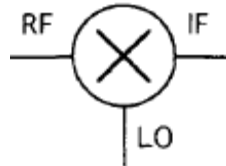


RF Mixers

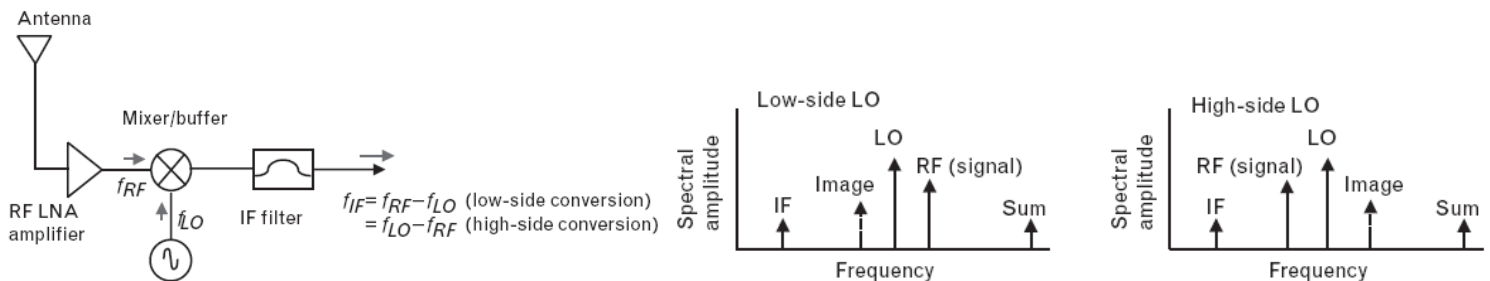
Iulian Rosu, YO3DAC / VA3IUL, <http://www.qsl.net/va3iul>

RF Mixers are 3-port active or passive devices. They 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.

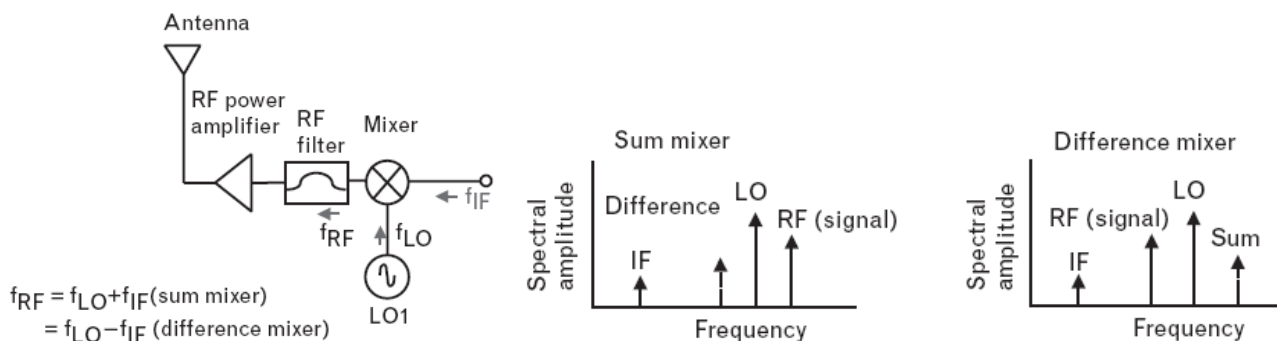
In addition to this, a Mixer can be used as a phase detector or as a demodulator.



The two signals inserted into the two input ports are usually the Local Oscillator signal, and the incoming (for a receiver) or outgoing (for a transmitter) signal. To produce a new frequency (or new frequencies) requires a nonlinear device. In a mixing process if we want to produce an output frequency that is lower than the input signal frequency, then it is called *down-conversion* and if we want to produce an output signal that is at a higher frequency than the input signal, it is referred to as *up-conversion*.



A down-conversion system



An up-conversion system

A common misunderstanding about mixers is that a Mixer is only a nonlinear device.

- Actually an RF Mixer is fundamentally a linear device, which is shifting a signal from one frequency to another, keeping (faithfully) the properties of the initial signal (phase and amplitude), and therefore doing a linear operation.

From the moment that we use a nonlinear device to perform the mixing operation, Mixers have relatively high levels of intermodulation distortion, spurious responses, and other undesirable nonlinear phenomena.

- In contrast to frequency multipliers and dividers, which also change signal frequency, Mixers theoretically preserve the amplitude and phase without affecting modulation properties of the signals at its ports.

Important Mixer properties are:

Conversion Gain or Loss, Intercept point, Isolation, Noise Figure, High-order spurious response rejection and Image noise suppression.

