

## C. Mixers

Perhaps the most important component of any receiver is the mixer—a non-linear microwave device.

### HO: Mixers

**Q:** *How efficient is a typical mixer at creating signals at new frequencies?*

**A:** HO: Mixer Conversion Loss

**Q:** *How large can the IF signal power be? Is there some limit?*

**A:** HO: Mixer Compression and Intercept Points

**Q:** *Are there any other important mixer performance specifications?*

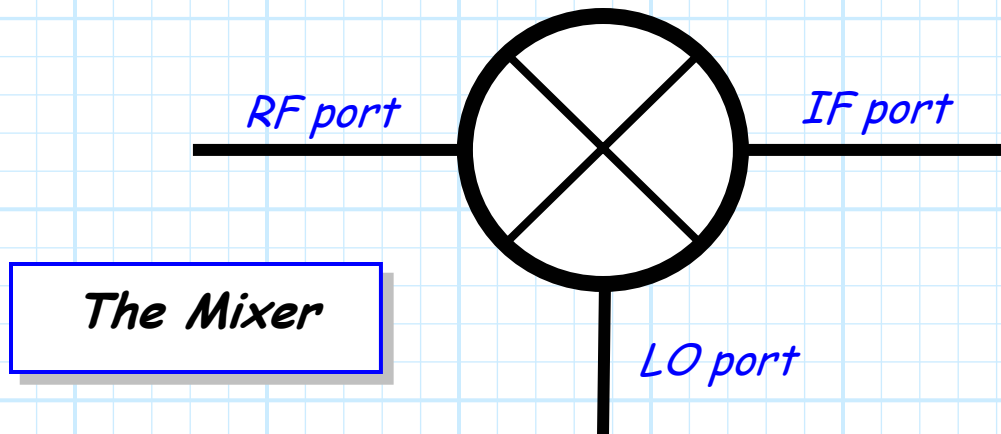
**A:** HO: Mixer Isolation

Once again, a spec sheet:

HO: The Mixer Spec Sheet

# Mixers

A **mixer** is a three-port, **non-linear** microwave device.



The three ports of a mixer are **distinct** and unique, and are typically referred to as:

- 1) The **RF** (Radio Frequency) port
- 2) The **IF** (Intermediate Frequency) port
- 3) The **LO** (Local Oscillator) port

**Q:** *So just what does a mixer do??*

**A:** A clue is in its symbol:  $\otimes$

**→** A mixer is a **multiplier** ( $\times$ ) !!

Say there is a signal  $v_{RF}(t)$  at the RF mixer port, and a signal  $v_{LO}(t)$  at the LO mixer port. An **ideal** mixer would then produce at the IF port, a signal  $v_{IF}(t)$ , where:

$$v_{RF}(t)v_{LO}(t) = v_{IF}(t) \quad (\text{an ideal mixer})$$

To see why this might be **useful**, consider a case where:

$$v_{RF}(t) = \cos \omega_{RF} t$$

$$v_{LO}(t) = \cos \omega_{LO} t$$

Multiplying these signals, we get:

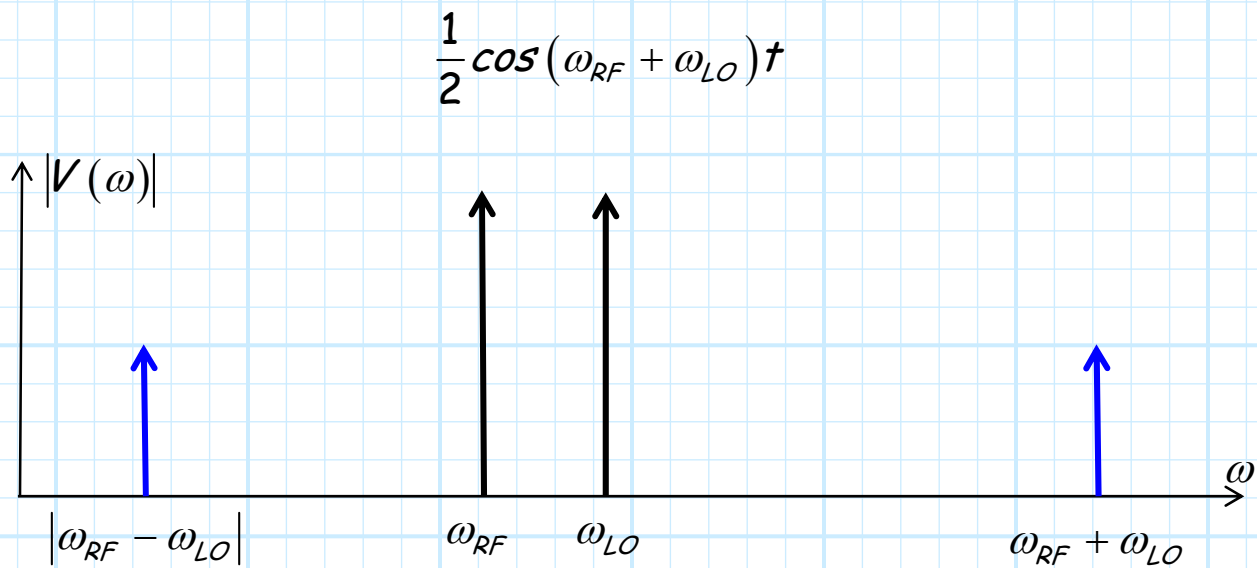
$$\begin{aligned} v_{IF}(t) &= v_{RF}(t)v_{LO}(t) \\ &= \cos(\omega_{RF}t)\cos(\omega_{LO}t) \\ &= \frac{1}{2}\cos(\omega_{RF} - \omega_{LO})t + \frac{1}{2}\cos(\omega_{RF} + \omega_{LO})t \end{aligned}$$

At the IF port we have created **two** signals with **new** frequencies!

One new signal has a frequency that is the **difference** of the LO and RF signal frequencies:

$$\frac{1}{2}\cos(\omega_{RF} - \omega_{LO})t$$

While the other new signal has a frequency that is the **sum** of the LO and RF signal frequencies:



But alas, mixers are **not ideal!**

A more **accurate** model of the (**non-ideal**) relationship between  $v_{RF}(t)$ ,  $v_{LO}(t)$ , and  $v_{IF}(t)$  is:

$$\begin{aligned}
 v_{IF}(t) = & a_1 v_{RF}(t) + a_2 v_{LO}(t) \\
 & + a_3 v_{RF}^2(t) + a_4 v_{RF}(t)v_{LO}(t) + a_5 v_{LO}^2(t) \\
 & + a_6 v_{RF}^3(t) + a_7 v_{RF}^2(t)v_{LO}(t) \\
 & + a_8 v_{RF}(t)v_{LO}^2(t) + a_9 v_{LO}^3(t) \\
 & + \dots
 \end{aligned}$$

where the values  $a_n$  are real-valued **constants**.

Just as with an amplifier, a mixer will produce **1<sup>st</sup>-order**, **2<sup>nd</sup>-order**, **3<sup>rd</sup>-order**, and even **higher order** terms!

As a result, there will be **many** signals created at the IF port. If we did **all** the trigonometry, we would find that the signal **frequencies** created from these terms (in relation to  $\omega_{RF}$  and  $\omega_{LO}$ ) are:

**1<sup>st</sup> order:**  $\omega_{RF}, \omega_{LO}$

**2<sup>nd</sup> order:**  $|\omega_{RF} - \omega_{LO}|, 2\omega_{RF}, 2\omega_{LO}, \omega_{RF} + \omega_{LO}$

**3<sup>rd</sup> order:**  $|2\omega_{RF} - \omega_{LO}|, |2\omega_{LO} - \omega_{RF}|, 3\omega_{RF},$   
 $3\omega_{LO}, 2\omega_{RF} + \omega_{LO}, \omega_{RF} + 2\omega_{LO}$

**examples of higher orders:**  $|4\omega_{RF} - 2\omega_{LO}|, 5\omega_{RF},$   
 $7\omega_{LO}, 827\omega_{RF} + 134\omega_{LO}$

Note that the **ideal** mixer (multiplier) occurs when all constants  $a_n$  are zero, **except** for the constant  $a_4$ . The result in this case being:

$$v_{IF}(t) = a_4 v_{RF}(t) v_{LO}(t) \quad (\text{ideal mixer response})$$

and thus the **only** signals created are the **2<sup>nd</sup> order** terms  $|\omega_{RF} - \omega_{LO}|$  and  $\omega_{RF} + \omega_{LO}$ .

Of course for a “real” mixer, all the constants  $a_n$  are **non-zero**, although for good mixers all but  $a_4$  are relatively **small**.

