# Mixers

## Introduction

Figure 1 shows the typical block diagram of a Transmitter and a Receiver. It can be seen that in both cases frequency translation is achieved by the use of a Mixer. The mixers can be either passive mixers using diodes or they can be active mixers using transistors or FETs. In many receivers and transmitters, a succession of mixing and filtering stages are used, to ensure that the filtering requirements can be satisfied.

A mixer is used as an up-converter when the output frequency is higher than the input frequency. This is typical in a transmitter. A mixer is used as a down-converter when the output frequency is lower than the input frequency. This is typical for a receiver.

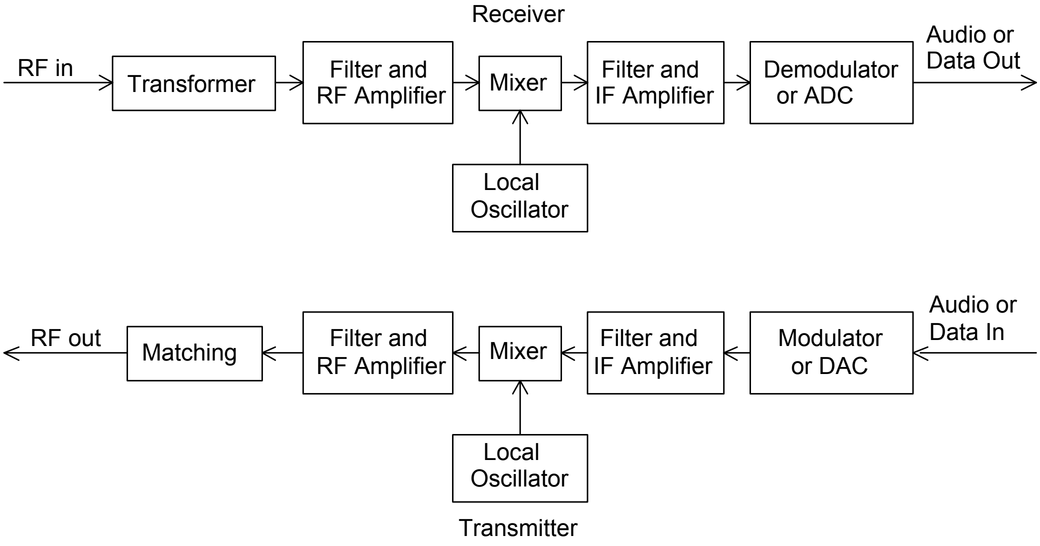



Figure 1. Typical transmitter and receiver block diagram.

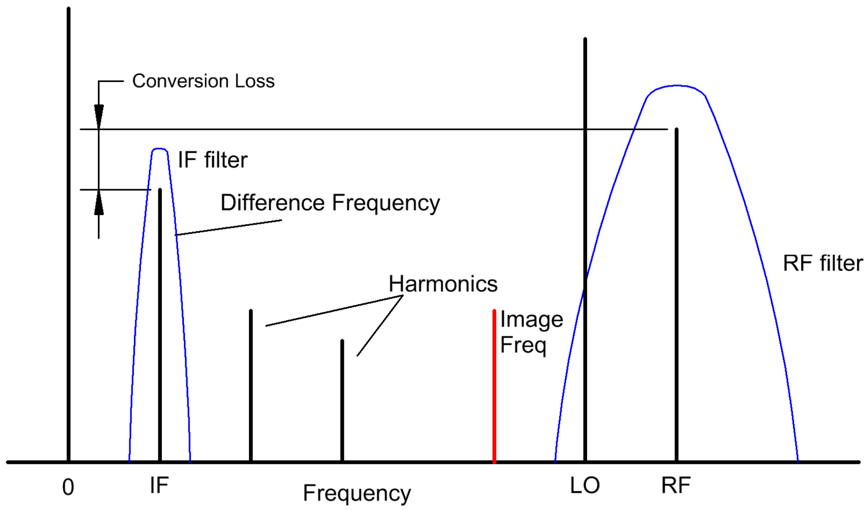



Figure 2. Frequencies of a mixer.

Figure 2 shows the frequencies that need to be considered when using a mixer. For a down-converter the Radio Frequency (RF) signal is mixed with a Local Oscillator (LO) signal to produce sum and difference frequencies. The sum frequency is outside the operating frequency range of the system and the difference frequency is the required Intermediate Frequency (IF) signal, which is filtered and amplified using an IF filter and its associated amplifiers.

The RF filter should be sufficiently narrow so that the image frequency is not passed through the RF filter, since the difference frequency of the image frequency and the local oscillator is at exactly the same frequency as the required IF signal.

An ideal multiplier is a perfect mixer since when the LO signal is multiplied by an RF signal then sum and difference frequencies are generated, the difference frequency being the required IF signal and the sum signal being an unwanted high frequency component, which is normally filtered out. For an up-converter, the LO signal is multiplied by an IF signal and a double sideband suppressed carrier RF signal results. The aim in mixer design is thus to make the mixer behave as close to an ideal multiplier as possible.

There are two types of mixers: 1) Passive mixers, using diodes, where the LO power provides the power for the mixer. 2) Active mixers, where transistors or FETs supplied with DC power provide the mixing action.

# Definition of Terms

## *Conversion Loss*

For a down-converter, the conversion loss is the ratio of the wanted IF output signal to the RF input signal. Most mixers are used in receivers, for which this definition is applicable. For up-conversion, the conversion loss is the ratio of one of the wanted RF output signal spectral components to the IF input signal. For an ideal mixer, half the input power is frequency shifted to the difference frequency and half the power is shifted to the sum frequency. The conversion loss is the ratio of either the sum or the difference component to the input signal. An ideal passive mixer will thus have a conversion loss of 3 dB. Practical balanced or double balanced mixers typically have a conversion loss of less than 6 dB. The conversion loss does depend on the amount of LO signal power applied to the LO port as can be seen in figures 11, 20 and 28. The mixer is normally operated at a LO power close to that giving the lowest conversion loss. Active mixers can have a conversion gain.

The conversion loss must be taken into account in noise figure calculations of a receiver. A mixer with a 6 dB conversion loss typically has a 6.5 dB noise figure. For high quality receivers, an amplifier with a gain much greater than the conversion loss is normally used before the mixer, to ensure that the mixer does not dominate the noise performance of the receiver.

## *Isolation*

In practice it is desirable to have isolation between the LO, RF and IF ports of the mixer. Typical double balanced mixers have more than 30 dB isolation between all ports. Single diode mixers have virtually no isolation between ports. Since single diode mixers are used in TV receivers, the LO signal is coupled to the antenna, which radiates the LO signal. In countries where TV licences are required, the “detector vans” look for the LO radiation and match the radiation coming from a house with any licence fee payment. One can also do a good survey to find out what TV channel people are watching by simply driving around a street with a spectrum analyser and noting the LO frequencies. For a balanced mixer, the isolation is directly related to the match between the diodes used. As a result many manufacturers sell matched sets of diodes, specially for use in mixers. In many cases two or 4 diodes come as one package.

## Compression Point

For an ideal down-conversion mixer the IF output produced should be directly proportional to the RF input signal. However as the RF input approaches about 10 dB below the LO power. The IF output starts to saturate and the conversion loss starts to decrease, as is shown in figure 3. Most manufacturers of mixers specify the 1 dB compression point for their mixers. The 1 dB compression point is typically 6 dB below the LO level for mixers up to +23 dBm LO power.

Since the 1 dB compression point is related to the LO drive, a higher LO level results in a higher 1 dB compression point and as a result a bigger dynamic range of the mixer.

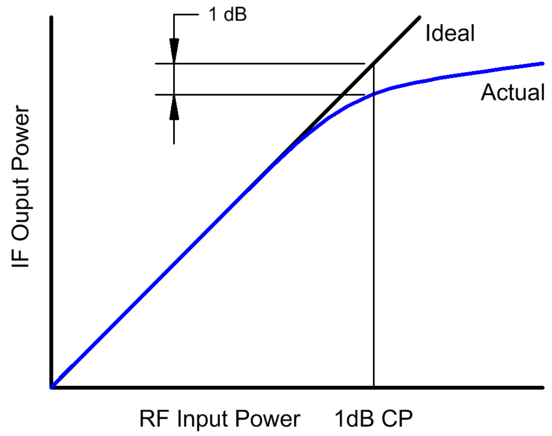



Figure 3. 1 dB Compression Point of a mixer.

## Dynamic Range

Dynamic range is the range over which a mixer provides useful operation. The upper limit of the dynamic range is determined by the 1 dB compression point. The lower limit of the dynamic range is limited by the noise figure of the mixer. Since the mixer noise figure is only about 0.5 dB higher than its conversion loss, the lowest conversion loss is desirable to obtain the largest dynamic range. High and Extra High level mixers have a higher 1 dB compression point and thus a bigger dynamic range. Higher level mixers are significantly more expensive and require more LO power, so that a compromise between cost, power consumption and dynamic range exists.

## Two-tone Third Order Intermodulation Distortion

In this section one considers the mixer as a “linear” device, since the for a down-converter, the IF mixer output amplitude is directly related to the RF input amplitude. The output Y(t) of a mixer or amplifier will depend on the input X(t). The gain of the device, relating the output to the input is $a_1$. In addition a DC component and harmonics of the input may be created due to the distortion of the device. The output is thus:

$$Y(t) = a_0 + a_1 X(t) + a_2 X(t)^2 + a_3 X(t)^3 + a_4 X(t)^4 + a_5 X(t)^5 + .... \qquad \text{Eqn. 1}$$

For the devices we are considering, the terms above the 5th harmonic are so small they can be ignored.

When two signals $X_1$ and $X_2$ are used as input. The output will then be:

$$\begin{aligned} Y(t) = a_0 + a_1[X_1(t) + X_2(t)] + a_2[X_1(t) + X_2(t)]^2 + a_3[X_1(t) + X_2(t)]^3 + \\ a_4[X_1(t) + X_2(t)]^4 + a_5[X_1(t) + X_2(t)]^5 + .... \end{aligned} \qquad \text{Eqn. 2}$$

When $X_1(t)$ is a sinewave of frequency $F_1$ and $X_2(t)$ is a sinewave of frequency $F_2$ , ($F_2 > F_1$) the frequency components at the fundamental and different intermodulation frequencies can be collected as follows:

The fundamental frequency component, i.e. at $F_1$ due to $X_1(t)$ and at $F_2$ due to $X_2(t)$ is:

$$Y_F = a_1 + (\frac{3}{4} + 3\frac{1}{2})a_3 + (\frac{5}{8} + 10\frac{3}{8} + 5\frac{3}{8})a_5 = a_1 + \frac{9}{4}a_3 + \frac{25}{4}a_5 \qquad \text{Eqn. 3}$$

The Third Order Intermodulation (3IM) frequencies are 3IM(upper) due to $\pm F_1 \pm 2F_2$ and 3IM(lower) due to $\pm 2F_1 \pm F_2$ , and are given by:

$$Y_{3IM} = \frac{3}{4}a_3 + \frac{1}{2}(5\frac{1}{2} + 10\frac{3}{8})a_5 = \frac{3}{4}a_3 + \frac{25}{8}a_5 \qquad \text{Eqn. 4}$$

The Fifth Order Intermodulation (5 IM) frequencies are 5IM(upper) due to $\pm 2F_1 \pm 3F_2$ and 5IM(lower) due to $\pm 3F_1 \pm 2F_2$ , and are given by:

$$Y_{5IM} = \frac{1}{2}10\frac{1}{8}a_5 = \frac{5}{8}a_5 \qquad \text{Eqn. 5}$$

The frequencies of these spectral components are shown in figure 4.

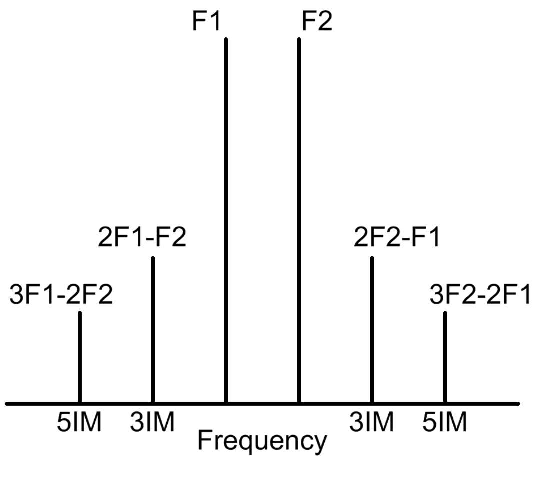



Figure 4. IM distortion of an amplifier or mixer.

The second order intermodulation (2IM) and the fourth order intermodulation (4IM) distortion produced by the amplifier or mixer does not create any components near the desired frequency components an as a result the 2IM and 4IM performance is less important for an amplifier. The second order intermodulation produces the required mixing action in a mixer and is thus of utmost importance.

The third order IM (3IM) and fifth order IM performance is very important in linear amplifiers since when two tones are used as an input to the amplifier, the 3IM and 5IM distortion results in additional frequency components, which again can not be filtered out, as can be seen in figure 4. The 5IM components are often too small to be observed in a spectrum like figure 4. For mobile phone base-stations, these IM signals are likely to create interference in adjacent mobile phone channels, as a result the IM performance of amplifiers and mixers are a critical part of their specification.

## *Third Order Intercept Point*

In practice $a_1 >> a_3 >> a_5$, so that the fundamental frequency components are proportional to $a_1$, the 3IM components are proportional to $a_3$ and the 5IM components are proportional to $a_5$. If the input signals are increased by 1 dB, then the 3IM components will increase by 3 dB since they are caused by $a_3[X_1(t)+X_2(t)]^3$ in equation 2 and the 5IM components will increase by 5 dB since they are caused by $a_5[X_1(t)+X_2(t)]^5$ in equation 2.

A popular method of determining the “linearity” of a mixer is the "third-order intercept" approach. The Third-Order Intercept Point is a theoretical point on the RF input versus IF output curve where the desired input signal and third-order products become equal in amplitude as RF input is raised.

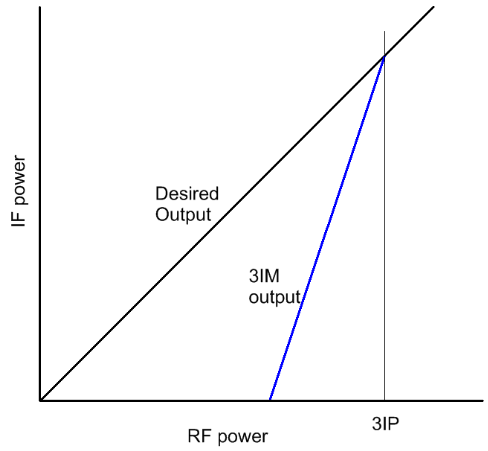



Figure 5. Third order intercept point.

As the RF signal increases by 1 dB, the 3IM distortion component increases 3 dB. The Third Order Intercept Point is determined by increasing the RF level and noting both the desired and the 3IM levels. The third order intercept point is the point where the extension of the plotted desired output and 3IM output level versus RF input meet, as shown in figure 5. It is not possible to drive the mixer to those RF levels. As a rule of thumb the third order intercept point is about 8 to 10 dB above the LO level for a typical diode based double balanced mixer and up to 15 dB above the LO level for passive FET mixers. Passive FET mixers however have a much narrower bandwidth.

The third order intercept point is useful in determining the RF level required for a specified 3IM distortion performance. If for example, the 3IM signal is to be 40 dB below the required signal, then the RF level must be 20 dB below the Third Order Intercept Point, since then the desired signal will be 20 dB below the intercept point and the 3IM signals will be 3*20 = 60 dB below the intercept point.

### LO Level

Mixer manufacturers make mixers to operate at different LO power levels. For standard level mixers, the LO power required is +7 dBm. Other mixer power levels are +10, +13, +17, +23, +27 dBm. Minicircuits denote their mixer according to the LO power required, so a Level 7 mixer requires a LO power of +7 dBm. For a good Double Balanced Mixer, the third order intercept point (IP3) is 10 dB above the LO level. By having a higher power level available, the manufacturers are able to control the diode I-V characteristics more to ensure that the $a_2$ coefficient in the binomial expansion of the diode I-V characteristic shown as Equation 1, 2, 6 and 7 is maximized in relation to the other terms, thus minimizing the unwanted components.