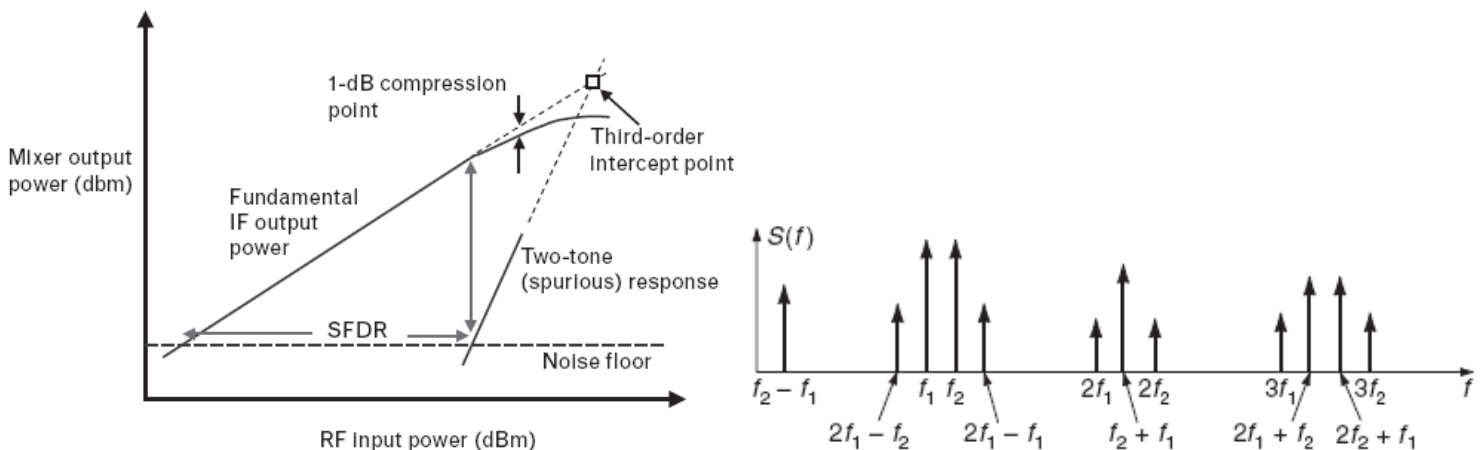
1. Conversion Gain or Loss of the RF Mixer is dependent by the type of the mixer (active or passive), but is also dependent by the load of the input RF circuit as well the output impedance at the RF port. Also is dependent by the level of the LO. The typical conversion gain of an active Mixer is approximately +10dB when the conversion loss of a typical diode mixer is approximately -6dB. The Conversion Gain or Loss of the RF Mixer measured in dB is given by:

$$\text{Conversion}_{[\text{dB}]} = \text{Output IF power delivered to the load}_{[\text{dBm}]} - \text{Available RF input signal power}_{[\text{dBm}]}$$

2. Input Intercept Point (IIP3) is the RF input power at which the output power levels of the unwanted intermodulation products and the desired IF output would be equal.

- From an RF System point of view, a Mixer linearity is more critical than Noise Figure.

The Third-Order intercept point (IP3) in a Mixer is defined by the extrapolated intersection of the primary IF response with the two-tone third-order intermodulation IF product that results when two RF signals are applied to the RF port of the Mixer.



3. Spurious products in a Mixer are problematic, and Mixer vendors frequently provide tables showing the relative amplitudes of each response under given LO drive conditions.

One way to reduce such products is to short-circuit the higher harmonics of the LO at the intrinsic Mixer terminals to lower the power in such responses. Reducing the second or third harmonic of the local oscillator reduces its harmonic products by 20 to 25 dB and 10 to 15 dB, respectively.

4. Isolation is the amount of local oscillator power that leaks into either the IF or the RF ports. There are multiple types of isolation: LO-to-RF, LO-to-IF and RF-to-IF isolation.

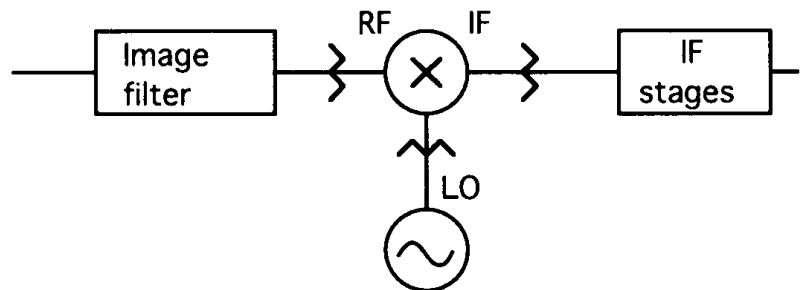
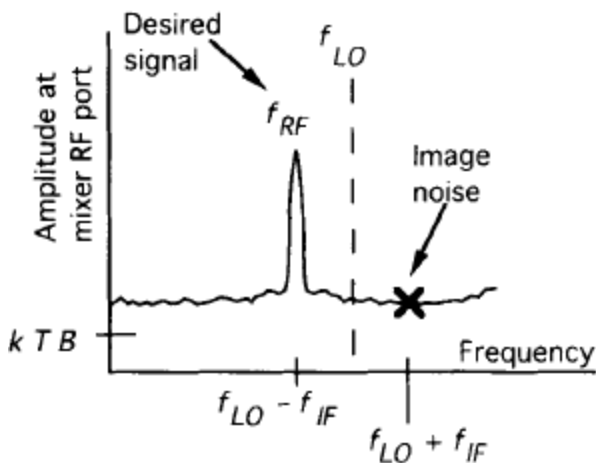
5. Noise Figure is a measure of the noise added by the Mixer itself, noise as it gets converted to the IF output.

- For a passive Mixer which has no gain and only loss, the Noise Figure is almost equal with the loss.
- In a mixer noise is replicated and translated by each harmonic of the LO that is referred to as Noise Folding.