Thus, for good mixers, most of the signals created at the IF output will be of relatively **low** power, with **exception** of the signal at frequencies  $|\omega_{RF} - \omega_{LO}|$  and  $\omega_{RF} + \omega_{LO}$ .



All **other** signals (meaning other than  $|\omega_{RF} - \omega_{LO}|$  and  $\omega_{RF} + \omega_{LO}$ ) at the IF are known as **spurious** signals—or in the vernacular of radio engineers, “**spurs**”.

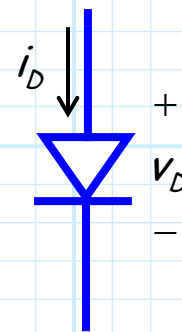
**Q:** *How are mixers constructed?*

**A:** Multiplication is a decidedly **non-linear** operation. As such, it requires **non-linear devices** to implement.

Typically, these non-linear devices are **diodes**, but sometimes transistors are used.

For example, as those of you who aced EECS 312 know, the **junction diode** equation is:

$$i_D = I_s \left( e^{v_D/nV_T} - 1 \right)$$



This **non-linear** function can be expanded using a **Taylor series** as:

$$i_D = I_s \left( e^{v_D/nV_T} - 1 \right) = b_1 v_D + b_2 v_D^2 + b_3 v_D^3 + \dots$$

And if, for example:

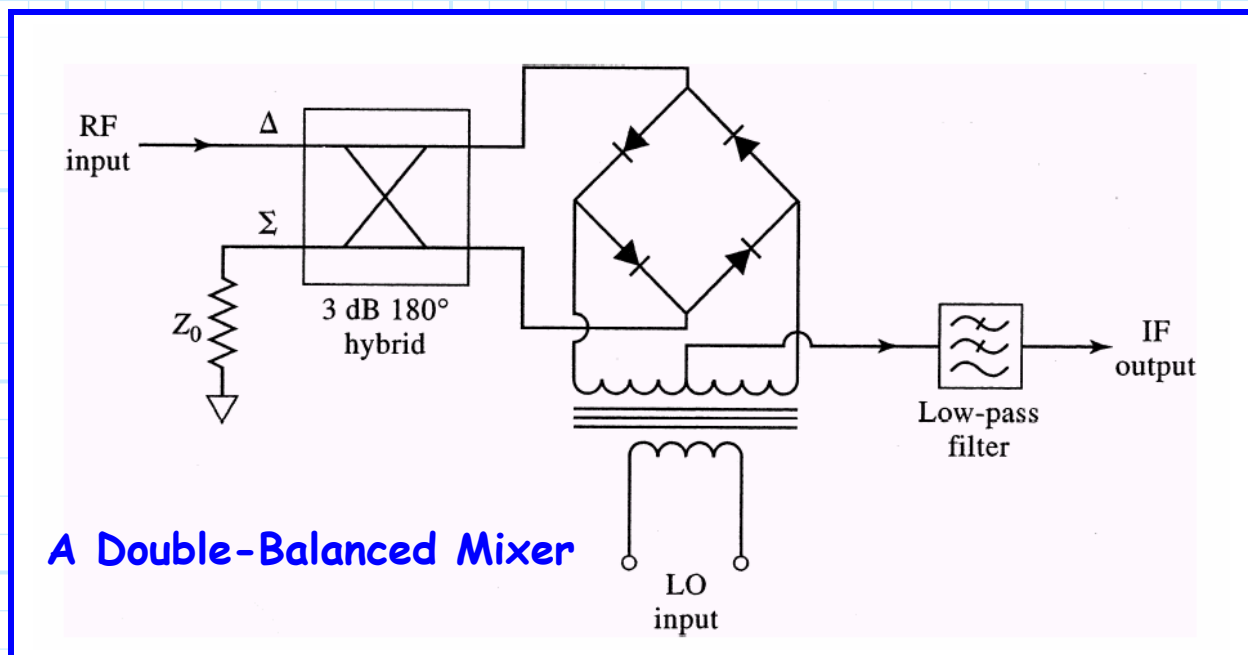
$$v_D(t) = v_{RF}(t) + v_{LO}(t)$$

we find that the diode will create **high-order** terms, including  $v_{RF}(t)v_{LO}(t)$ :

$$b_2(v_{RF}(t) + v_{LO}(t))^2 = b_2(v_{RF}^2(t) + 2v_{RF}(t)v_{LO}(t) + v_{LO}^2(t))$$