### Example

A maximum RF input signal of -10 dBm and a level of third order intermodulation products (3IM) of 60 dB below the desired signals is required for a specific application. For a typical 7 level mixer, the IP3 point is +17 dBm. The RF signal at -10 dBm is thus 27 dB below the IP3 point. This will result in the 3IM signals being (3-1)*27= 54 dB below the wanted signal.

Similarly, a level 10 mixer will result in the 3IM signals being (3-1)*30 = 60 dB below the wanted signals, a level 13 mixer will result in the 3IM signals being (3-1)*33 = 66 dB below the wanted signals. A level 17 mixer will result in the 3IM signals being (3-1)*37 = 74 dB below the wanted signals. A level 23 mixer will result in the 3IM signals being (3-1)*43 = 86 dB below the wanted signals and a level 27 mixer will result in the 3IM signals being (3-1)*47 = 94 dB below the wanted signals. The higher the LO level, the higher the cost of the mixer. A level 10 mixer with thus be the lowest cost device, which will satisfy the specifications.

## Single Diode Mixer

Single diode mixers use a single diode to produce the required frequency components.

Single diode mixers are often used in cost critical applications, such as Radio or TV receivers, where the low cost is more important than good performance. With the advent of low cost active mixer IC's, single diode mixers are progressively being used less. Single diode mixers are very suitable for microwave applications like speed guns and shopping centre door openers, where the transmitted signal is used as the LO for the received signal, and the receiver diode is simply mounted in the antenna horn. The resulting IF signal is the difference frequency, which is due to the speed of the car being detected or the speed of the person moving towards the door.

A single diode mixer requires a diplexer to separate the high frequency RF and LO signal from the low frequency IF signal. Since the single diode mixer is normally a lower cost consumer type application, the diplexer is normally kept simple with either a first or second order high pass and low pass filters.

Figure 6 shows a simple diplexer consisting of second order high pass and low pass filters. The crossover frequency is chosen to be 20 MHz, allowing baseband signals up to 15 MHz to be used. To obtain the best impedance looking into port 1, series elements are required to connect to port 1. A Butterworth high pass and low pass filter design is a good starting point and optimisation can be used to improve the impedance matches resulting in the diplexer performance as shown in figure 7.

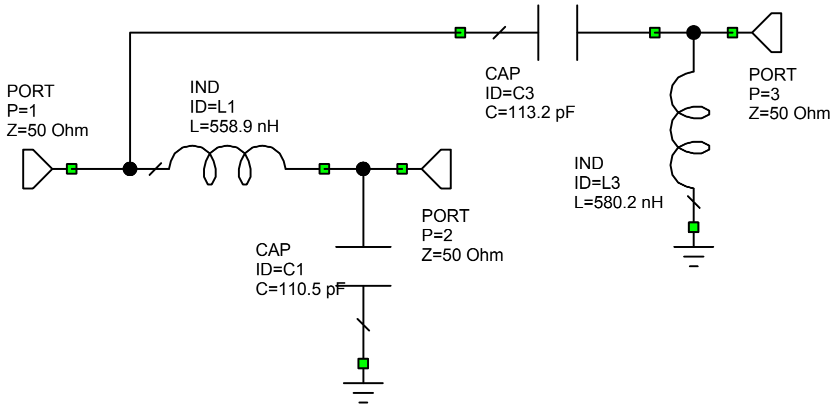



Figure 6. Diplexer circuit.

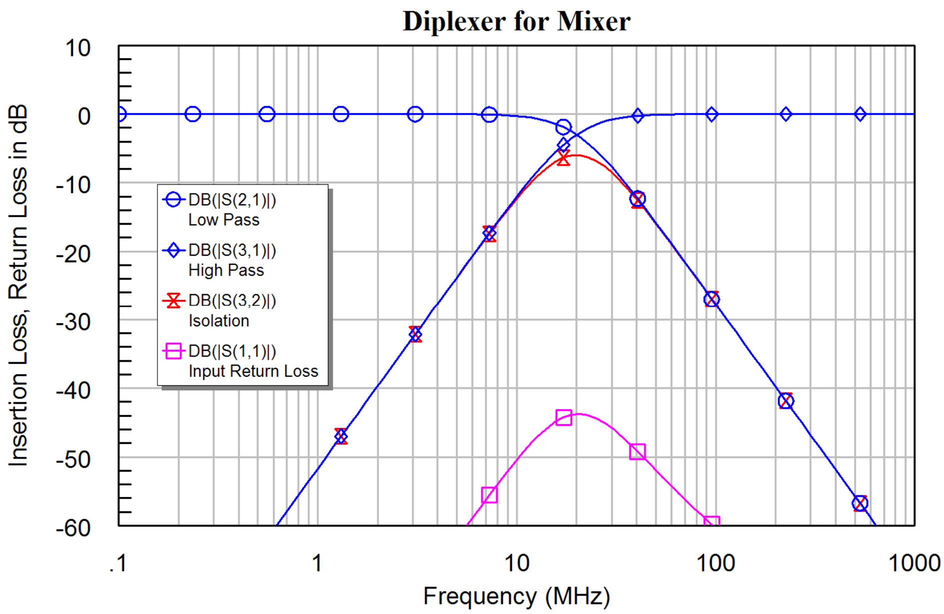



Figure 7. Frequency response of diplexer after optimisation.

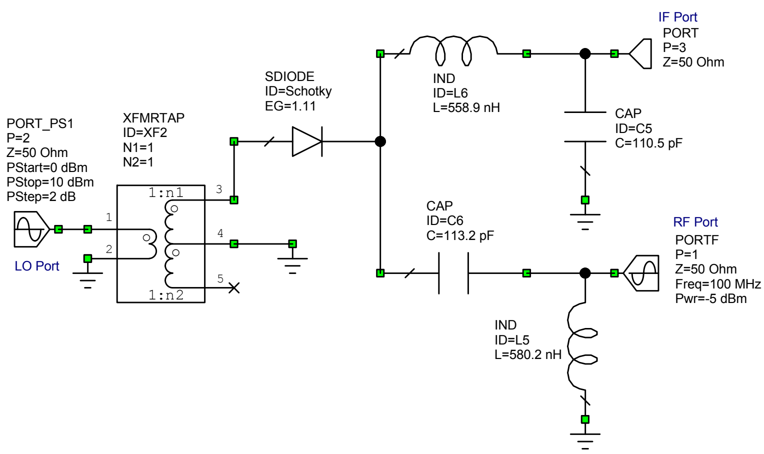



Figure 8. Circuit diagram of a single diode mixer as a down-converter.

Figure 8 shows the circuit diagram of a single diode mixer. The transformer is normally not included in the circuit, since in this case it is simply a non-inverting transformer. It is included here to illustrate the differences between the single diode mixer of figure 8 and the balanced mixer of figure 19.

The mixing behaviour of a single diode mixer can be demonstrated by considering the current flowing through the diode of figure 8. The current can be expressed as:

$$I_a = a_0 + a_1 V_a + a_2 V_a^2 + a_3 V_a^3 + a_4 V_a^4 + a_5 V_a^5 + \dots \qquad \text{Eqn. 6}$$

If two voltages $V_a$ and $V_b$ are now applied to the diode, due to the LO and the RF signals, then the current will be

$$\begin{aligned} I_a = {} & a_0 + a_1(V_a + V_b) + a_2(V_a + V_b)^2 + a_3(V_a + V_b)^3 \\ & + a_4(V_a + V_b)^4 + a_5(V_a + V_b)^5 + \dots \end{aligned} \qquad \text{Eqn. 7}$$

The term $a_2(V_a + V_b)^2 = a_2(V_a^2 + 2V_aV_b + V_b^2)$ contains the required $2a_2V_aV_b$, which results in the sum and difference frequencies. All the other terms cause unwanted frequency components. It is thus desirable to use diodes with an I-V characteristic where $a_2$ is large in comparison with the other terms in the binomial expansion of the I-V characteristic. Some of the additional frequency components due to the $a_3$ , $a_4$ and higher order diode nonlinearities, can fall close to the desired frequency thus causing an interference.

## Computer simulation of Mixers

The advanced RF Computer simulation programs like MWO and ADS allow mixers to be simulated accurately. A mixer requires two inputs, both at different frequencies and the output is normally at a frequency that is different from both the inputs to the mixer. The simulation is thus very different from that of a linear device, like a transformer, hybrid or filter.

The frequencies used for the simulation are set by the Project Options menu. For the single diode mixer of figure 8, these frequencies are used by the PORT_PS1 port element, which is applied to the LO port (Port 2). The PORT_PS1 element allows the signal power to be varied as specified by the parameters for the PORT_PS1 element.

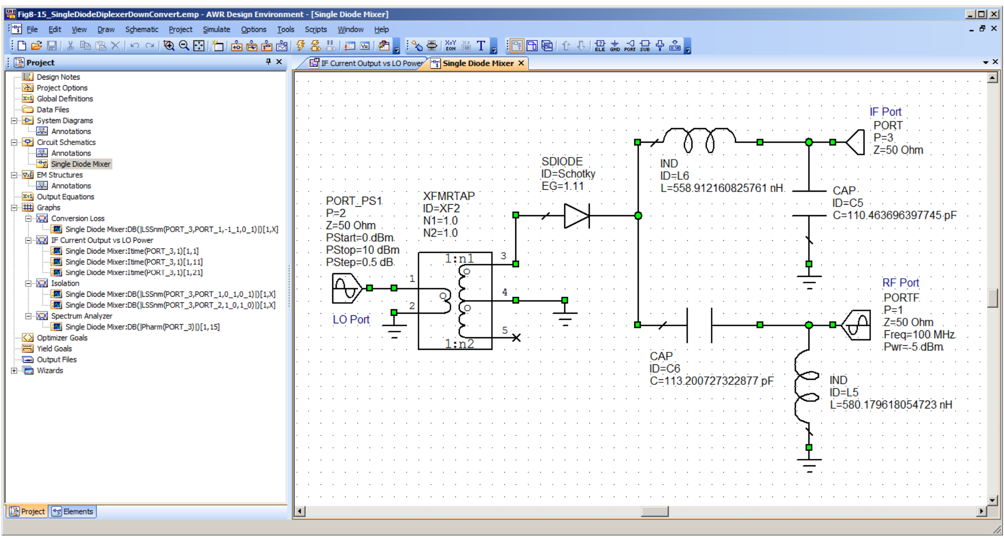



Figure 9. Typical Measurements for a mixer.

A PORTF element produces a single tone signal with frequency and power level set by the parameters for that element. For a down-conversion mixer, the PORTF element is applied to the RF port. The RF simulation will then use these frequency and power levels to determine the time waveforms at the IF port, using a Spice modelling of the diode and the circuit. Figure 9 shows the typical measurements that can be made on a mixer. The first one is the conversion loss.

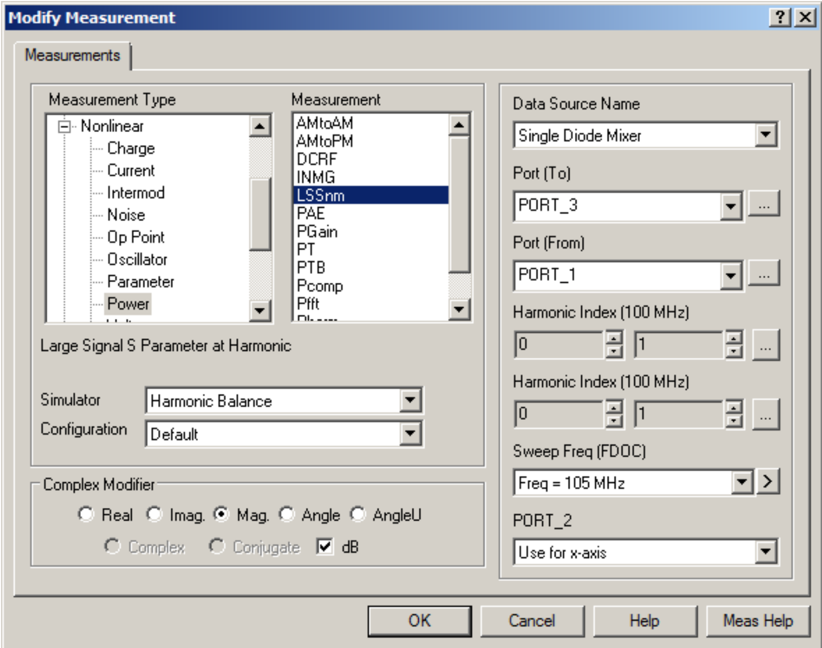



Figure 10. Parameters for conversion loss measurements.

The conversion loss of the mixer can be determined as the LO power level is varied, by setting the relevant parameters of the PORT_PS1 element to provide a power level sweep at the LO port. The sum or difference frequency that is analysed for determining the conversion loss is set by the parameters for the Large Signal S parameter (LSSnm) measurement shown in figure 10. The conversion loss is determined as the ratio of the power levels at the specified frequencies of port 1 as input and port 3 as output.

For a realistic determination of performance of the mixer, a LO frequency of 105 MHz and an RF frequency of 100 MHz with a level of -5 dBm is chosen. The project frequency is set as a single frequency at 105 MHz. If a range of frequencies are specified, then one or all of these can be used for the conversion loss. It is thus possible to determine the conversion loss for a range of LO frequencies as well. For a LO input at 105 MHz and an RF input at 100 MHz, the desired IF output is at 5 MHz. The appropriate harmonic index combinations are selected such that the input is at 100 MHz and the output is at 5 MHz, as indicated in figure 10. MWO automatically calculates the relevant frequency as the harmonic indices are changed.

Figure 11 shows the resulting conversion loss as a function of LO power level for the single diode mixer of figure 8. Note that the conversion loss decreases with an increasing LO drive level. A higher LO power level increases the power consumption of the mixer, requires a higher power LO source and dissipates more heat. By comparing figures 11 and 20, it can be seen that the conversion loss of the single diode mixer is very poor.

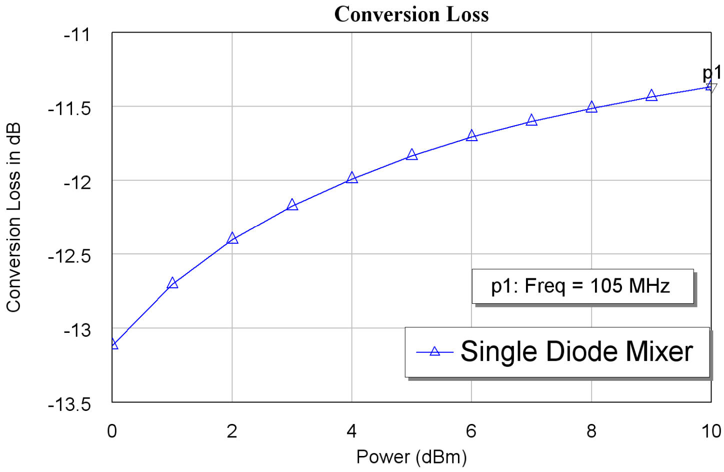



Figure 11. Conversion loss of a single diode mixer.

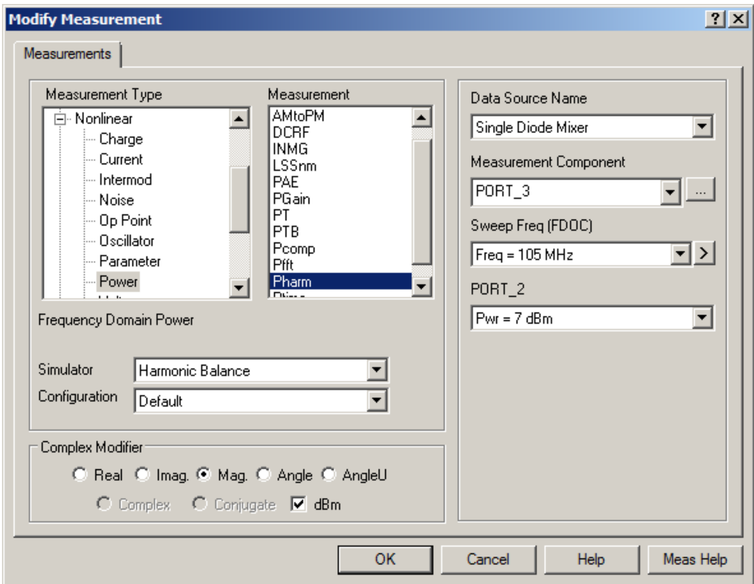



Figure 12. Frequency domain power measurement.