In addition to the degradation in system Noise Figure introduced by the conversion loss of the Mixer, noise sources within the Mixer device itself further corrupt the Noise Figure. For example, the effect of $1/f$ noise in MESFETs can be severe if the IF frequency is below the corner frequency of the flicker noise (normally less than 1 MHz), as this noise will add to the output.

- A Mixer will convert energy in the upper or lower sidebands with equal efficiency. Consequently the noise in the side band with no signal will be added to the IF output, which will increase the Noise Figure at the IF port by 3dB, no matter how good the preceding component noise figure is. An Image Filter at the RF input of the Mixer could suppress this noise.

Also there are some particular Image Reject mixers that suppress the image noise by their topology.



The wideband noise of the Local Oscillator is another parameter that can raise the IF noise level, degrading in this way the overall Noise Figure. So, the wideband noise separated from the LO frequency by $\pm f_{IF}$ spacing will mix to produce noise at IF frequency.

- Any noise that is near a multiple of the LO frequency can also be mixed down to the IF, just like the noise at the RF.
This noise conversion process is related, *but not the same as*, the LO-to-RF isolation.
- Noise at frequencies of $\pm f_{IF}$ spacing from the LO harmonics also contributes to overall system Noise Figure.
- Wideband LO noise is down-converted to IF with much higher conversion loss than the desired signal and image noise.

- A Band Pass Filter between LO and the Mixer could help reducing the wideband LO noise.
- In case of Mixers, the Noise Figure is defined for both the image and RF responses, and the output noise is generated by the input termination includes only the noise arising from the principal frequency transformation of the system.

When a Single Sideband Noise Figure at the RF input is to be determined, the output noise arising from the input termination, at the image frequency is not included. Furthermore, it is impossible to measure directly the noise figure thus defined, because noiseless image terminations are difficult to obtain. The use of a filter to eliminate the image response (only to do accurate NF measurement) does not help because it changes the image-frequency embedding impedance, and hence changes the noise temperature. So, an alternate definition of *SSB Noise Figure* has found more common use.

When a noisy LO signal is applied to the Mixer, its noise components at the RF and image frequencies are down converted and appear at the IF port, just as if they had been applied to the RF input. It is important to pick the IF frequency high enough so that noise at the RF and image frequencies are well separated from the LO and can be filtered effectively.

- SSB NF assumes signal input from only one sideband, but noise inputs from both sidebands. Measuring SSB noise figure is relevant for Superheterodyne receiver architectures in which the image frequency is removed by filtering or cancellation.
- DSB NF includes both signal and noise inputs from both sidebands. A DSB NF is easier to measure; wideband excess noise is introduced at both the signal and image frequencies. It will be 3 dB less than the SSB noise figure in most cases. This is perhaps more relevant for Direct Conversion receivers where the image cannot be filtered out from the signal.

Mixers can be divided into several classes:

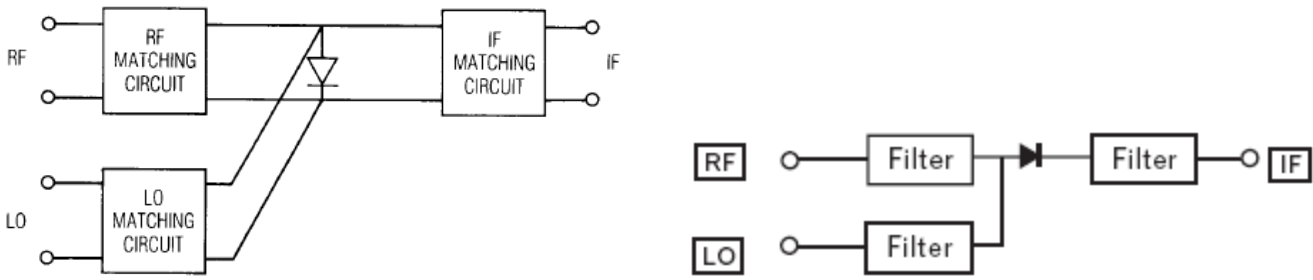
1. Single-device Mixer
2. Single Balanced Mixer
3. Double Balanced Mixer.

1. **Single-device Mixer** which is using one nonlinear component (one diode, or one transistor) has the disadvantage of not attenuating local oscillator AM noise and always requires an injection filter.

Single-device mixers need to follow some general design rules for best performance.

- To get the maximum conversion gain the LO node should be a short circuit at the RF and IF frequencies, while the RF node should be a short circuit at the LO frequency to prevent the LO leakage into the RF port.

Single-device Mixer using one diode is primarily a process of matching the pumped diode to the RF input and IF output, terminating the diode properly at LO harmonics and unwanted mixing frequencies (other than the RF and IF), and isolating the RF, LO, and IF ports. That isolation, and in some cases the termination, can be provided by using filters, a balanced structure, or both. The choice depends on the frequency range and the intended application.



The diode used for mixing can be modeled at the RF frequency as a resistor and capacitor in parallel. The resistor is usually in a range of 50 to 150 ohms and the capacitor between 1 and 1.5 times the junction capacitance. The IF output impedance is usually between 75 ohms and 150 ohms. At low IF frequencies the output impedance is almost pure resistive.