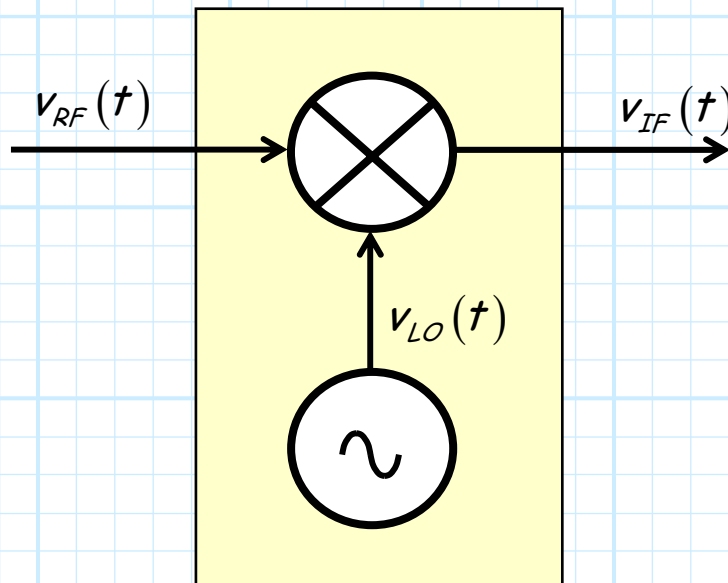
Basically, generating high-order terms with **any** non-linear device is **not** at all difficult (just try and **keep** it from happening!). The trick is to generate **only** the 2<sup>nd</sup> order term  $v_{RF}(t)v_{LO}(t)$ , while somehow **suppressing** the rest.

Thus, mixer design is as much **art** as it is science! Popular designs include the **balanced mixer** (with 2 junction diodes), and the **double balanced mixer** (with 4 junction diodes).



# Mixer Conversion Loss

Let's examine the **typical application** of a mixer.



Generally, the signal delivered to the Local Oscillator port is a **large, pure tone** generated by a device called—a **Local Oscillator!**

$$v_{LO}(t) = A_{LO} \cos \omega_{LO} t$$

Additionally, we will find that the local oscillator is **tunable**—we can **adjust** the frequency  $\omega_{LO}$  to fit our purposes (this is **very important!**).

Typically, every mixer will be **paired** with a local oscillator. As a result, we can view a mixer as a non-linear, **two-port** device! The **input** to the "device" is the RF port, whereas the **output** is the IF port.



In contrast to the LO signal, the **RF input signal** is generally a low-power, modulated signal, operating at a carrier frequency  $\omega_{RF}$  that is relatively large—it's a **received** signal!

$$v_{RF}(t) = a(t) \cos(\omega_{RF}t + \phi(t))$$

where  $a(t)$  and  $\phi(t)$  represent amplitude and phase modulation.

**Q:** So, what "output" signal is created?

**A:** Let's for a second **ignore** all mixer terms, **except** for the **ideal** term:

$$v_{IF}(t) \approx K v_{RF}(t) v_{LO}(t)$$

where  $K$  indicates the **conversion** factor of the mixer (i.e.,  $K = a_4$ ).

Inserting our expressions for the RF and LO signals, we find:

$$\begin{aligned} v_{IF}(t) &= K v_{RF}(t) v_{LO}(t) \\ &= K a(t) \cos(\omega_{RF}t + \phi(t)) A_{LO} \cos \omega_{LO}t \\ &= \frac{K A_{LO}}{2} a(t) \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)] \\ &\quad + \frac{K A_{LO}}{2} a(t) \cos[(\omega_{RF} + \omega_{LO})t + \phi(t)] \end{aligned}$$

As we expected, we generate **two** signals, one at frequency  $|\omega_{RF} - \omega_{LO}|$  and the other at frequency  $\omega_{RF} + \omega_{LO}$ .

Typically, the high frequency term is **filtered** out, so the IF output is:

$$v_{IF}(t) = \frac{K A_{LO}}{2} a(t) \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]$$

Look at what this means!

It means that the output **IF** signal is nearly **identical** to the input **RF** signal. The **only** differences are that:

- 1) The IF signal has different **magnitude** (typically, a smaller magnitude).
- 2) The IF signal has a different **frequency** (typically, a much lower frequency).