The IF spectrum can be determined using the Frequency Domain Power Measurement shown in figure 12. The waveform at the IF port is determined using the harmonic balance simulator. The spectral components are determined from that waveform. Figure 13 shows the resulting IF spectrum for an input power at the LO port of +6 dBm. It is possible to select other values or to plot the spectra for a sweep of power values. Comparing this with the corresponding figure 21 for the balanced mixer, and figure 29 for the double balanced mixer, it can be seen that the harmonics produced by the single diode mixer are much higher than those of balanced mixers.

The resulting IF spectrum is shown in figure 13. The desired 5 MHz component is -16.6 dBm. Since the RF signal is -5 dBm, the conversion loss is 11.6 dB. The LO signal at 105 MHz is 7 dBm and the LO signal at the IF port is -30.261 dB. The LO to IF isolation is thus 37.26 dB. The RF signal at 100 MHz signal is -5 dBm and the RF signal appearing at the IF port is -28.66 dBm. The RF to IF isolation is thus 23.661 dB. By comparing the conversion loss, the levels of the harmonics and the isolation with the corresponding figure 21 for the balanced mixer, it can be seen that the performance of a single diode mixer is significantly worse.

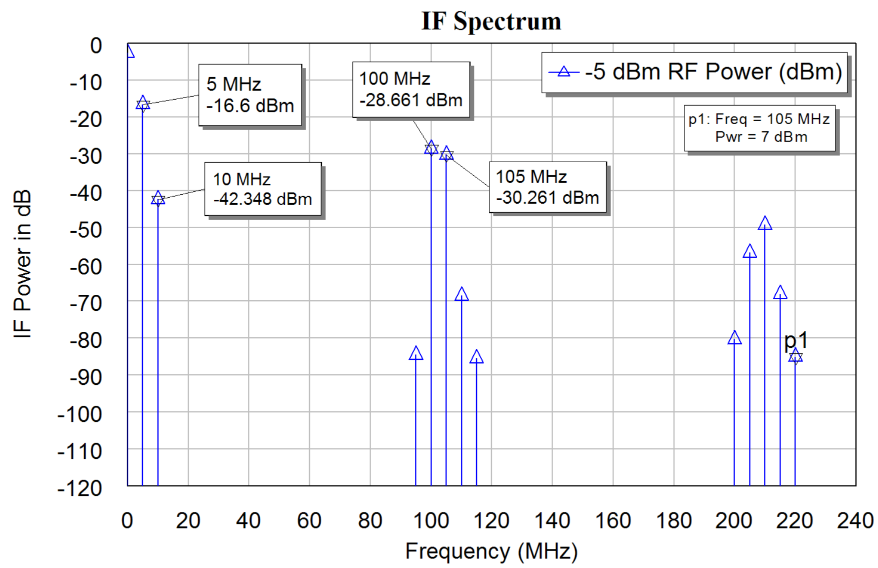



Figure 13. IF spectrum of a single diode mixer as a down-converter.

If a two-tone RF input signal is used, the single diode mixer has a high level of IM components. As a result, the single diode mixer requires more stringent RF filtering to avoid those IM signals being generated by the mixer and appearing in the IF output. The single diode mixer also requires more stringent IF filtering to remove those unwanted IF components from the IF signal, to prevent the unwanted signals from effecting the demodulated output from the receiver. Most AM radios use single diode mixers and this is one reason why their performance is poor compared to FM radios.

The voltage and current time waveforms can also be determined, using the Vtime and Itime measurements. The measurements can be done at a single LO power level or at a range of levels as is done by selecting plot all traces instead of the 0 dBm level in the Port_2 entry of the Itime measurement window shown in figure 14. Alternately, as has been done in this project, a limited power sweep can be obtained by performing multiple single level measurements as shown in figure 9.

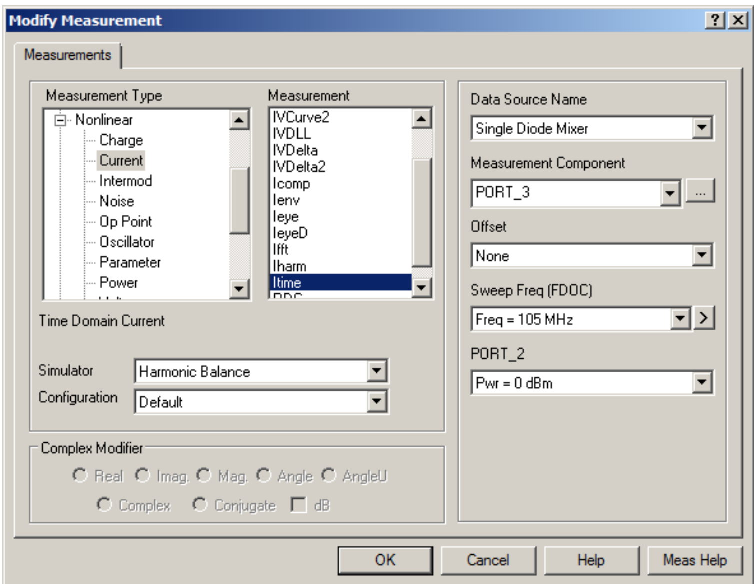



Figure 14. Itime measurement setting.

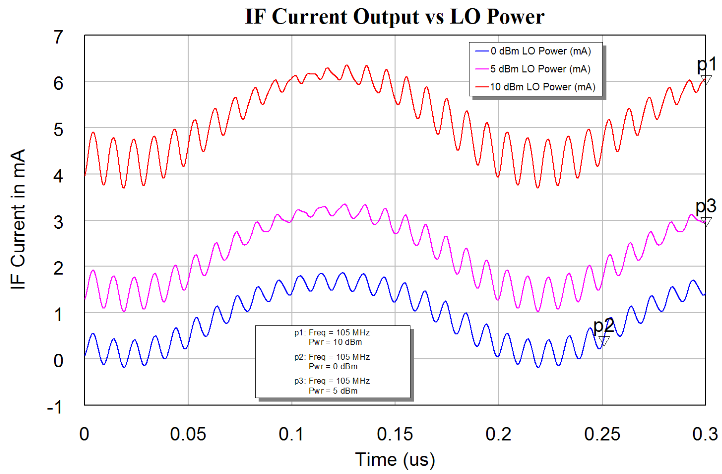



Figure 15. IF currents for a single diode mixer as a down-converter.

Figure 15 shows the resulting IF currents of a single diode mixer, notice with the 2nd order filters used in the diplexer, there is still significant RF current components present in the IF signal. A higher order filter will improve the isolation, but will not improve the performance sufficiently to justify the additional cost. For the frequencies used, the output spectra and conversion loss will be the same if higher order diplexer filters are used. As can be seen from figure 15, the single diode mixer has a significant DC current component, which changes with LO drive level.

To operate the mixer as an up-converter, the PORTF element is applied to the IF port and the signal generated by that port is set to 5 MHz and a power of -5 dBm. The mixer output is then at the RF port. The resulting circuit diagram for the single diode mixer as an up-converter is shown in figure 16. The same measurements can be performed as for the down-converter.

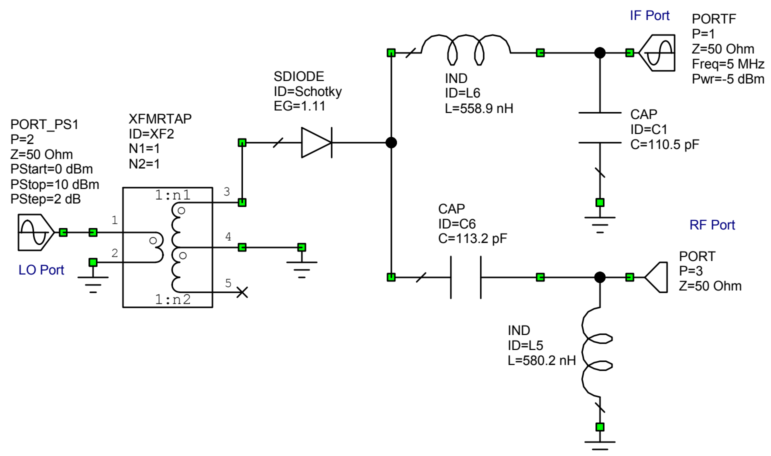



Figure 16. Circuit diagram of a single diode mixer as an up-converter.

The RF output spectrum is shown in figure 17. From this spectrum it can be seen that the conversion loss, being the amplitude of the 100 MHz RF component due to the 5 MHz IF signal is the same as for the down-converter. The components around 100 MHz show a large 105 MHz LO component in the RF output, indicating only a 8.6 dB LO-RF isolation. The LO spectral component at the RF port is larger than any of the wanted components. The second harmonic components at 90 MHz and 110 MHz are slightly asymmetrical. There are significant components at harmonics of the LO frequency, which must be filtered out in most practical applications.

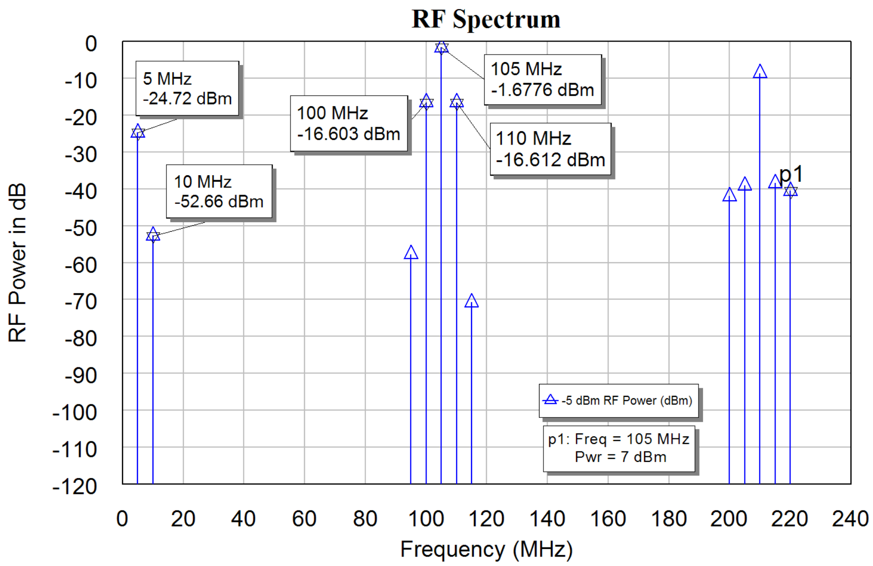



Figure 17. RF spectrum of a single diode mixer as an up-converter.

The RF current waveforms can be determined using the Itime measurement in a similar manner as for the down-converter shown in figure 15. The results for the up-converter are shown in figure 18 and are highly asymmetrical. The waveform is rich in harmonics as can be seen from the spectrum of figure 17.

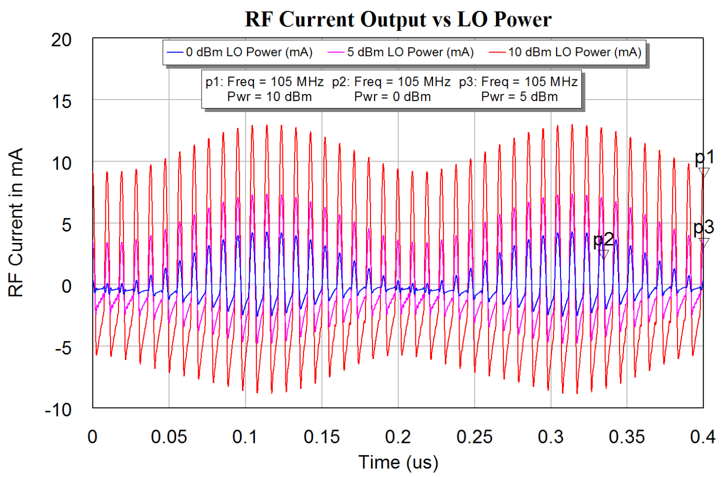



Figure 18. RF currents for a single diode mixer as an up-converter.

**Advantages of single diode mixers:**

1. Can be used at very high (microwave) frequencies.
2. Low cost, one diode.

**Disadvantages of single diode mixers:**

3. High Conversion loss.
4. High level of unwanted components.
5. No RF to LO isolation, IF to LO and IF to RF isolation only due to diplexer.

## Balanced Mixer

Adding a second diode to the circuit shown in figure 19 results in a balanced mixer. The first diode has $V_a+V_b$ across it and the second diode has $V_a-V_b$ where voltage $V_a$ is the LO and $V_b$ is the RF voltage. The currents through the diodes are thus:

$$I_{D1} = a_0 + a_1(V_a+V_b) + a_2(V_a+V_b)^2 + a_3(V_a+V_b)^3 + a_4(V_a+V_b)^4 + a_5(V_a+V_b)^5 + \ldots \qquad \text{Eqn. 8}$$

$$I_{D2} = a_0 + a_1(V_a-V_b) + a_2(V_a-V_b)^2 - a_3(V_a-V_b)^3 + a_4(V_a-V_b)^4 + a_5(V_a-V_b)^5 + \ldots \qquad \text{Eqn. 9}$$

The difference between the diode currents flows into the IF port and RF port, so that the current flowing through the IF and RF port is:

$$I_{IF-RF} = I_{D1} - I_{D2} = +2a_1V_b + 4a_2V_aV_b + 6a_3V_a{}^2V_b + 2V_b{}^3 + 8a_4(V_a{}^3V_b + V_aV_b{}^3) + 10a_5V_a{}^4V_b + 20a_5V_a{}^2V_b{}^3 + 2a_5V_b{}^5 + \ldots \qquad \text{Eqn. 10}$$

For a single diode mixer the current through the IF and RF port is the same as is shown in equation 8. Comparing equation 10 with equation 8, it can be seen that most of the unwanted components cancel. The only components that are in the IF band are:

$$I_{IF} = 4a_2V_aV_b + 8a_4(V_a^3V_b + V_aV_b^3) + \ldots \qquad \text{Eqn. 11}$$

Which is close to ideal multiplication as the $a_4$ term is normally very small.

Since the LO voltage, $V_a$ >> the RF voltage, $V_b$ , the $V_aV_b$ and the $V_a^3V_b$ terms dominate. The $V_b$ and the $V_a^2V_b$ terms do not produce any frequency components in the region of interest. For an ideal mixer one wants the a, c, d and e components to be as small as possible, the manufacturers of mixers ensure their diodes satisfy this as much as possible. The balanced mixer will thus have a much better performance than the single diode mixer.

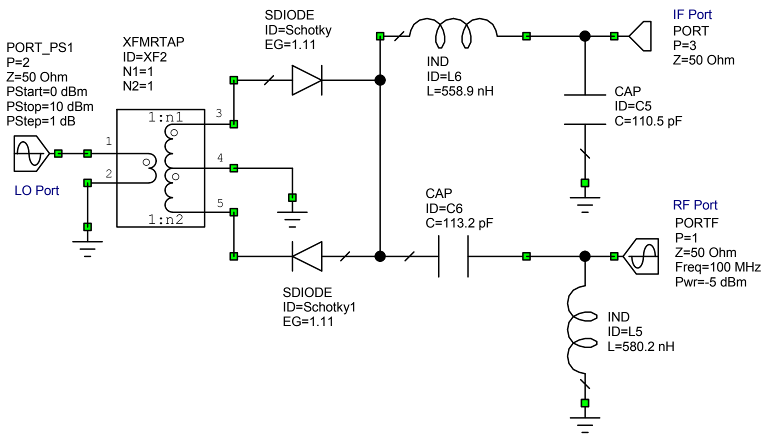



Figure 19. Circuit diagram of a balanced mixer.

The circuit diagram of the balanced mixer is shown in figure 19. The only difference between that and the circuit for the single diode mixer of figure 8 is the use of the second diode, but having the second diode results in a significant performance improvement.