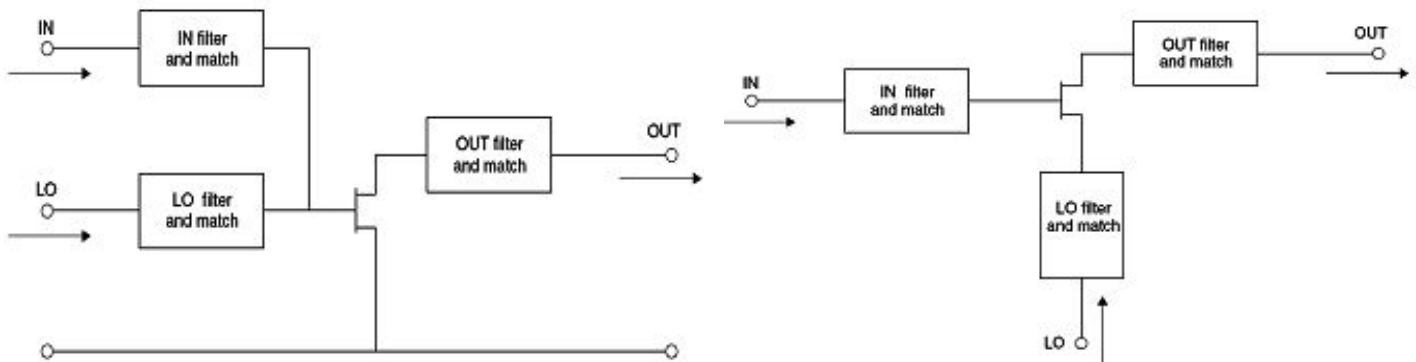
As the LO level increases, both RF and the LO input impedances decrease. The RF and IF input impedances mentioned above (high or low end on the range) are affected by the IF port termination on unwanted and LO harmonics frequencies. The diode's termination at the image frequency is the most critical of all the terminations at unwanted mixing frequencies.

- Terminating the IF port in a reactance at image frequency can improve the conversion efficiency of the Mixer.

For selecting the mixing diode have to look for the cut-off frequency of the diode, for series resistance R_s and junction capacitance C_j . Minimizing both R_s and C_j is necessary to achieve low conversion loss and distortion, but they are inverse trade-offs.

- Sometimes it helps to apply a DC bias to a single-diode mixer which can reduce the required LO power and provides a degree of freedom for adjusting the mixer's input and output impedances.

In active Single-device design case (i.e. one-transistor Mixer), to prevent oscillations the IF node should be a short circuit at both LO and RF frequencies, and RF should be low impedance at IF frequency. This also prevent that the noise at the IF frequency is not amplified and added to the output.

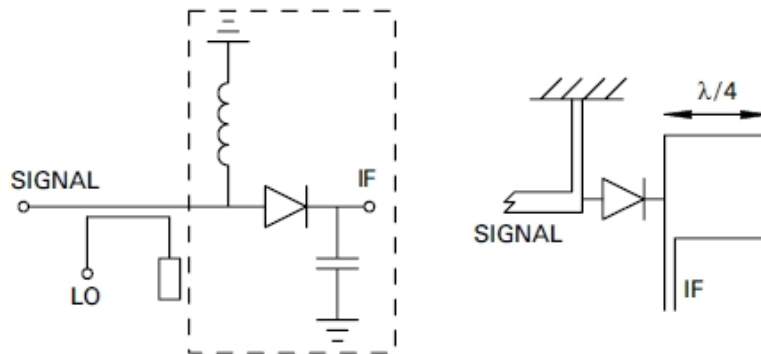


Single-device Mixers using FETs (two approaches for LO input)

The input filters, which are necessary to achieve RF-to-LO isolation and prevent radiation of the LO back through the antenna or other RF input, should attempt to short-circuit all unwanted frequencies (i.e., those other than the RF-and-LO) so there are no interfering voltages appearing at the input.

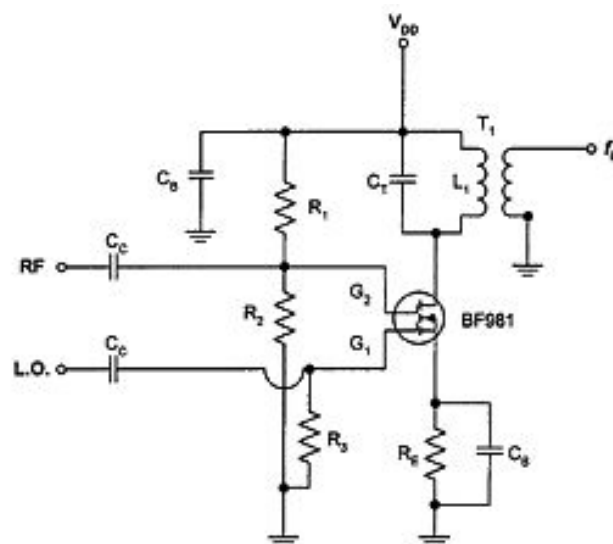
The input should be matched to the RF to maximize conversion gain and noise figure, and if possible, to the LO as well for LO power transfer. The image frequency should be short-circuited (if possible), as well as the IF, so neither noise nor spurious signals are amplified by the device. It is important that the device not behave as an amplifier at the IF, especially if the IF is low where the device gain is high.