Thus, the modulation **information** has been **preserved** in this "mixing" process. We can accurately **recover** the information  $a(t)$  and  $\phi(t)$  from the IF signal!

Moreover, the RF signal has been "**downconverted**" from a high frequency  $\omega_{RF}$  to a typically **low** signal frequency  $|\omega_{RF} - \omega_{LO}|$ .

**Q:** *Why would we every want to "downconvert" an RF signal to a lower frequency?*

**A:** Eventually, we will need to process the signal to recover  $a(t)$  and  $\phi(t)$ . At lower frequencies, this processing becomes **easier, cheaper, and more accurate!**

Now, we **additionally** want our IF signal to be as **large** as possible. It is evident that if:

$$v_{IF}(t) = \frac{K A_{LO}}{2} a(t) \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]$$

the local oscillator **magnitude**  $A_{LO}$  needs to be as **large** as possible!

But, we find that there is a **limit** on how large we can make the LO signal power. At some point, the mixer LO port will **saturate**—increasing the LO power further will not result in an increase in  $v_{IF}(t)$ .

We call this LO maximum the **LO drive power**. For diode mixers, we find that this power is **typically** in a range from **+5.0 to +20.0 dBm**.

→ It is **very** important that the local oscillator power **meet** or **exceed** the LO drive power requirement of the mixer!

Now, let's consider the "**gain**" of this 2-port device:

$$\text{Mixer "Gain"} = \frac{P_{IF}}{P_{RF}} = \left( \frac{K A_{LO}}{2} \right)^2$$

We find that **typically**, when the LO drive power requirement for a diode mixer is met, that:

$$K A_{LO} \approx 1$$

And thus, the mixer **gain** for a properly driven diode mixer will be **roughly**:

$$\text{Mixer "Gain"} = \frac{P_{IF}}{P_{RF}} \approx \left(\frac{1}{2}\right)^2 \approx \frac{1}{4}$$

Therefore, we find that a diode mixer gain will be in the range of **-6.0 dB**. This is a **rough** approximation, and **typically** we find the "gain" of a properly driven diode mixer **ranges** from about **-3.0 dB to -10 dB**.

Note that this mixer "gain" is actually a **loss**. This makes sense, as most mixers are, after all, **passive** devices.

Thus, mixers are not specified in terms of their gain, but instead in terms of its **conversion loss**:

$$\text{Conversion Loss} \doteq -10 \log_{10} \left( \frac{P_{RF}}{P_{IF}} \right)$$

Note that conversion loss is simply the **inverse** of mixer gain, and thus we find that **typical** values of conversion loss will range from **3.0 dB to 10.0 dB**.

→ We want a mixer with as **low** a conversion loss as **possible!**

\* One final note, we find that if the LO power drops **below** the required mixer drive power, the conversion loss will increase **proportionately**.

For **example**, say a mixer requires an LO drive power of +12.0 dBm, and exhibits a conversion loss of 6.0 dB. If we **mistakenly** drive the mixer with an LO signal of only +5 dBm, we will find that the mixer conversion loss will **increase** to 13.0 dB!

In other words, if we "**starve**" our mixer LO by 7.0 dB, then we will increase the **conversion loss** by 7.0 dB.

\* OK, one **more** final note. We have focused on the **desired** IF output signal, the one created by the **ideal** mixer term. Recall, however, that there will be many more **spurious** signals at our IF output!

Likewise, we have assumed that there is only **one** signal present at the **RF** port. We find this is **rarely** the case, and instead there will be at the RF port a whole **range** of different received signals, spread across a wide **bandwidth** of RF frequencies.

For example, at the RF port of a mixer in an **FM radio** receiver, **all** of the radio stations within the FM band (88 MHz to 108 MHz) will be present! As a result, **each** of these