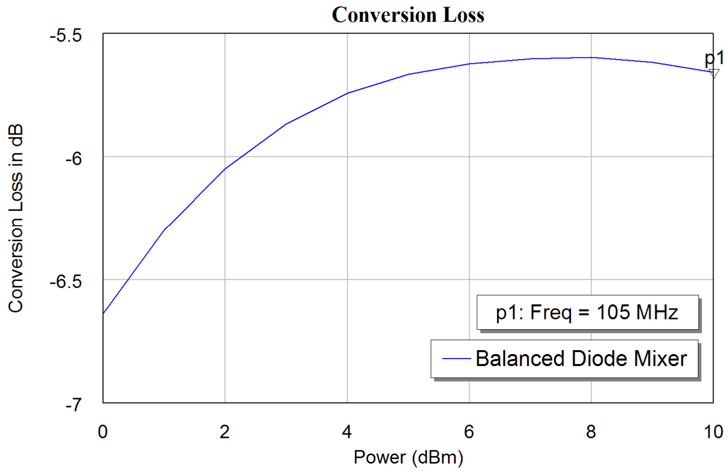



Figure 20. Conversion loss of a balanced diode mixer.

The conversion loss of the mixer is shown in figure 20. The conversion loss is far less than that of a single diode mixer. For LO levels of around 7 dBm, any variation in LO power does not cause any change in conversion loss, so that the mixer is then very insensitive to AM noise of the LO. This is an important advantage of the balanced mixer over the single diode mixer.

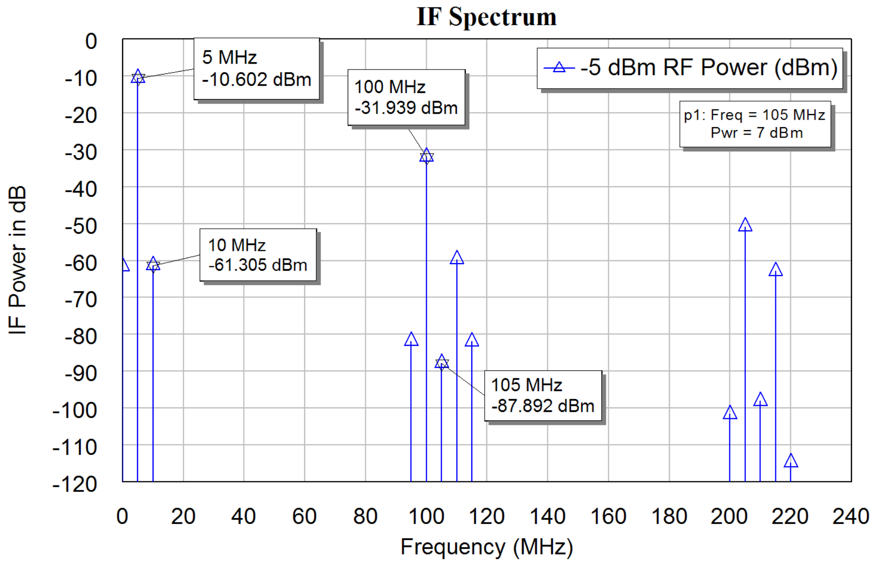



Figure 21. IF spectrum of a balanced diode mixer as a down-converter.

Figure 21 shows the IF spectrum of the balanced mixer. As expected from the equation 10, many of the unwanted spectral components have significantly reduced amplitudes compared with the single diode mixer. The second harmonic of the desired IF signal, at 10 MHz and caused by the mixing process, is more than 40 dB below the desired 5 MHz signal. The LO signal appearing in the IF spectrum is -87.9 dBm, since the LO signal is 7 dBm, the LO to IF isolation is 94.9 dB.

The RF signal appearing at the IF port is -31.939 dBm. Since the RF signal is -5 dBm, The RF to IF is isolation is 26.9 dB. This can only be improved by using a higher order diplexer as part of the mixer, or by using another mixer configuration like the double balanced mixer.

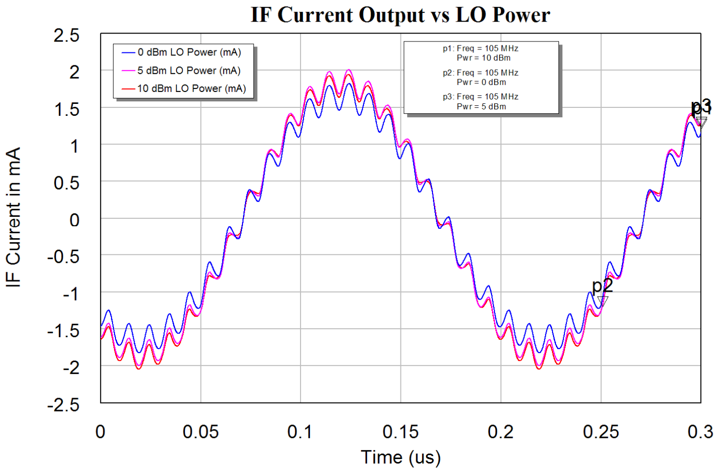



Figure 22. IF currents for a balanced diode mixer as a down-converter.

Figure 22 shows the IF currents for the balanced mixer and it can be seen that the waveforms are much more like a pure sine wave than the corresponding waveforms for the single diode mixer. With the second order filters used in the diplexer, there are still some RF signals present at the IF output but they are small enough not to cause any problems. As expected from equation 10, the balanced diodes mixer has is no DC component produced at the IF port, in contrast to the single diode mixer.

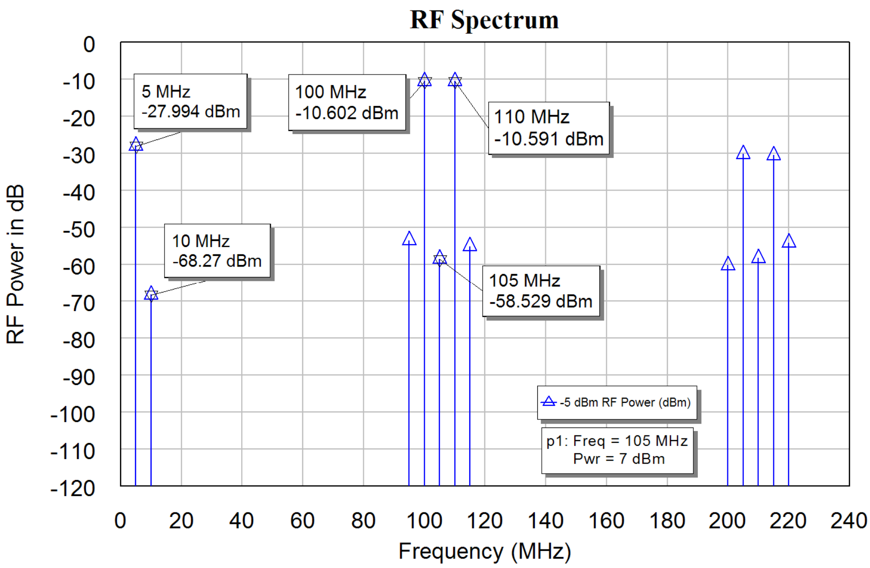



Figure 23. RF spectrum of a balanced diode mixer as an up-converter.

Figure 23 shows the performance of the balanced mixer as an up-converter. It can be seen that a near ideal mixer performance is obtained, with all the unwanted components more than 40 dB below the wanted components. This is good enough for practical applications. The 3IM components increase 3 dB for every 1 dB increase in the RF and IF levels. The RF level can thus be varied to obtain the specified 3IM performance, thereby maximising IF signal and the dynamic range. The LO feedthrough at the RF port can be minimised by adding a very small DC signal to the IF port and adjusting that DC signal to cancel the LO signal at the RF port. This cancellation is temperature dependent, since the diode characteristics change slightly with temperature.

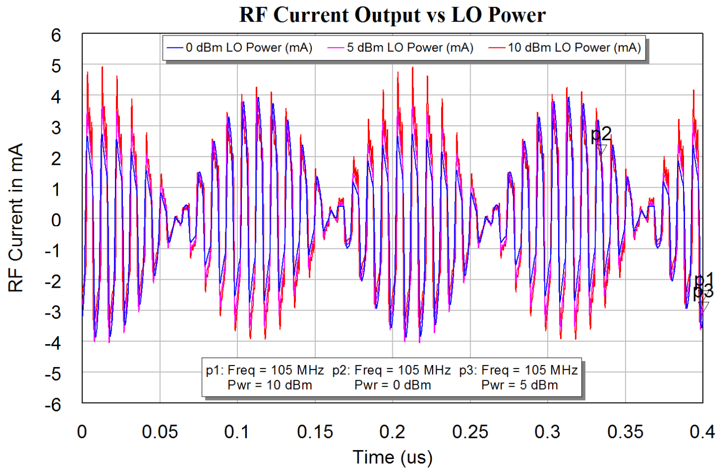


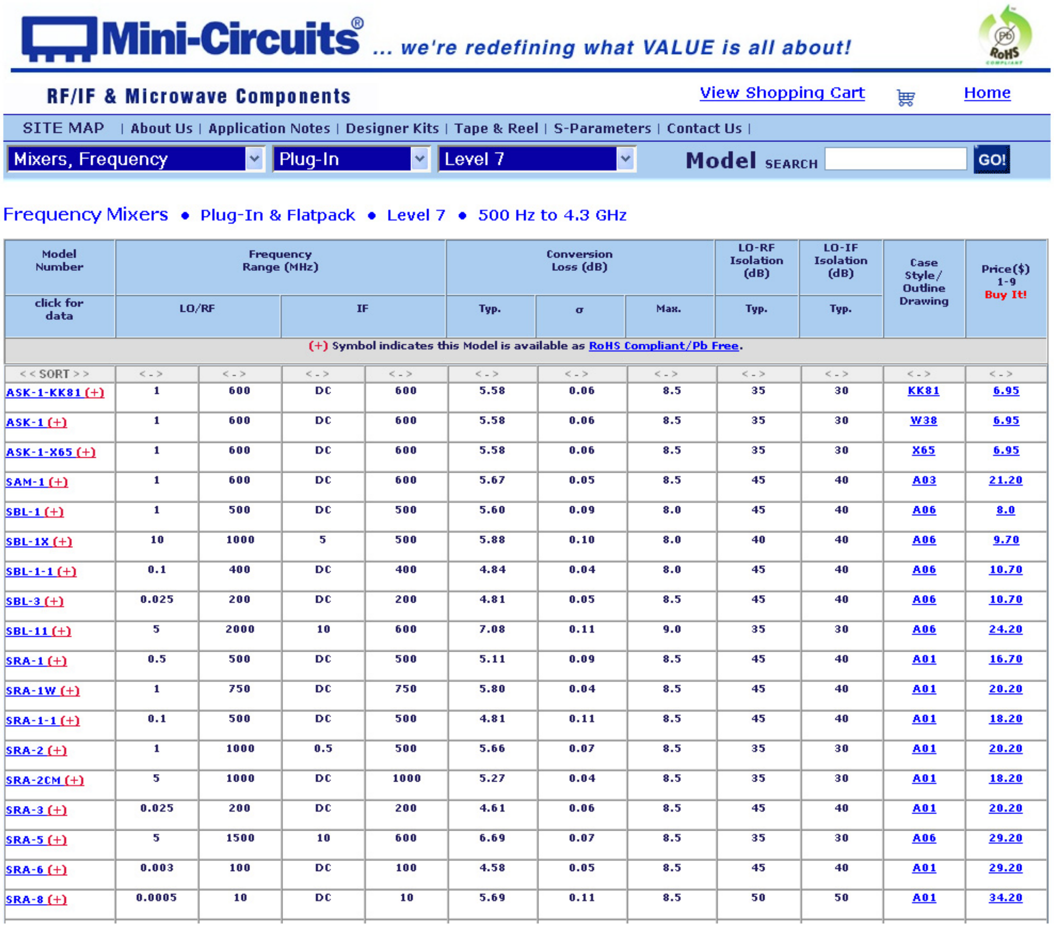

Figure 24. RF currents for a balanced diode mixer as an up-converter.

Figure 24 shows the RF currents for the balanced mixer, note that the waveforms closely resemble the ideal double balanced waveforms obtained from:

The results from the simulation closely agree with those obtained in practice.

There are however still some IF components present, which are due to the limited RF-IF isolation caused by the diplexer. The Double Balanced mixer overcomes those limitations.

# Double Balanced Mixer




| Model Number | Frequency Range (MHz) | | | | Conversion Loss (dB) | | | LO-RF Isolation (dB) | LO-IF Isolation (dB) | Case Style/ Outline Drawing | Price($) 1-9 Buy It! |
|---|---|---|---|---|---|---|---|---|---|---|---|
| click for data | LO/RF | | IF | | Typ. | σ | Max. | Typ. | Typ. | | |
| (+) Symbol indicates this Model is available as RoHS Compliant/Pb Free. | | | | | | | | | | | |
| << SORT >> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> |
| ASK-1-KK81 (+) | 1 | 600 | DC | 600 | 5.58 | 0.06 | 8.5 | 35 | 30 | KK81 | 6.95 |
| ASK-1 (+) | 1 | 600 | DC | 600 | 5.58 | 0.06 | 8.5 | 35 | 30 | W38 | 6.95 |
| ASK-1-X65 (+) | 1 | 600 | DC | 600 | 5.58 | 0.06 | 8.5 | 35 | 30 | X65 | 6.95 |
| SAM-1 (+) | 1 | 600 | DC | 600 | 5.67 | 0.05 | 8.5 | 45 | 40 | A03 | 21.20 |
| SBL-1 (+) | 1 | 500 | DC | 500 | 5.60 | 0.09 | 8.0 | 45 | 40 | A06 | 8.0 |
| SBL-1X (+) | 10 | 1000 | 5 | 500 | 5.88 | 0.10 | 8.0 | 40 | 40 | A06 | 9.70 |
| SBL-1-1 (+) | 0.1 | 400 | DC | 400 | 4.84 | 0.04 | 8.0 | 45 | 40 | A06 | 10.70 |
| SBL-3 (+) | 0.025 | 200 | DC | 200 | 4.81 | 0.05 | 8.5 | 45 | 40 | A06 | 10.70 |
| SBL-11 (+) | 5 | 2000 | 10 | 600 | 7.08 | 0.11 | 9.0 | 35 | 30 | A06 | 24.20 |
| SRA-1 (+) | 0.5 | 500 | DC | 500 | 5.11 | 0.09 | 8.5 | 45 | 40 | A01 | 16.70 |
| SRA-1W (+) | 1 | 750 | DC | 750 | 5.80 | 0.04 | 8.5 | 45 | 40 | A01 | 20.20 |
| SRA-1-1 (+) | 0.1 | 500 | DC | 500 | 4.81 | 0.11 | 8.5 | 45 | 40 | A01 | 18.20 |
| SRA-2 (+) | 1 | 1000 | 0.5 | 500 | 5.66 | 0.07 | 8.5 | 35 | 30 | A01 | 20.20 |
| SRA-2CM (+) | 5 | 1000 | DC | 1000 | 5.27 | 0.04 | 8.5 | 35 | 30 | A01 | 18.20 |
| SRA-3 (+) | 0.025 | 200 | DC | 200 | 4.61 | 0.06 | 8.5 | 45 | 40 | A01 | 20.20 |
| SRA-5 (+) | 5 | 1500 | 10 | 600 | 6.69 | 0.07 | 8.5 | 35 | 30 | A06 | 29.20 |
| SRA-6 (+) | 0.003 | 100 | DC | 100 | 4.58 | 0.05 | 8.5 | 45 | 40 | A01 | 29.20 |
| SRA-8 (+) | 0.0005 | 10 | DC | 10 | 5.69 | 0.11 | 8.5 | 50 | 50 | A01 | 34.20 |