- As a general rule in active Mixer design, all undesired frequencies should be short-circuited at both the input and the output to minimize distortion, noise, and for stability.
- The IF port impedance at IF frequency should be relative high for best conversion gain, but in this way decreasing the IM distortion performance.
- The IF port should provide enough rejection of the LO frequency in order to do not overload any further IF amplifiers down the chain.
- FET mixers, especially single-gate FET mixers with LO and RF applied to the gate, have more serious LO-to-RF isolation problem because the LO signal is amplified by the FET.



Single-device Mixers using one Diode

A dual-gate MOSFET will give much improvement for LO-to-RF isolation (approximately 20dB).



Dual-gate MOSFET Mixer

2. Balanced Mixers are grossly divided into two classes, called Singly-Balanced Mixers (SBM) and Doubly-Balanced Mixers (DBM).

- **Singly-Balanced mixers** use two devices, and are usually realized as two single-device mixers connected via a 180-degree or 90-degree hybrid.

Double balanced mixers usually consist of four un-tuned devices interconnected by multiple hybrids, transformers or baluns.

The advantages of balanced mixers over single-device mixers are:

- Rejection of spurious responses and intermodulation products.
- Better LO-to-RF, RF-to-IF and LO-to-IF isolation.
- Rejection of AM noise in the LO

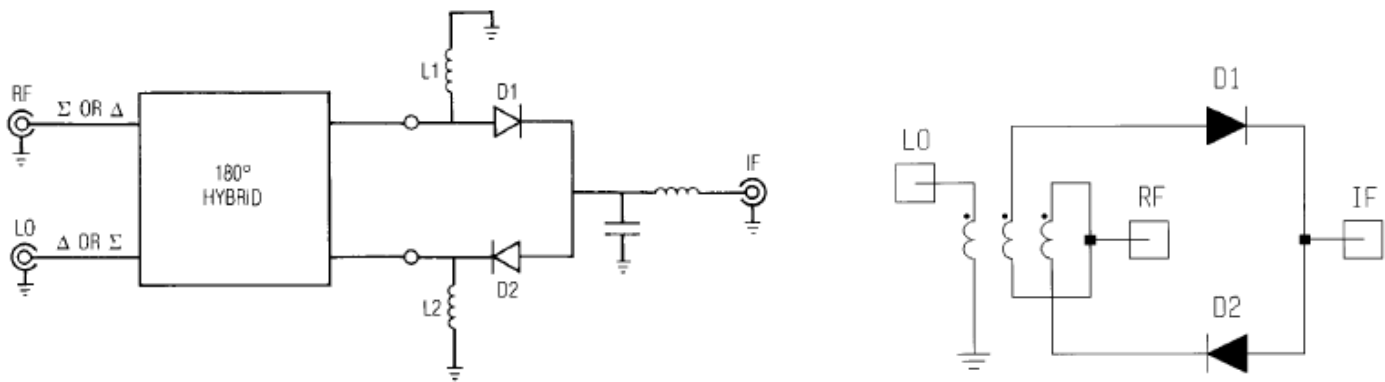
The disadvantage of balanced mixers is their greater LO power requirements.

Balanced mixers often used to separate the RF and LO ports when their frequency overlaps and filtering is impossible. In practice a perfect doubly balanced mixer give 10-30dB isolation without any filtering (depends by frequency and structure)

A Singly-Balanced Mixer consists of two single-diode mixing elements, which may be two diodes or two transistors.

In a singly-balanced diode Mixer it is essential that the DC path through the diodes to be continuous.

If the diodes are open-circuited at DC, the Mixer it will not work. Often, the hybrid provides that path.



In single-balanced using a quadrature hybrid the LO power reflected from the individual mixers does not return to the LO port, but instead exits the RF port; similarly, reflected RF power exits the LO port.

The LO-to-RF and RF-to-LO isolation is therefore equal to the input return loss of the individual mixers at the LO and RF frequencies, respectively; the port isolation of the quadrature hybrid mixer depends primarily on the input VSWRs of the two individual mixers, not on the isolation of the hybrid itself. Isolation of 10dB is typical.

If the RF port termination has a poor VSWR at the LO frequency, the circuit's balance can be upset and the LO pumping of the individual mixers becomes unequal.

The same, a poor LO port termination at the RF frequency can upset RF balance.

The even LO harmonics rejection depends by which port is used for LO input (Sigma or Delta).

