 7.20 A popular IC active mixer.

To Design

1. Add the coupling/decoupling components as shown.
2. Supply the grounds and V_{CC}.
3. Done!

7.2.4 Active Mixer Issues

No circuit synthesis design software or calculation will produce a realizable mixer with 100% accuracy. This is due to the practical inability of formulas and programs to take into account PCB layout and component parasitic effects, as well as nonlinear device issues. Indeed, in order to obtain a realistic and optimized mixer stage, we must tune the as-calculated circuit values within a nonlinear RF simulator. This will also mean adding all the appropriate PCB traces, substrate, circuit elements, layout geometry, and full active/passive device models to the nonlinear mixer simulation. Therefore, unless the proper physical PCB layout, assembly, and circuit tuning have occurred within the RF software, then no microwave or RF circuit will operate as expected or as designed. Further, we will then have to perform, realistically, a certain amount of bench tuning in order to arrive at a final, reproducible mixer circuit that is fully optimized.

When an active mixer is utilized in any up conversion role, the input and output ports should not be swapped, as they would for a passive mixer (such as a DBM). The active mixer’s input port will still be for the RF, while the output port will still be for the IF. However, since the IF port is generally capable of less than half, to as low as a quarter, of the output frequency that the RF input port is capable of, then up conversion, at least with any gain, will be limited to the rated output frequency of the IF port. Thus, many active IC mixers will be incapable of being used for upconverting a signal beyond 1 or 2 GHz.

Since most active mixers are much less sensitive to port mismatches than passive diode models, the LO input to the active mixer will normally not require an external buffer amplifier, nor will the IF port need a diplexer.

Many IC mixers will have DC voltages present at all ports, necessitating a series blocking capacitor at the RF, IF, and LO ports.

7.3 Image-Reject and Harmonic Mixers

7.3.1 Introduction

An *image-reject mixer* in a superheterodyne receiver can be used to phase cancel an offending image frequency and noise, instead of employing a filter for this purpose, while a *harmonic-mode* mixer permits a designer to employ a much lower LO frequency than would normally be required.

7.3.2 Image-Reject Mixers

One way a mixer can be exploited to suppress image frequencies and noise in a receiver is shown in Fig. 7.21. By using Mixer1 and Mixer2 to downconvert both the desired signal *and* the image to baseband by a 0° and +90° phase-shifted LO, the baseband Q leg of the signal is altered by 90°, while the I leg is not phase shifted at all. These two signals are then inserted into the combiner and added, which cancels the image frequency, and

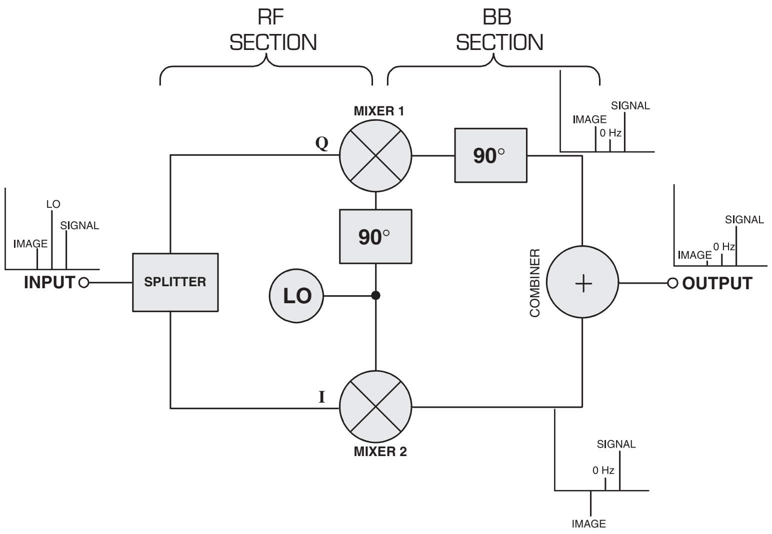


Figure 7.21 An image-reject mixer circuit.

adds the desired signal, doubling its amplitude. Image suppression is rarely better than 30 dB; however, so any high-amplitude signals present at the image frequency would still cause interference in channel.

7.3.3 Harmonic-Mode Mixers

Operating a mixer in harmonic mode allows a system designer to use a much lower LO frequency than would normally be required. Ordinarily, only the sum or difference frequencies are employed at the IF output of a mixer, but any convenient mixing product may be used for this purpose, such as $f_{RF} - 3f_{LO}$, $f_{RF} - 5f_{LO}$, $f_{RF} + 3f_{LO}$, or the $f_{RF} + 5f_{LO}$ products.

Nonreflective filtering must generally be placed at the mixer's output port, typically using a diplexer. The nonreflective filtering is necessary due to the reflective stopbands of a normal output IF filter, since the undesired signals and products would be reflected back into the IF port of the mixer, causing two-tone IMD performance to suffer.