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| Model Number | LO Level (dBm) | RF in @1dBm Comp. Typ. (dBm) | Frequency Range (MHz) | | | Conversion Loss (dB) | | | LO-RF Isolation (dB) | LO-IF Isolation (dB) | IP3@ center band Typ. (dBm) | Case Style/ Outline Drawing | PCB Layout PL- | Price($) 10-24 Buy It! |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| click for data | | | LO/RF | | IF | Typ. | σ | Max. | Typ. | Typ. | | | | |
| (+) Symbol indicates this Model is available as RoHS Compliant/Pb Free. | | | | | | | | | | | | | | |
| << SORT >> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> | <-> |
| ADE-1 (+) | 7.0 | 1.0 | 0.5 | 500 | DC | 500 | 5.0 | 0.10 | 7.8 | 55 | 40 | 15 | CD636 | 052 | 1.99 |
| ADE-1ASK (+) | 7.0 | 1.0 | 2.0 | 600 | DC | 600 | 5.3 | 0.10 | 7.5 | 50 | 45 | 16 | CD542 | 052 | 3.95 |
| ADE-2ASK (+) | 7.0 | 1.0 | 1.0 | 1000 | DC | 1000 | 5.4 | 0.10 | 9.5 | 45 | 32 | 12 | CD542 | 052 | 4.25 |
| ADE-2 (+) | 7.0 | 1.0 | 5.0 | 1000 | DC | 1000 | 6.67 | 0.26 | 9.5 | 47 | 45 | 20 | CD542 | 052 | 1.99 |
| ADE-3G (+) | 7.0 | 1.0 | 2300 | 2700 | DC | 400 | 5.6 | 0.10 | 7.0 | 36 | 26 | 13 | CD542 | 052 | 3.45 |
| ADE-3GL (+) | 7.0 | 1.0 | 2100 | 2600 | DC | 600 | 6.0 | 0.25 | 8.8 | 34 | 20 | 17 | CD541 | 051 | 4.95 |
| ADE-4 (+) | 7.0 | 1.0 | 200 | 1000 | DC | 800 | 6.8 | 0.10 | 8.5 | 53 | 40 | 15 | CD542 | 052 | 4.25 |
| ADE-5 (+) | 7.0 | 1.2 | 5.0 | 1500 | DC | 1000 | 6.6 | 0.10 | 9.3 | 40 | 30 | 15 | CD542 | 052 | 3.45 |
| ADE-6 (+) | 7.0 | 1.0 | 0.05 | 250 | DC | 200 | 4.6 | 0.05 | 8.4 | 40 | 45 | 10 | CD637 | 052 | 4.95 |
| ADE-11X (+) | 7.0 | 1.0 | 10 | 2000 | 5 | 1000 | 7.1 | 0.10 | 9.8 | 36 | 37 | 9 | CD542 | 052 | 1.99 |
| ADE-12 (+) | 7.0 | 1.0 | 50 | 1000 | DC | 1000 | 7.0 | 0.15 | 9.0 | 33 | 37 | 17 | CD541 | 051 | 2.95 |
| ADE-13 (+) | 7.0 | 1.0 | 50 | 1600 | 50 | 1000 | 8.1 | 0.10 | 9.8 | 40 | 35 | 11 | CD541 | 051 | 3.10 |
| ADE-14 (+) | 7.0 | 1.0 | 800 | 1000 | DC | 200 | 7.4 | 0.20 | 8.9 | 32 | 34 | 17 | CD541 | 051 | 3.25 |
| ADE-18W (+) | 7.0 | 1.0 | 1750 | 3500 | DC | 700 | 5.4 | 0.30 | 8.9 | 33 | 12 | 11 | CD542 | 051 | 3.95 |
| ADE-20 (+) | 7.0 | 1.0 | 1500 | 2000 | DC | 300 | 5.4 | 0.10 | 7.8 | 31 | 28 | 14 | CD542 | 051 | 4.95 |
| ADE-30 (+) | 7.0 | 1.0 | 200 | 3000 | DC | 1000 | 4.5 | 0.20 | 9.8 | 35 | 20 | 14 | CD542 | 052 | 6.95 |
| ADE-30W (+) | 7.0 | 1.0 | 300 | 4000 | DC | 950 | 6.8 | 0.20 | 9.8 | 35 | 16 | 12 | CD542 | 052 | 8.95 |
| ADE-35 (+) | 7.0 | 1.0 | 1600 | 3500 | DC | 1500 | 6.3 | 0.50 | 9.8 | 25 | 22 | 11 | CD542 | 051 | 4.95 |

Figure 25. Minicircuit mixer catalogue.

Double balanced mixers, together with the active mixers are the dominant mixers used in non-consumer oriented transmitters and receivers. There are several companies making double balanced mixers, Minicircuits is one of the largest of these. A part of a web page of their mixer catalogue is shown in figure 25. There are many different packages available and as can be seen from Figure 25 surface mount packages are a lot cheaper and thus more popular. It is interesting to see the change in price for the SRA-1. For many years this was $1.95 (US). In recent years the price has risen significantly, reflecting cost increases for that style of packaging, while the cost of surface mount packages is decreasing.

The circuit diagram of a Double Balanced Mixer is shown in figure 26. The two transformers provide isolation for all ports. Four diodes are now required.

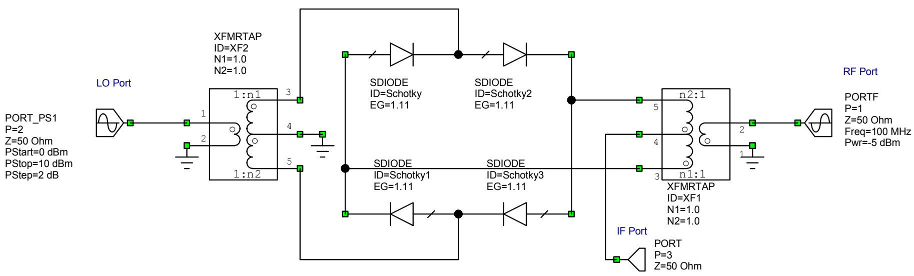


Figure 26. Circuit diagram of a double balanced mixer.

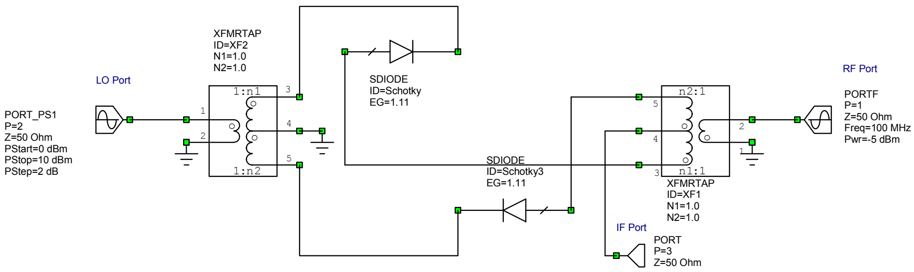


Figure 27a Mixer with +ve voltage applied at the IF port.

For the analysis of the mixer consists of considering what happens if a +ve input signal is applied to the IF port. Under those conditions the diodes shown in figure 27a conduct and the others are an open circuit. As a result a positive signal applied to the LO port, then a positive signal is obtained at the RF port.

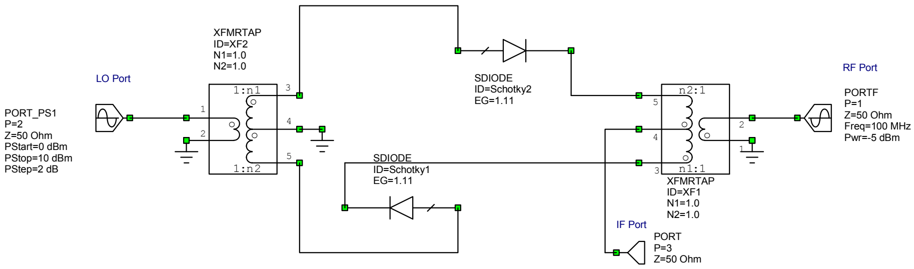


Figure 27 b. Mixer with –ve voltage applied at the IF port.

If a -ve input signal is applied to the IF port, the diodes shown in figure 27b conduct and the others are an open circuit. As a result if a positive signal is applied to the LO port, then a positive signal is obtained at the RF port. If a zero voltage signal is applied at the IF port all the diodes are equal resistances and the LO signal is cancelled at the RF port. In practice having a smaller IF voltage results in a smaller RF voltage. The RF signal is thus the LO signal multiplied by the IF signal, resulting in a proper mixing action.

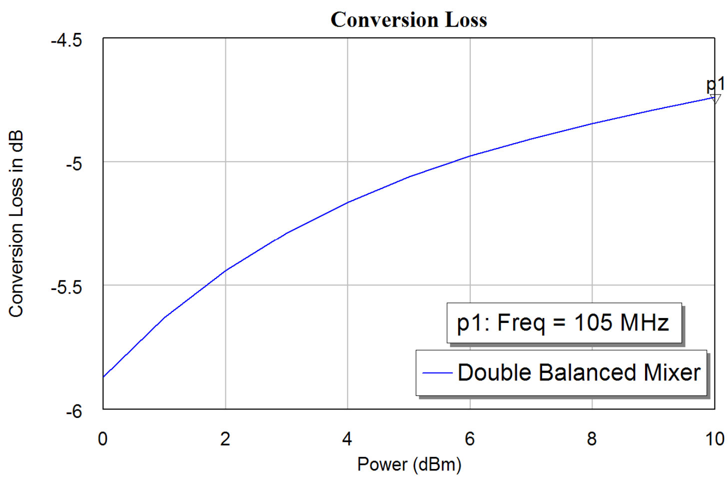


Figure 28. Conversion loss of a double balanced diode mixer.

Figure 28 shows that the conversion loss of a Double Balanced Mixer is approximately 0.5 dB less than that of a balanced mixer and more than 6 dB less than that of a single diode mixer. Comparing the IF spectrum of a down-converting Double Balanced Mixer as shown in figure 29 this with the corresponding figures 13 and 21 for single and balanced diode mixers, it can be seen that there are no spectral components in the 80 to 120 MHz frequency range. The difference signal at 5 MHz and the sum signal at 205 MHz are the same amplitude. The signal at 215 MHz is due to the third harmonic of the input signal mixing with the local oscillator. In a receiver, these harmonic signals must be evaluated, to ensure that they do not cause signals in the IF frequency band.

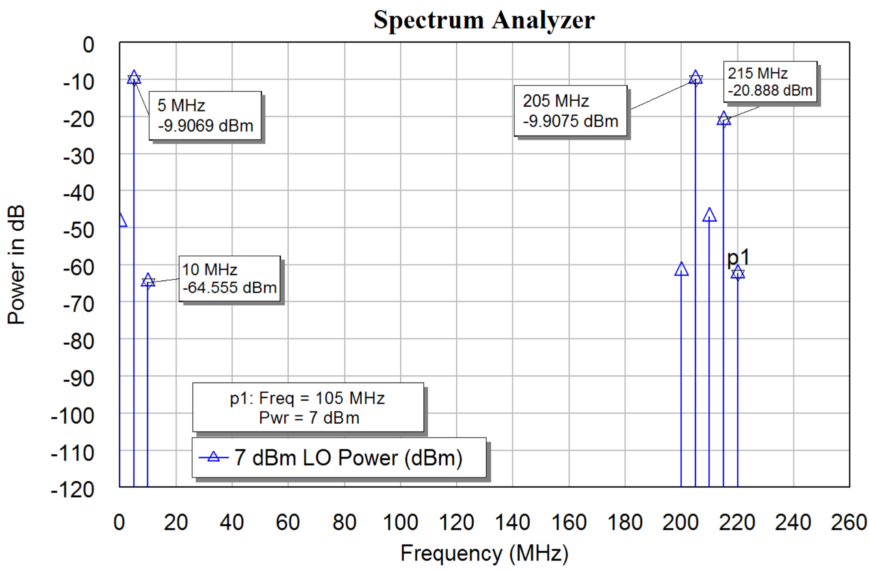


Figure 29. IF spectrum of a double balanced diode mixer as a down-converter.

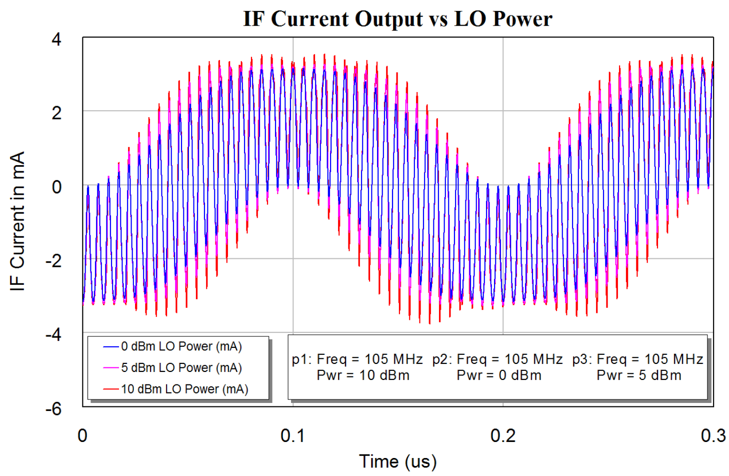


Figure 30. IF currents for a balanced diode mixer as a down-converter.

Figure 30 shows the IF currents. There is a significant high frequency content. Figure 31 shows the same IF currents with the IF signal passed through a 25 MHz low pass filter to remove the high frequency components. The waveform looks like an ideal Sine wave and there is little change in the output as the LO power is changes between 0 dBm and 10 dBm. The LO AM noise will thus have little effect on the IF output.

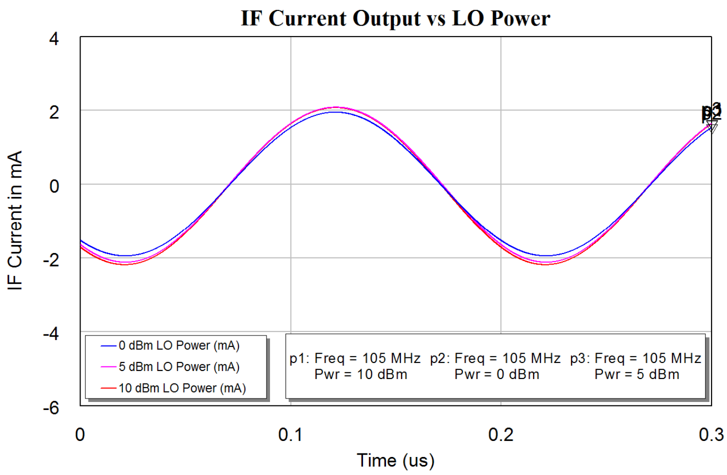


Figure 31. IF currents of figure 29 with frequency components >25 MHz removed.

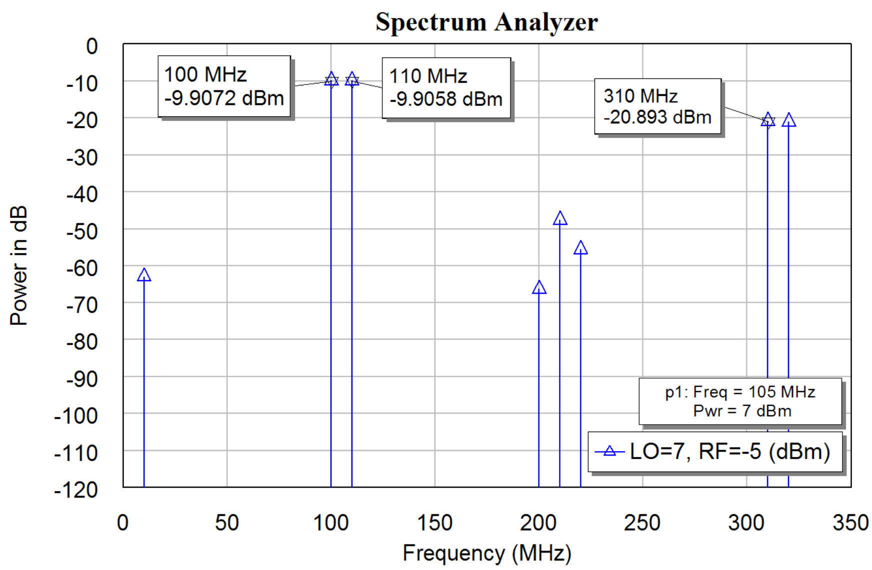


Figure 32. RF spectrum of a double balanced diode mixer as an up-converter.

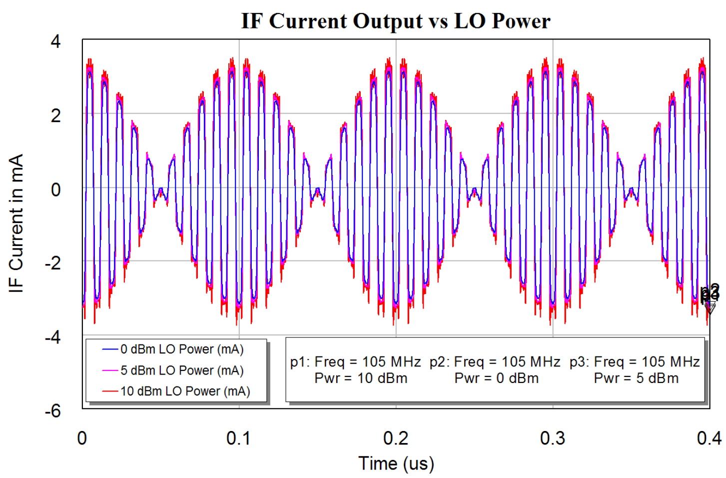


Figure 33. RF currents for a double Balanced Diode Mixer as an up-converter.