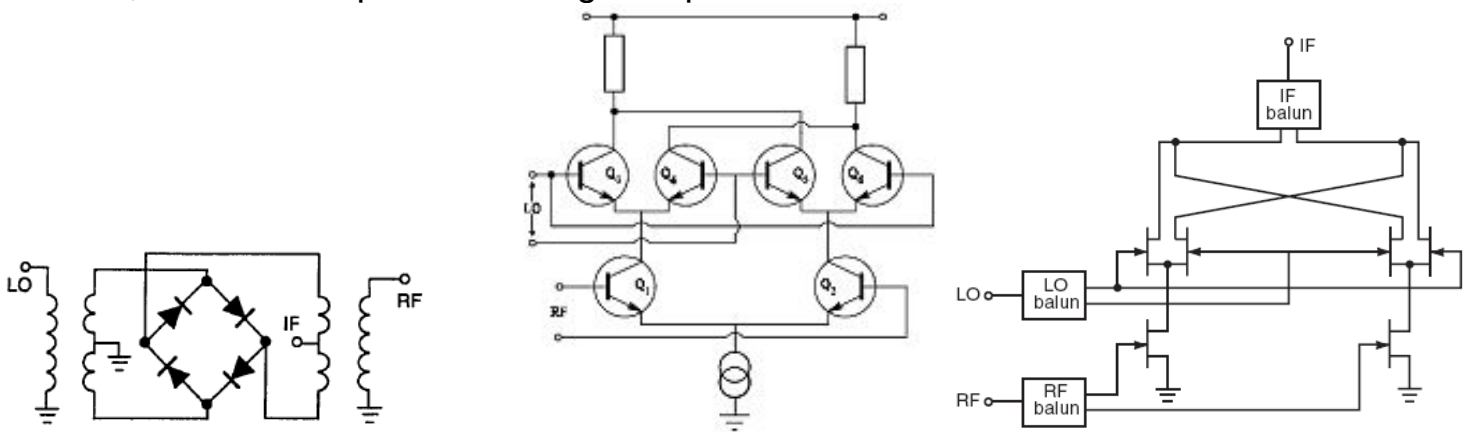
Whatever input is used for LO the mixer reject the even LO harmonics that mix with the even RF harmonics.

- To reduce the overall Noise Figure of the Mixer the two diodes shall be well matched. Diodes can be matched on RF characteristics (conversion loss, IF impedance and VSWR), but are more easily matched on DC parameters (junction capacitance, series resistance and forward voltage) that can be measured readily for all diode outlines, including beam lead types.

- **Doubly-Balanced Mixers** have higher conversion loss (or lower gain) than Singly-balanced Mixers and lower limit in maximum frequency, but has broader bandwidth.

The two most common types of doubly balanced mixers are the Ring Mixer and the Star Mixer.

The Ring Mixer is more suitable for low-frequency applications, in which transformers can be used, but it is also practical at high frequencies.



Double-balanced Mixers (Diodes, BJTs, FETs)

Ring Double-balanced Mixers can be described by treating its nonlinear components (diode or transistors) as switches, which are turned ON and OFF by the LO. This approach assumes that the conductance waveform of the diodes is a square wave, which is approximately true, as long as the LO level is great enough and its frequency is not too high.

- In Double-balanced diode Mixers because of the symmetry, even-order spurious responses are also rejected.
- Because the RF voltage is split between four diodes, the RF power in each diode is one-quarter that of a single-balanced mixer, so the 1-dB compression point and third-order intercept point are almost 6 dB higher.
- However, four times as much LO power is now required to pump the diodes to the same degree.
- The conversion loss is the same, because the RF power is split four ways and the IF power recombined four ways; therefore, the increase in intercept point provides a true increase in dynamic range due to the increase in output compared to a single diode.

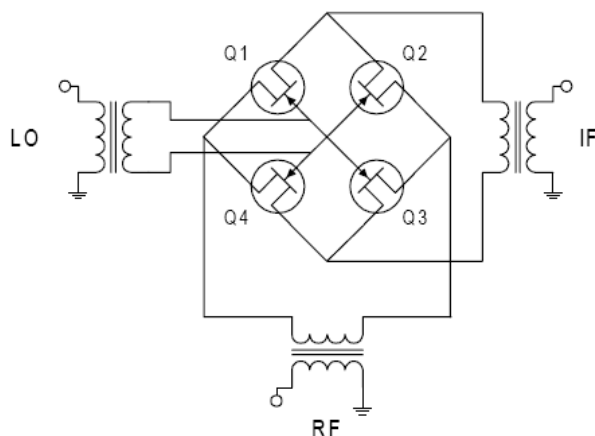
Beyond about +10dBm LO power, the increase in intercept point does not rise as fast as the LO power, because the ON diodes begin to limit the LO voltage across the OFF diodes, which are in parallel. To each diode, the RF current is indistinguishable from the LO current, and the total RF swing is therefore limited in the OFF condition. This can be improved by using two or more diodes in series in place of the single diodes shown.

- Many of the advantages of balanced structures, such as improved isolation, reduced spurious response, and improved intercept point, can be achieved for Active Mixers in the same way as for Diode Mixers.

Symmetric or anti-symmetric pairing of identical basic mixers provides an effective means to attenuate some unwanted frequency components in the spectra of the input and output signals.

The suppression is especially needed for the large local oscillator signal, which could saturate or seriously reduce the performances of an IF amplifier stage, but it is important for components with smaller amplitude also. Intermodulation within external systems of these unwanted components could mix with wanted signal and produce spurious signals that can interfere with other circuits of the system.

- Double-balanced FET Mixers can be designed for both passive and active use.
- Active FET Mixers based on Gilbert-cell architecture with biased semiconductor devices, can work with low LO levels and often provide conversion gain, but with decreased linearity compared to passive mixers.
- Passive FET Mixers, usually based on FET quads, provide good linearity but require high LO levels and exhibit high conversion loss.