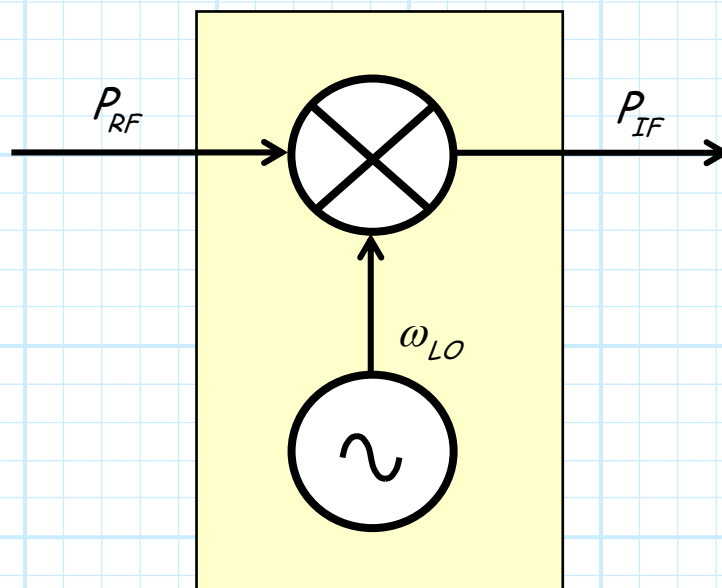
stations will be down-converted, **each** of these stations will appear at the IF output, and each will create there own set of **spurious** signals!

# Mixer Compression and Intercept Points

Recall we discussed the 1 dB compression point and the 3<sup>rd</sup> order intercept point for amplifiers.

The same concepts are also valid for mixers!

Instead of the values  $P_{in}$  and  $P_{out}$ , consider now  $P_{RF}$  and  $P_{IF}$ .



Recall that we could define the "gain" of the mixer (from RF port to IF port) as:

$$\begin{aligned} \text{"Gain"}(\text{dB}) &= 10 \log_{10} \left( \frac{P_{IF}}{P_{RF}} \right) \\ &= -\text{Conversion Loss (dB)} \end{aligned}$$

E.G., if the conversion loss of a mixer is 6 dB, then its "gain" is -6 dB.

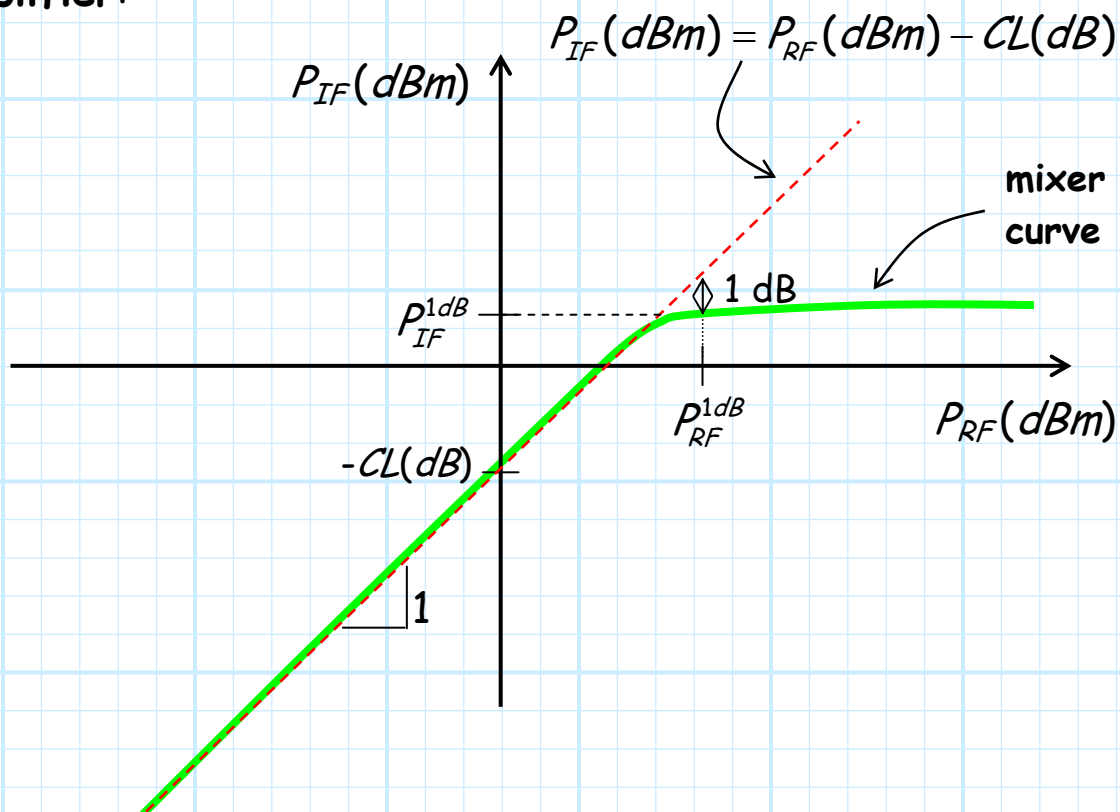
For **small** values of  $P_{RF}$ , this gain (conversion loss) is **constant** with respect to RF power.