Figure 32 shows the RF spectrum of a double balanced mixer as an up-converter. The desired spectrum around the 105 MHz LO is ideal, with no unwanted spectral components. Figure 33 shows the corresponding RF currents. The spectrum and the waveform is very similar to that for an ideal multiplier. Double balanced mixers can be used as analogue multipliers in applications like a phase detector or a true RMS power meter.

Figure 34 shows the construction of a simple home made double balanced mixer, the transformers are held in-place with Silastic (Silicone Sealant). The diodes are conventional Shottky-Barrier diodes that have been matched for their V-I characteristic in order to obtain the best LO ⇨ RF isolation.

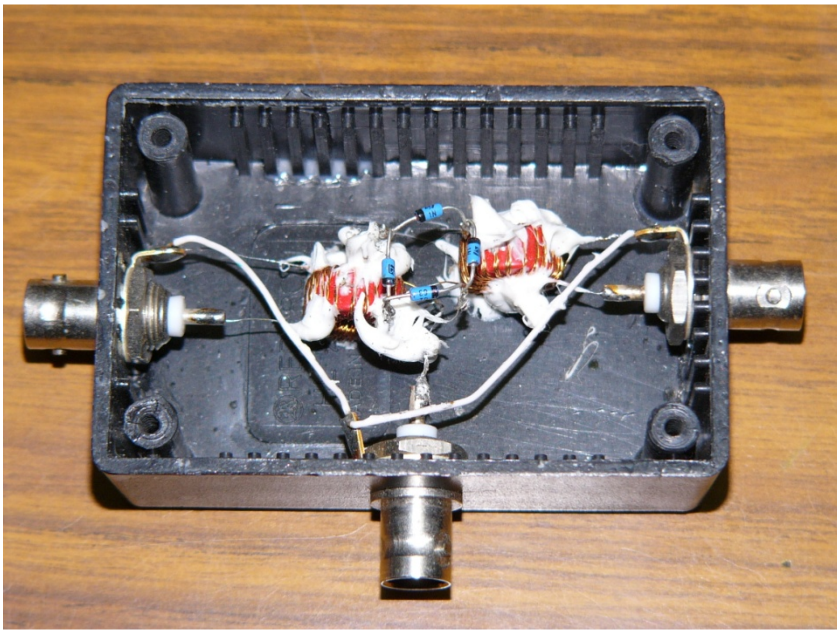

Figure 34. Construction of a Double Balanced Mixer for use in Practical Sessions.

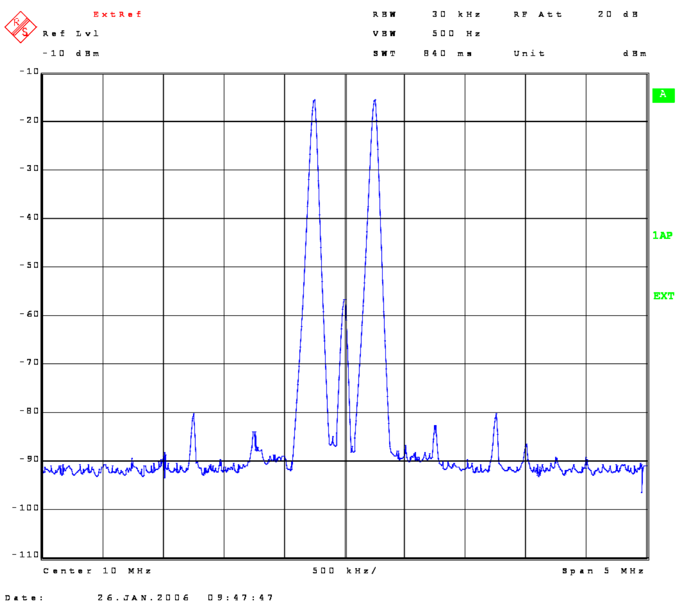


Figure 35. Measured performance of the mixer of figure 34.

The measured performance of the mixer is shown in Figure 35. The transformers for this mixer were designed for operation at 1 MHz, as a result an IF frequency of 250 kHz and an LO of 10 MHz was used for the spectrum in figure 35. For the measurement of figure 35, the LO signal was at a frequency of 10 MHz and a level of +7 dBm. The IF signal was at a frequency of 300 Hz and a level of -10 dBm. The measured conversion loss is 6 dB and the LO ⇨ RF isolation is -60 dB. This mixer performs well for RF and LO signals in the range of 30 kHz to 30 MHz and IF signals up to 30 MHz.

Comparing the spectrum around the LO in figure 35 with the corresponding spectrum around the LO in figure 32, shows that in practice there will be some LO ⇨ RF carrier feed-through due to a slight mismatch of the diodes. Figure 35 shows that the 5IM distortion components, 1.250 MHz from the LO frequency at the centre of the plot, are bigger than the 3IM components , 750 kHz from the LO frequency.

## Microwave Mixers

At microwave frequencies (>1 GHz) transformers become difficult to make. In addition the capacitance associated with the diodes used in the mixer cause the diodes to become less efficient as a mixer. As a result, mixers at microwave frequencies have higher conversion losses than mixers used at lower frequencies. Conversion losses of 6 to 10 dB are typical. Transformer based mixers are available for frequencies up to 12 GHz.

At microwave frequencies, transmission lines are often used to produce the two outputs with a 180° phase shift, to provide a replacement for the transformer in the balanced mixer shown the figure 19. The circuit for the corresponding microwave mixer is shown in figure 36. In this design, the mixer is used for a down-converter for a weather satellite receiver and uses a 1565 MHz Local Oscillator to shift a 1700 MHz RF signal to a 135 MHz IF frequency.

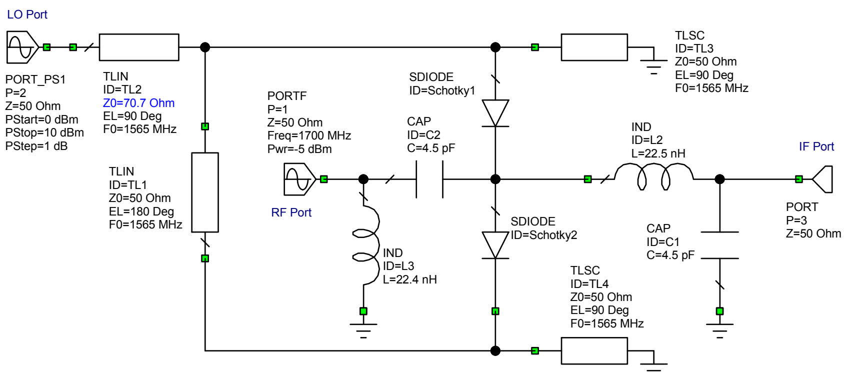


Figure 36. Circuit diagram of a Microwave Balanced mixer.

The conversion loss for this mixer is shown in figure 37, and is 0.3 dB less than the conversion loss for corresponding transformer based mixer, shown in figure 20. Figure 38 shows the spectrum for the mixer as a down converter. The mixer performs well and the spectrum is similar to that of the transformer based mixer in figure 21.

Changing the transformer to a transmission line will thus not change the performance of the mixer very much apart from a reduction of the bandwidth, since the transmission line only produces a 180° phase shift at a single frequency. However in many microwave applications the resulting bandwidth is sufficient. The mixer can also be used as an up-converter.

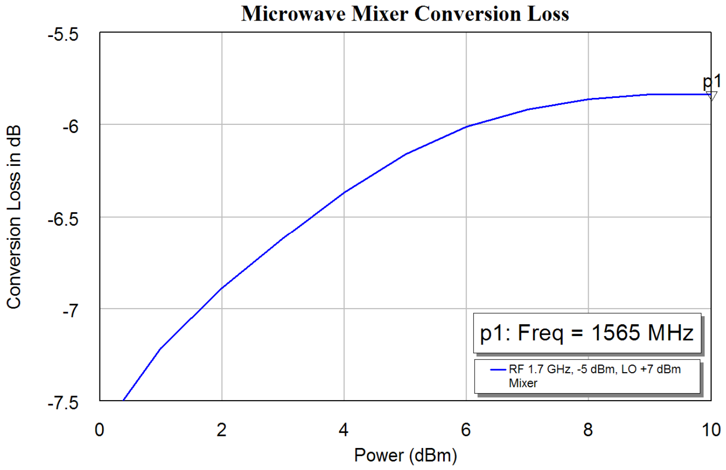


Figure 37. Conversion loss of a Microwave Balanced Diode mixer.

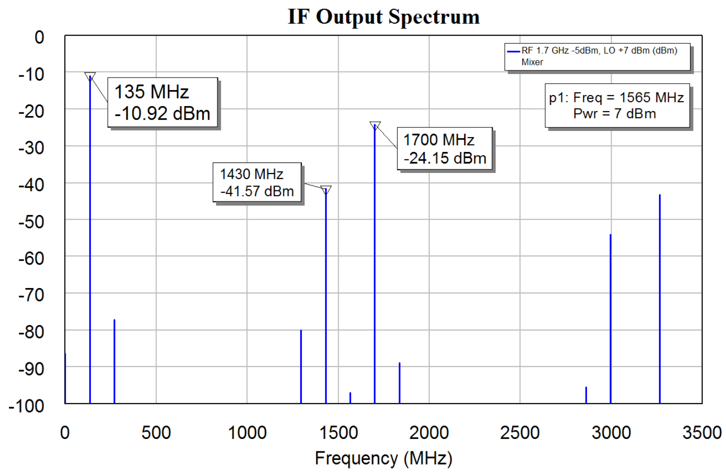


Figure 38. IF Spectrum of a Microwave Balanced Diode mixer as a down-converter.

A transmission line, used to produce the 180° phase shift in figure 36 produces a linear phase shift with frequency. As shown in the lecture notes on Branchline couplers, the Branchline coupler has a nearly constant 90° phase shift over a 10% bandwidth.

The Branchline coupler can be used to produce the required phase shifts for efficient mixing. If the LO signal is applied at port 1 of the Branchline coupler in figure 40 and the RF signal is applied to port 2. The frequency of the Branchline coupler is chosen such that full isolation is obtained at the RF port for the LO signal, since the LO signal is much bigger in power than the RF signal. For a practical down-converting mixer, the LO and RF signals are within 10% of each other, so that reasonable isolation will be obtained for the RF signal at the LO port. The signal at Port 3 will then be LO∠90° + RF∠180° and the signal at Port 4 will be LO ∠180° + RF∠90°. The phase angle between the LO and RF signals is +∠90° at Port 3 and -∠90° at Port 4. These are the correct conditions for obtaining balanced mixing in a down-converter.

## *Microwave mixer using a Branchline Coupler*

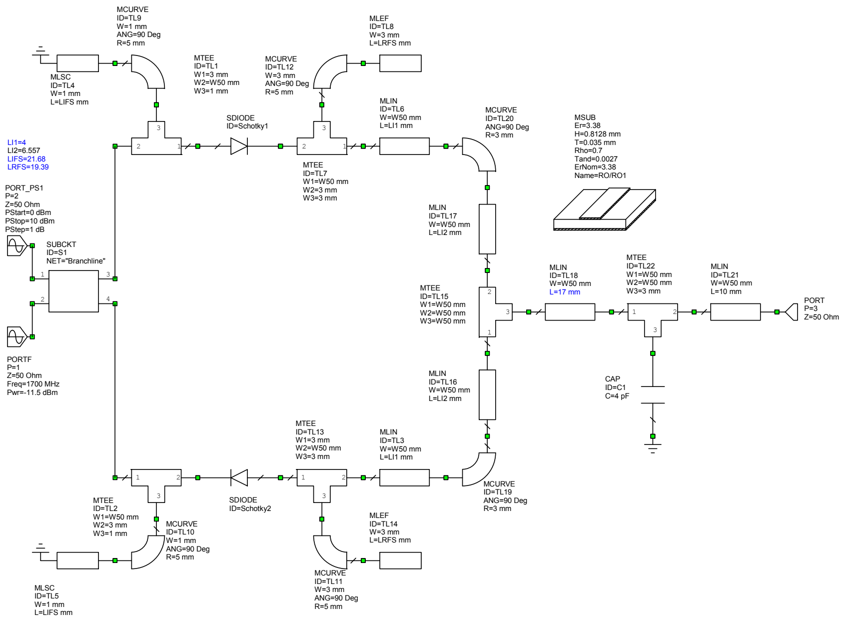

Figure 39. Circuit diagram of a balanced mixer with a Branchline coupler.

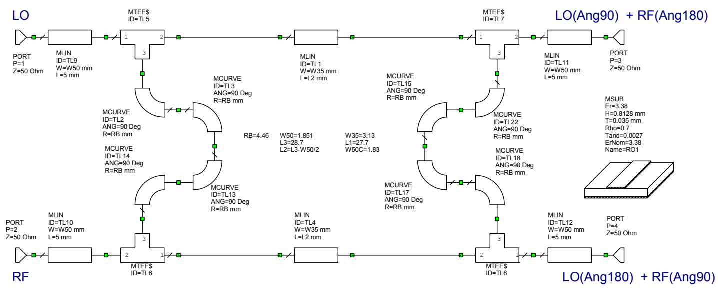


Figure 40. Circuit diagram the Branchline coupler used as a subcircuit in Figure 39.

Correct biasing for the diodes must be provided, such that all the RF and LO energy is dissipated in the diodes and all the resulting low frequency energy is passed to the IF port and is not reflected back into the RF or LO ports.

The transmission lines consisting of TL12 and TL8 and consisting of TL11 and TL14 are also one quarter wavelength long at the RF and LO frequencies and thus form a short circuit at those frequencies and an open circuit at the IF frequency. All the RF and LO energy coming from the Branchline coupler is thus dissipated in the diodes.

The Short circuited transmission lines consisting of TL9 and TL4 and consisting of TL10 and TL5 are one quarter wavelength long at the LO and RF frequencies, so that they are an open circuit at the LO and RF frequencies and a short circuit at the IF frequency. All the frequency components at the IF signal band are thus passed unhindered to the IF port 3 of the mixer. To make the removal of the LO and RF signals at the IF port as effective as possible, the size of capacitor C1 is chosen to act as a short circuit to the RF and LO signals but have little effect at the IF frequency.

Figure 41 shows the layout of the PCB layout corresponding to the circuit diagram of figure 39 and 40. The vertical transmission lines of the Branchline coupler are folded using bends, to reduce the size of the PCB. The green pads are the locations for the diodes and the capacitor. The short circuited quarter wave stubs are thin, corresponding to a high characteristic impedance to ensure as high an impedance over as wide a bandwidth around the LO and RF frequencies. The open circuited quarter wavelength stubs are wide transmission lines, providing a low shunt impedance for as wide a bandwidth as possible corresponding to as wide a bandwidth around the LO and RF frequencies, so that as much of the RF energy is converted to IF signals as possible. The distance between the capacitor and each of the diodes is half a wavelength at the LO frequency, to ensure that the low impedance of the capacitor reflects as a low impedance at the diodes. The length of the transmission line between the diodes is a half wavelength at the LO frequency to ensure each open- circuited stubs reflect as a short circuit at both diodes, thus enhancing the efficiency of the frequency conversion.

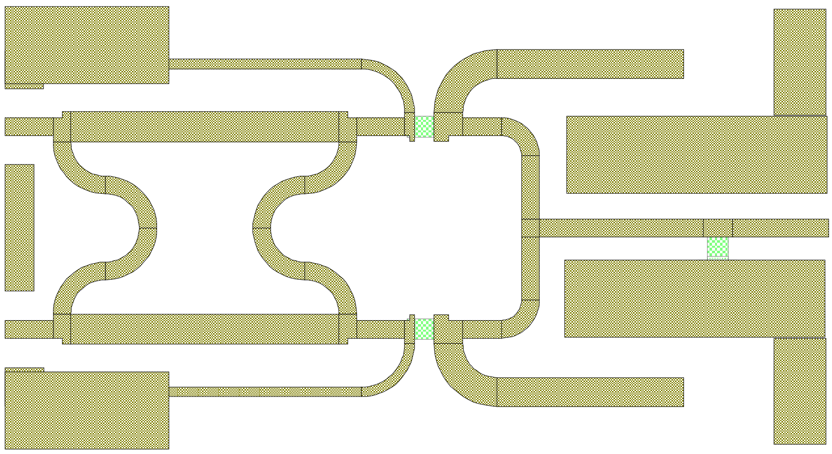

Figure 41. Branchline mixer layout.