The operation of this type of Mixer is similar to that of a conventional diode-based Double-balanced Mixer. The main difference is that the FET Mixer has six terminals, compared to the four terminals of the Double-balanced diode Mixer.

During the positive half-cycle of the LO signal to the FET mixer, two of the FETs are in conduction while the other two are turned off. As a result, the secondary winding of the RF balun is connected to the secondary winding of the IF balun through the FETs that are switched on. During the LO signal's negative half-cycle, the FETs which were on during the positive half-cycle are turned off and vice versa.

This results in a reversal of the polarity of the RF signal reaching the IF balun.

The frequency at which the FETs are turned on and off is determined by the frequency of the LO signal. This is mathematically equivalent to a multiplication of the RF and LO signals, resulting in the generation of sum and difference frequencies at the IF port. Compared to diode mixers, FET mixers have better P1dB compression point performances.

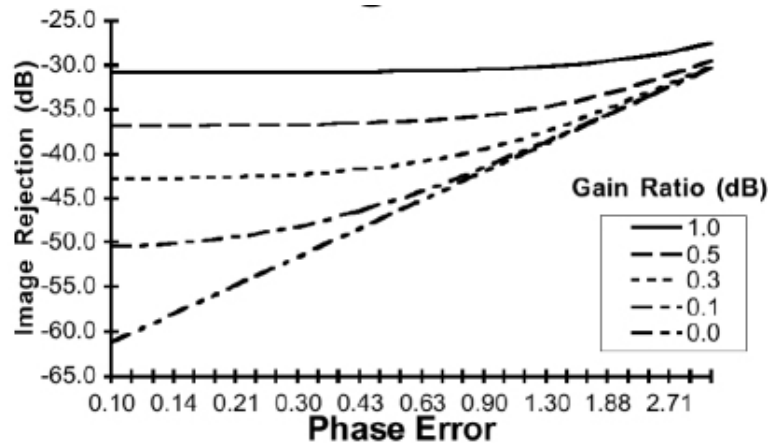
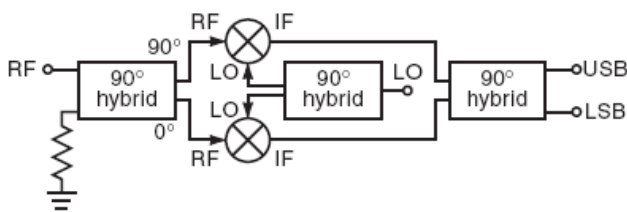
The linearity performance of a FET mixer, as evaluated in terms of the third-order intercept point, is affected by variations in the load impedance. Thus, the most predictable performance occurs with a purely resistance termination as the load. This type of stable termination can be achieved by terminating the mixer with a filter, but the filter appears purely resistive only within its 3-dB passband. As the filter's impedance rises beyond its passband, the mixer's intercept performance degrades.

- In an active FET mixer, the devices are biased for gain, but at the expense of intercept-point performance.
- Passive mixers require higher LO power levels, but provide better third-order-intercept performance.

Image-Reject Mixers

The Image-rejection Mixer is realized as the interconnection of a pair of balanced Mixers. It is especially useful for applications where the image and RF bands overlap, or the image is too close to the RF to be rejected by a filter.

The LO ports of the balanced mixers are driven in phase, but the signals applied to the RF ports have 90 degrees phase difference. A 90-degree IF hybrid is used to separate the RF and image bands.



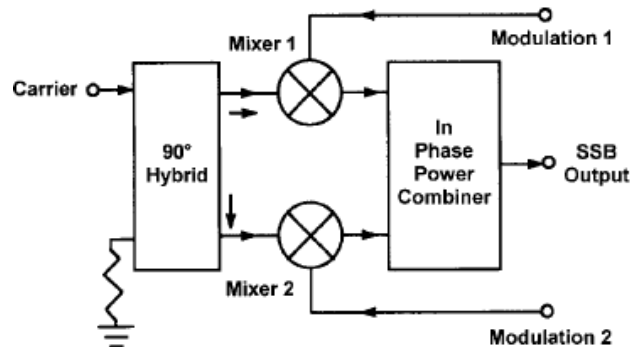
- Image Rejection improves with higher LO.
- Image rejection depends more strongly on phase mismatch.

Single-Sideband (SSB) or In-Phase/Quadrature (I/Q) Mixers

SSB or I/Q modulators are useful in discriminating and removing the lower sideband (LSB) or upper sideband (USB) generated during frequency conversion, especially when sidebands are very close in frequency and attenuation of one of the sidebands cannot be achieved with filtering.

- With an I/Q modulator, one of the sidebands is attenuated along with its carrier.

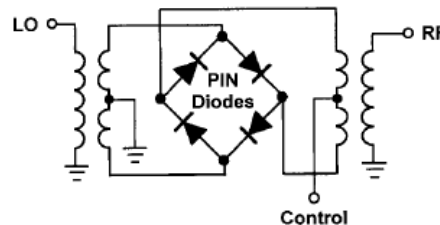
I/Q modulators basically consist of two Double-balanced Mixers. The Mixers are fed at the LO ports by a carrier phase-shifted with 90 degrees (0 degrees to one mixer and 90 degrees to the other mixer). Modulation signals are fed externally in phase quadrature to the two mixers IF ports. The modulated mixers outputs are combined through a two-way in-phase combiner.