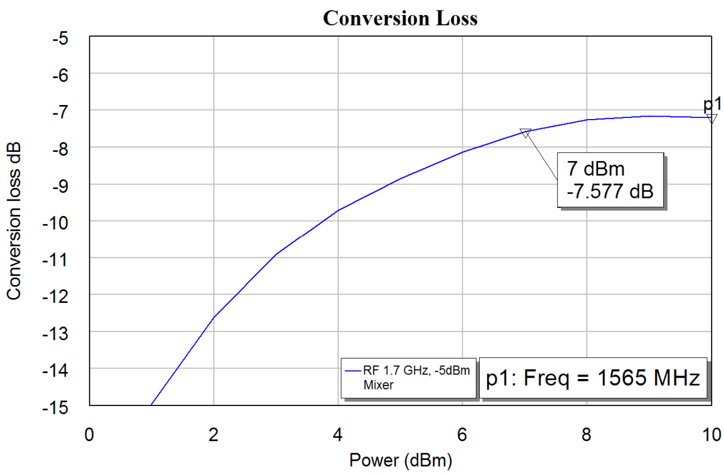


Figure 42. Conversion loss of a balanced mixer with a Branchline coupler.

Figure 42 shows the conversion loss of the microwave mixer of figure 41. The conversion loss is 1.5 dB worse than that of the ideal microwave mixer of figure 36.

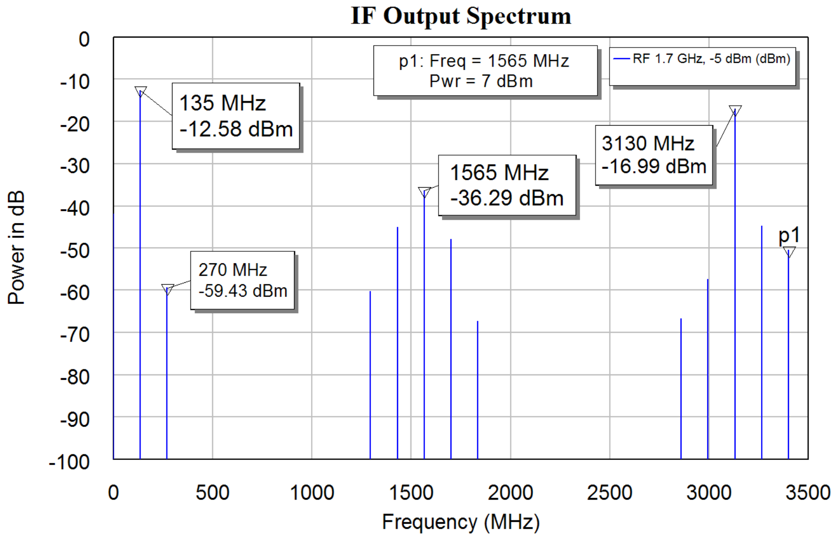


Figure 43. IF spectrum of a balanced mixer with a Branchline coupler.

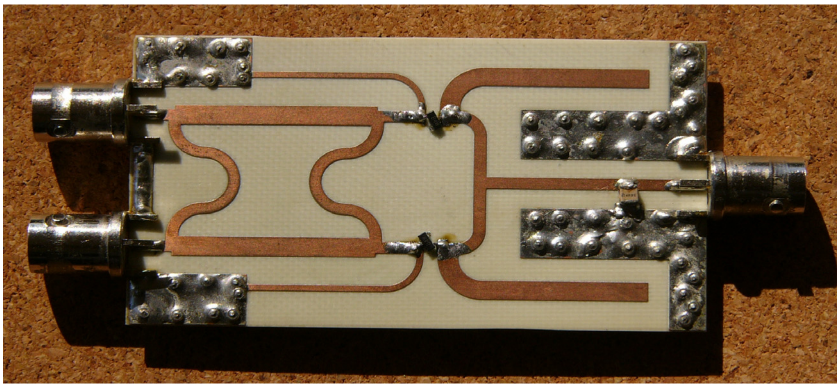

Figure 44. Hardware realisation of the balanced mixer using a Branchline coupler.

The conversion loss includes approximately 0.5 dB losses in the PCB tracks. Figure 43 shows the IF spectrum of the mixer and it can be seen that the mixer performs well. The components above 1 GHz can easily be filtered out using a simple low pass filter at the IF output. Figure 43 shows the hardware for the PCB layout of figure 42.

Figure 45 shows the measured performance of the hardware of figure 44. The IF spectrum closely resembles the results obtained from simulation and shown in figure 43. The measured conversion loss for a LO level of 5 dBm at 1.565 GHz and an RF signal of –5 dBm at 1.7 GHz was 7.25 dB, being within 0.4 dB of the performance shown in figure 35. The second harmonic distortion at 270 MHz, at -55 dBm, is 5 dB larger than in the computer simulation. The LO feedthrough is 10 dB larger, but two microwave diodes were selected for the mixer, without being matched. A third harmonic distortion is not present in figure 43, but it is present in figure 45. The signal components in the region 88 to 108 MHz at -80 dBm are the local FM transmitters, located less than 5 km from JCU.

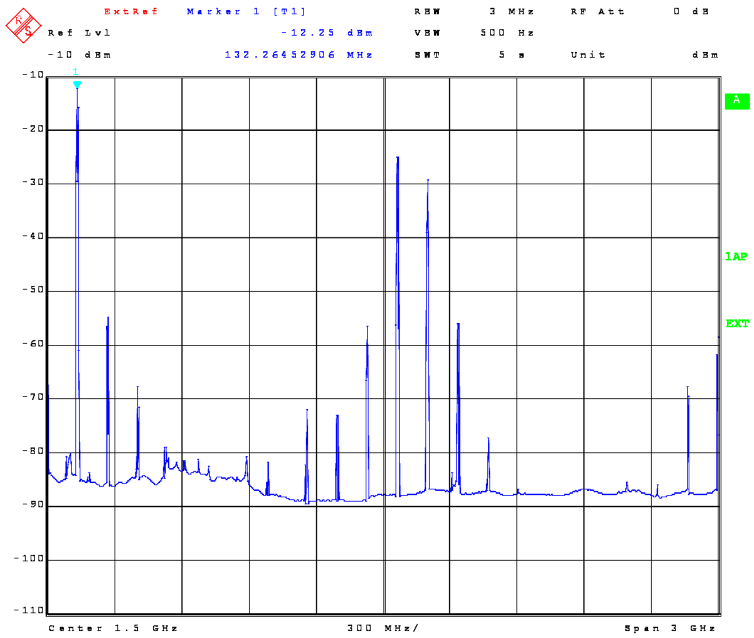


Figure. 45, Measured spectrum of Branchline coupler mixer of figure 44.

# Active Single transistor mixer

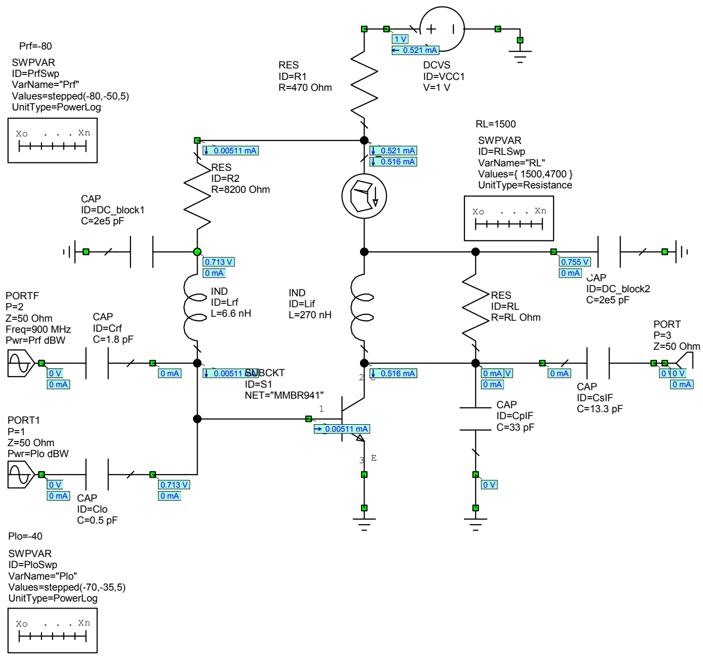


Figure 46. Active single diode mixer (AWR example, Low_Power_Mixer).

Figure 46 shows the *Low_Power_Mixer* active single diode mixer from the Microwave office mixer examples. An active single transistor mixer has a similar spectral performance to a passive single diode mixer, but has a conversion gain. The mixer of figure 46 has a conversion gain of more than 10 dB. Active single transistor mixers are used in many consumer devices like radio and TV.

# Gilbert Cell Active Mixer:

It is possible to use two transistors in a push-push amplifier configuration and thus produce an active balanced mixer. However, the Gilbert Cell or long tail multiplier is much more commonly used as an active mixer, as it provides close to ideal multiplier performance. The Gilbert cell mixer is used in many IC's. There is a *Gilbert-Cell* mixer in the examples provided by MWO. That Gilbert cell example has been simplified to illustrate it's principle of operation as shown in figure 45. Gilbert Cell mixers with very good IM performances and a frequency range from DC to 5 GHz are available.

Figure 47 shows the basic circuit diagram of a Gilbert Cell mixer. Normally all these components would be included in an IC. Figure 48 shows the corresponding conversion gain. The LO and RF frequencies are chosen to be the same as that for the microwave mixer of figure 36 and 39. The circuit consists of 3 parts, the left part consisting of transistors TR1 to TR7 is the Gilbert Cell multiplier. Transistor TR1 is a constant current source for the long tail pair amplifiers making up the Gilbert Cell. The resistor chain R1 to R4 is a biasing chain, providing the biasing voltages. Transistors TR8 to TR11 form the output buffer amplifier, with transistors TR9 and TR11 being constant current sources and TR8 and TR10 being voltage followers.

A fully differential output circuit is required to obtain the best LO isolation, without having to tune the RL13 and RL24 for best LO ⇒ IF isolation. The differential IF output also minimises the IF harmonic output at 270 MHz.

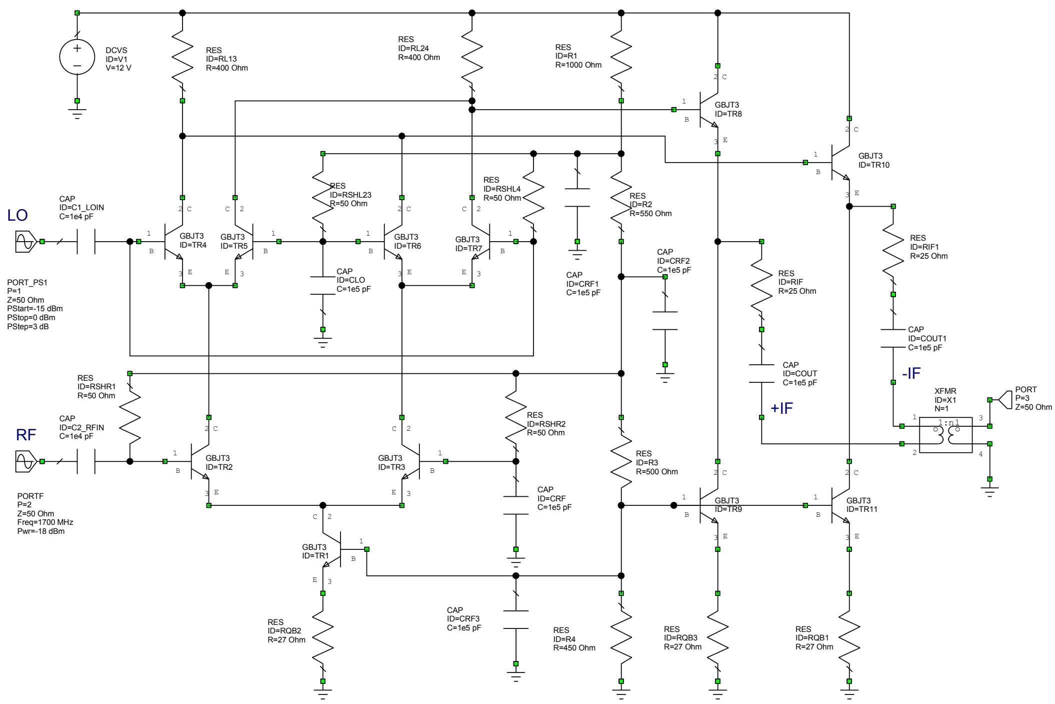


Figure 47. Basic Gilbert Cell active multiplier.

The Gilbert Cell mixer is different from the diode mixers in that the best performance is obtained when the LO signal does not cause saturation in the transistors of the Gilbert Cell. Figure 48 shows that the largest signal that can be used without the mixer saturating too much is -6 dBm and that level of LO power has been used for the subsequent measurements. Using a lower LO power gives more ideal mixer action but reduces the conversion gain. The RF level of -18 dBm corresponds to a 1 dB reduction of the conversion gain of the mixer and thus corresponds to the 1 dB compression point.

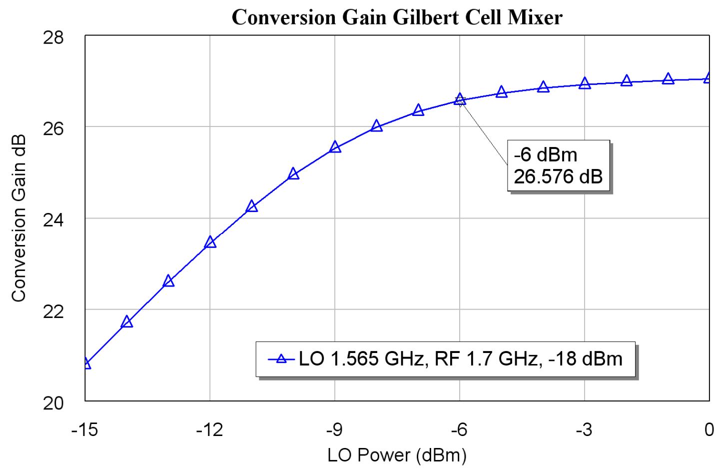


Figure 48. Conversion gain of the Gilbert Cell mixer of figure 45.

Figure 49 shows the IF spectrum of the Gilbert Cell Mixer. The LO power is -6 dBm and the RF level is -18 dBm corresponding to the maximum levels for each of these. Using a lower RF power level gives a better performance with a better LO and RF isolation at the IF output. The RF signal is at 1.7 GHz and the LO signal is at 1.585 GHz resulting in a difference signal at 135 MHz and a sum signal at 3.265 GHz. Figure 49 shows that these are of equal power level and are the largest signals. The Gilbert cell acts thus as a near ideal mixer.

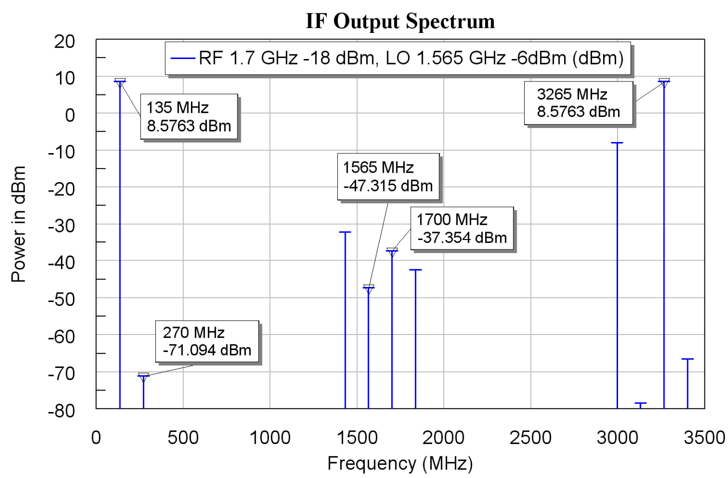


Figure 49. IF spectrum of the Gilbert Cell mixer of figure 45 as a down-converter.

Figure 50 shows the RF spectra of the Gilbert Cell mixer used as an up-converter, when the IF signal level is varied. The LO signal is -6 dBm and IF signal level is -18 dBm, -23 dBm and -28 dBm. For an IF signal of -28 dBm, the unwanted components are more than 55 dB below the wanted components, so that the Gilbert Cell is near ideal mixer. Changing the IF level by 5 dB, from -28 dBm to -23 dBm, causes a 4.9 dB change in level of the 1.7 GHz and 1.43HGz components and a 15.5 dB change in the 3IM component at 1.16 GHz. The mixer is thus operating in a linear range and the expected third order intercept point is at (0.5*(56.628-0.48462)-0.48462) = 27.587 dBm at the output and 27.587-27.515=0.072 dBm at the IF input. Changing the IF level by 5 dB, from -23 dBm to -18 dBm causes a 4.157 dB change in the level of the 1.7 GHz and 1.43HGz components, so that the -18 dBm IF input power corresponds closely to the 1 dB compression point. The computer simulations or similar measurements on the actual devices can thus easily be used to determine the critical mixer parameters. Passive Double Balanced mixers, can operate at higher input levels, but produce lower output levels.

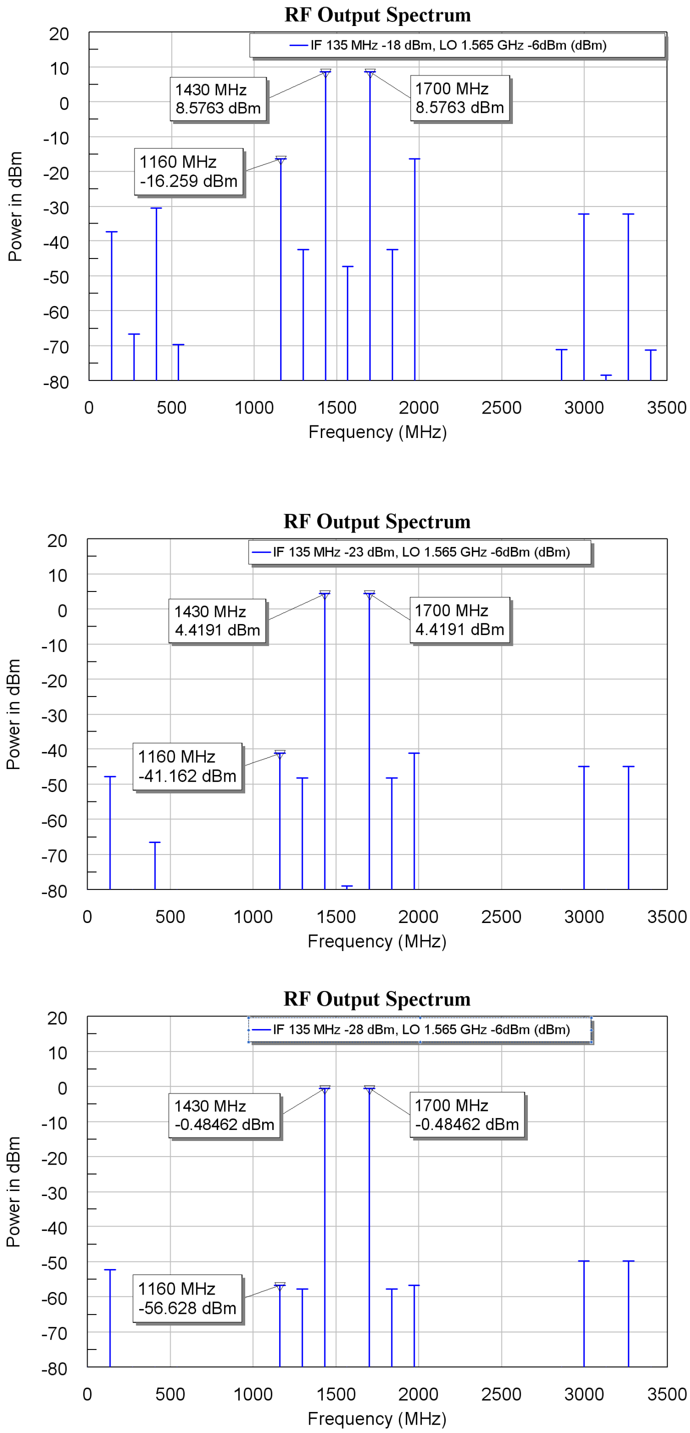


Figure 50. RF spectra of the Gilbert Cell mixer of figure 47 as an up-converter, RF levels of -18dBm (top), -23 dBm (middle) -28 dBm (bottom).

Figure 51 shows the corresponding RF waveform. The waveform corresponds to an ideal Double Sideband Suppressed Carrier waveform and any unwanted signals cannot be observed in the time waveform, but can be detected in the spectrum of figure 50.

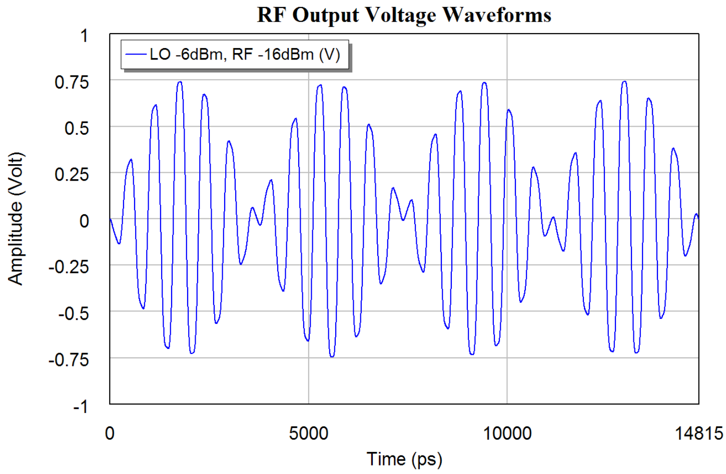


Figure 51. RF Waveform corresponding to figure 47.

## *Examples of Commercial Active Mixers*

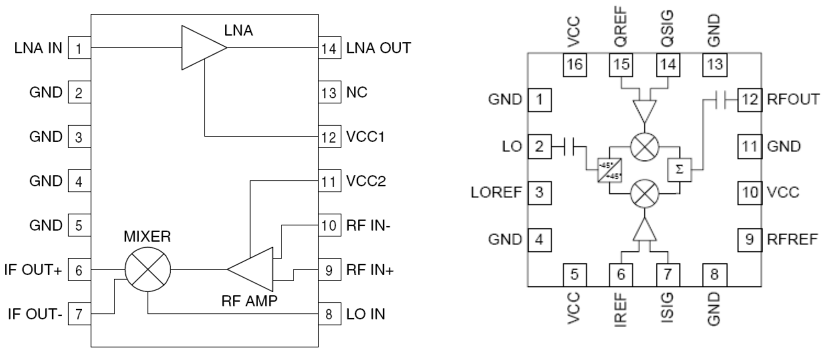


Fig 52. RF MicroDevices RF2411 LNA and Mixer and RF2850, IQ active mixer

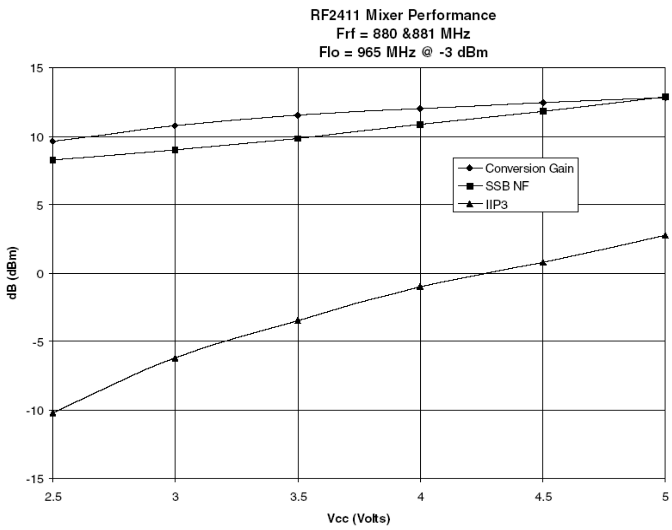


Figure 53. RF MicroDevices RF2411 LNA and mixer performance.

Many manufacturers produce active mixers for use in commercial equipment. In particular mixers for use in mobile and cordless phones, wireless LANs and similar consumer devices are readily available. The RF2411 Receiver front end and the RF2850 IQ active mixer, produced by RF MicroDevices are some examples of commercial active mixers. Figure 52 shows the pin connections of two commercial mixer IC's.

As shown in figure 53, the LNA used in the RF2411 IC, has a noise figure which varies from 1.7 dB at 500 MHz to 2.5 dB at 1500 MHz. The gain of the LNA is 17 dB at 1 MHz and slopes to 11 dB at 1500 MHz. The RF2411 can thus be used in many commercial applications.

# Quadrature Mixers

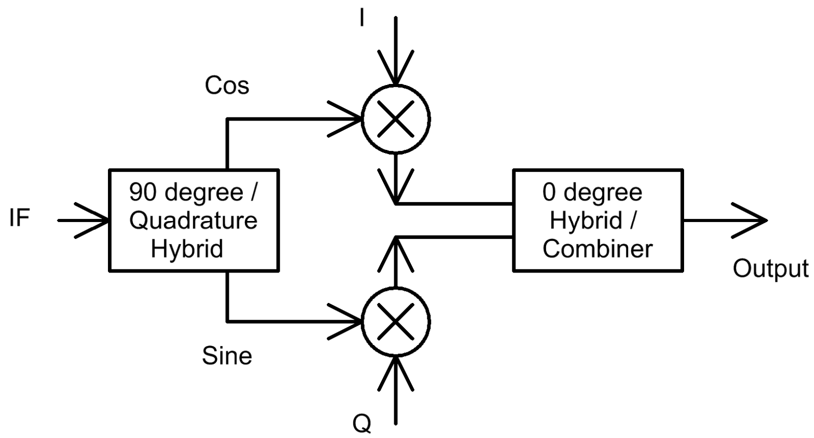


Figure 54. Block diagram of a quadrature mixer.

In quadrature mixers a 90 degree hybrid, like a Branchline coupler is used to produce two LO signals, corresponding to Sine and Cosine of the LO frequency. The Cosine signal is then multiplied with the In-Phase (I) component of the baseband signal, and the Sine signal is multiplied with the Quadrature (Q) component of the baseband signal, as shown in figure 54. The resulting signals are then added using a combiner like a Wilkinson hybrid to produce the RF signal. When the I and Q signals are the Hilbert transform of each other, then a Single Sideband RF signal results. When the I and Q signals are an RF signal that is passed through a 90° hybrid then the image frequency components are suppressed. When the I and Q signals are individually controlled baseband signals a vector modulated RF signal results. In most cases the I and Q signals are produced using Digital Signal Processing techniques. Quadrature mixers are thus required for the vector modulation used in many modern communication systems.

The 90 Degree hybrids required for quadrature mixers can also be produced using LC networks, so that quadrature hybrids at frequencies below 500 MHz are possible. As an example, Minicircuits make quadrature mixers at a wide range of frequencies as shown in figure 55.

Local oscillators produced using phase locked loops or using Direct Digital Synthesis, can have two outputs which have an exact 90 degree phase difference over a wide range of frequencies, as is required for the quadrature mixers.


JCIR-4MH (+15 dBm LO)
JCIR-25 (+13 dBm LO)

| MODEL NO. | FREQUENCY MHz RF $f_L$-$f_U$ | LO $f_L$-$f_U$ | IF | CONVERSION LOSS dB $\bar{X}$ | σ | Max. | IMAGE REJECTION dBc RF>LO | LO>RF | Typ. | Min. | LO-RF ISOLATION dB M Typ. | Min. | LO-IF ISOLATION dB M Typ. | Min. | RF-IF ISOLATION dB M Typ. | Min. | IP3@ center band (dBm) Typ. | CASE STYLE | CONNECTION | PRICE $ QTY. (1-9) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ◆ JCIR-4MH | 430-930 | 500-1000 | 65-75 | 7.9 | 0.15 | 9.0 | ● | | 28 | 18 | 55 | 40 | 25 | 20 | 25 | 15 | 20 | BG291 | kj | 54.95 |
| ◆ JCIR-25 | 2490-2550 | 2420-2480 | 57-83 | 7.0 | — | 8.5 | | ● | 27 | 17 | 35 | 25 | 26 | 18 | 25 | | 16 | BG291 | kk | 44.95 |

L = low range [$f_L$ to 10 $f_L$] M = mid range [10 $f_L$ to $f_U$/2] U = upper range [$f_U$/2 to $f_U$]
m = mid band [2$f_L$ to $f_U$/2]

features
- excellent image rejection, 28 dB typ. (JCIR-4MH)
- low conversion loss, 7.9 dB typ. (JCIR-4MH)
  7.0 dB typ. (JCIR-25)
- solder plated J-leads for excellent solderability & strain relief

applications
- cellular
- ISM

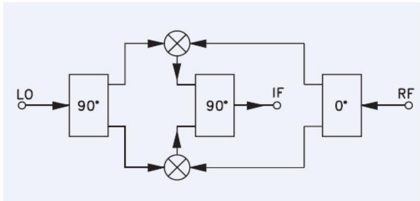


Fig 55. Minicircuit IQ mixers. (From their catalogue)

## Active IQ Mixers

The RF2850 IQ mixer shown in figure 52, is used as an up-converter for mobile radio applications. This mixer used Gilbert cells for the mixers. Using an IQ mixer allows the required RF output signal to be produced, without the need to filter out unwanted sidebands. In addition a zero IF frequency can be used, so that the LO is at the centre of the RF band, again avoiding the need for filters. Such RF filters are large and heavy. It is desirable to have a small and light mobile phone. An I and Q signal, up to 250 MHz can be used, together with a LO signal in the range 1.7 GHz to 2.5 GHz, to produce a quadrature modulated RF signal in the range 1.7 GHz to 2.5 GHz. A typical carrier suppression of 25 dB unadjusted and 55 dB adjusted is obtained. The mixer has a typical (unadjusted) unwanted sideband suppression of 45 dB. The mixer performance satisfies all the mobile radio standards. These are low cost devices aimed for a consumer market.

For modern signal generators, IQ modulation is used to produce the complex modulated waveforms used in modern communication systems. The mixers used in such signal generators are often active (Gilbert cell) IQ mixers. Computer controlled DC bias (control and calibration) signals are used to ensure that the carrier feed-through, Quadrature phase shifts and I and Q gains are correct. The design of such IC's can cost more than one million dollars. The resulting devices have a better performance than those of figure 55 or 56, but each mixer will also be more expensive.

## LTC Mixers

At higher frequencies, it becomes more difficult to wind the transformers required for the mixers. Low Temperature Cofired (LTC) thick film technology allows a circuit to be made up from multiple layers of ceramic materials. By depositing conductive of magnetic inks, a set of layers can form a strip-line transmission line, a ferrite loaded hybrid or it can contain semiconductor elements like diodes. Because high dielectric constant materials are used, the resulting package can be made small. Since the process can be automated, lower production costs result. Minicircuits use this technology for producing high frequency mixers. A typical example is their IQBG-2000 I&Q modulator. The block diagram is the same as the IQ mixer in figure 54. This device is designed for the 1.8 GHz to 2 GHz mobile phone market. The Package is shown in figure 56. This LTC IQ mixer has an image rejection of better than 30 dB, which is comparable to the transformer based mixers shown in figure 53, but this isolation could not be obtained using conventional transformer based technology. More details on LTC circuits are given in the lectures on Circuit Manufacture.

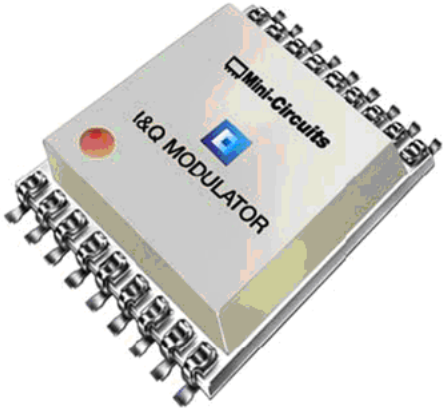


Fig 56. Minicircuits LTC IQ mixer, IQBG-2000. (From www.minicircuits.com)

## Other Mixers

Mixer manufacturers make other types of mixers, such as triple balanced mixers, which result in a better input impedance and double balanced mixers using FETs in a passive mode (no DC supplied to the FET) in order to obtain an improved IP3 performance. The description of such devices are beyond the scope of these notes, but some further details can be found at the Minicircuits web site (www.minicircuits.com).