The circuit forms a phase cancellation network to one sidebands and a phase addition network to the other sideband. The carrier is also attenuated and is directly dependent on the LO-to-RF isolation of the two mixers.

Phase and amplitude imbalance errors affect the side band suppression.

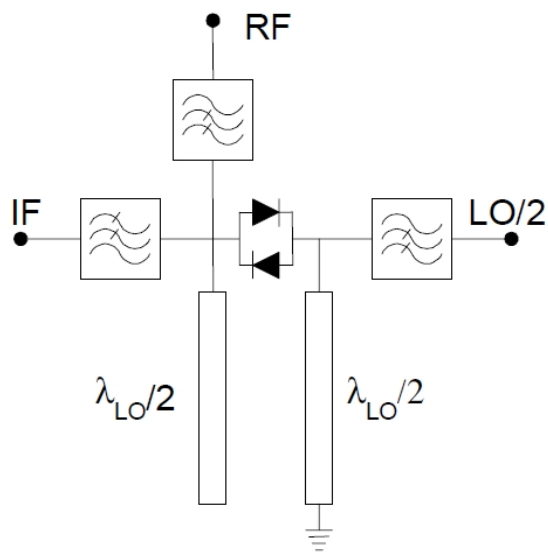
- A diode Double-balanced Mixer can be used as a **DC-controlled attenuator** if PIN diodes are used instead of Schottky devices in its ring.



Sub-harmonic Mixers

A Sub-harmonic Mixer has an LO input at frequency = LO/n . They are useful at higher frequencies when it can be difficult to produce a suitable LO signal (low phase noise, tuning range and output power all become more difficult to achieve with increasing frequency, whilst cost increases).

- Sub-harmonic mixers use anti-parallel diode pairs.
- These mixers produce most of their power at “odd” products of the input signals.
- Even products are rejected due to the I-V characteristics of the diodes.
- Attenuation of even harmonics is determined by diodes “balance”.
- Diode “match” is critical.



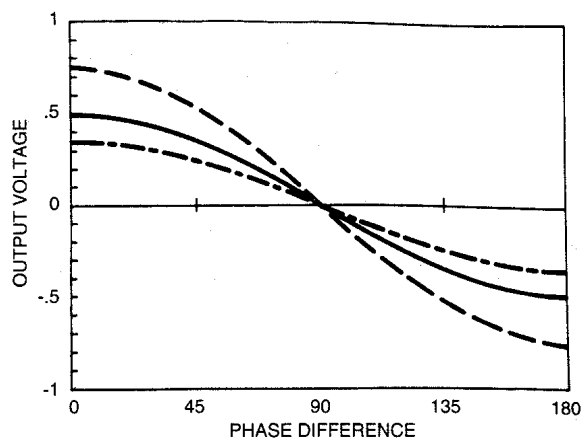
- The short circuit $\lambda_{LO/2}$ stub at the LO port is a quarter of a wavelength long at the input frequency of LO/2 and so is open circuit. However, at RF frequency this stub is approximately a half wavelength long, so providing a short circuit to the RF signal.
- At the RF input the open circuit $\lambda_{LO/2}$ stub presents a good open circuit to the RF but is a quarter wavelength long at the frequency LO/2 and so is short circuit.
- The IF is normally far enough away from the RF frequency to allow easy realization of an IF filter presenting an open circuit output to the RF port.

Mixers as Phase Detectors

In a Double-balanced Mixer the output at the IF port contains the sum and difference of the frequencies of the signals input to the LO and RF ports.

- If the RF and LO signals have identical frequencies, then their difference is zero Hz, or DC, which is the desired output for a phase detector. Their sum, which is twice the input frequency, can be selectively filtered out if it is not already beyond the frequency response of the IF port.

The voltage at the IF port will be DC and will vary as the cosine of the phase difference between the LO and RF signals. Null readings for IF voltage are thus obtained whenever the phase difference between the LO and RF signals is equal to $n \cdot \pi/2$ with $n = \pm 1, \pm 3, \dots$, while maximum and minimum readings are obtained for phase difference equal with $n \cdot \pi$ where $n = 0, \pm 1, \pm 2, \dots$



Practical mixers that are used as phase detectors they often display some characteristics which differ from those of idealized mixers.

The characteristics of most interest are DC offset and/or mixer-induced phase shift of the signals due to circuit imbalance. Parameters that affects these characteristics are: frequency, LO and RF drive levels, load resistance, and temperature.

- The origin of DC offset voltages is a combination of diode imbalance and transformer asymmetry and can come from either or both input signals. In addition to isolation and LO drive level, DC offset is also affected by the load resistance and temperature.
- Even after the effects of DC offset have been minimized, it is still possible that a null reading will be obtained at some relative phase other than $\pi/2$ (90 degrees). This is because the mixer itself may change the relative phase of the two input signals due to the fact that the electrical length from the LO-to-IF port is not identical to that from the RF-to-IF port.
- Frequency affects the DC offset by virtue of its effect upon isolation.
- Higher the isolation between ports, lower the DC offset.
- Also, as conversion loss decreases, maximum output DC voltage increases.

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