However, if the RF input power becomes **too large**, then the mixer will begin to **saturate** (i.e., compress)—just like an amplifier!

When in saturation, an increase in  $P_{RF}$  will **not** result in a proportionate increase in  $P_{IF}$ ! I.E.:

$$P_{IF}(\text{dBm}) < P_{RF}(\text{dBm}) - \text{Conversion Loss}(\text{dB})$$

We therefore can **plot** a behavior that reminds us of an **amplifier**:





There is **one** (and only one!) point on the mixer curve that satisfies the equation:

$$P_{IF}(\text{dBm}) = P_{RF}(\text{dBm}) - \text{Conversion Loss}(\text{dB}) - 1 \text{ dB}$$

This point is the **1 dB compression point** of the mixer!

- \* At the **1 dB compression point**, the conversion loss appears to be **1 dB greater** than its normal (i.e., low power) value.
- \* We define the RF power at this compression point as  $P_{RF}^{1dB}$ , and the IF power  $P_{IF}^{1dB}$ .
- \* We can conclude that  $P_{IF}^{1dB}$  is the **maximum output power** of the mixer (for second-order signals).
- \* The largest RF signal power that should ever be put into the mixer is therefore  $P_{RF}^{1dB}$ .
- \* Typically, mixer manufactures will specify the compression point in terms of the **input RF signal power** (i.e.,  $P_{RF}^{1dB}$ ).
- \* Note that this is in distinct **contrast** with amplifiers, as manufactures of those components specify the compression point in terms of **output power** (i.e.,  $P_{1dB}$ ), as opposed to the input power (i.e.,  $P_{in}^{max}$ ).
- \* **Typical mixer compression points range from 0 to 15 dBm.**

### 3<sup>rd</sup> Order Intercept Point

Manufacturers also typically specify a **third-order intercept point** (generally in dBm). This is actually a parameter describing "**two-tone**" intermodulation distortion—that is, the RF input includes two (or more) signals at dissimilar frequencies:

$$V_{RF} = a \cos \omega_1 t + a \cos \omega_2 t$$

In addition to the desired IF signals at frequencies  $|\omega_1 \pm \omega_{LO}|$  and  $|\omega_2 \pm \omega_{LO}|$ , the two input signals combine to form **third order** intermodulation distortion products at frequencies  $|(2\omega_1 - \omega_2) \pm \omega_{LO}|$  and  $|(2\omega_2 - \omega_1) \pm \omega_{LO}|$ .

- \* Being third order products, the power of these IF signals are proportional to the RF power **cubed**.
- \* Theoretically, if the power of the RF input is large enough, the these third order intermodulation terms can become **equal** in power to the "fundamental" signals  $|\omega_1 \pm \omega_{LO}|$  and  $|\omega_2 \pm \omega_{LO}|$ .
- \* Of course, this 3<sup>rd</sup> order intercept point is a **theoretical** value, as the mixer IF output will **saturate** before the 3<sup>rd</sup> order intermodulation terms can get that large.
- \* However, the mixer 3<sup>rd</sup> order intercept power does provide an indication of the mixers intermodulation **distortion performance**.

- \* Just like an amplifier, the **higher** the two-tone 3<sup>rd</sup> order intercept point, the **better**.
- \* **Typically**, the two-tone 3<sup>rd</sup> order intercept point of a mixer is **10 to 20 dB** greater than its **1 dB compression point**.

# Mixer Isolation

**Q:** In our earlier discussion of the products generated at the mixer IF port, I spotted a couple of **first-order terms**:

$$\begin{aligned}
 v_{IF}(t) = & a_1 v_{RF}(t) + a_2 v_{LO}(t) \\
 & + a_3 v_{RF}^2(t) + a_4 v_{RF}(t)v_{LO}(t) + a_5 v_{LO}^2(t) \\
 & + a_6 v_{RF}^3(t) + a_7 v_{RF}^2(t)v_{LO}(t) \\
 & + a_8 v_{RF}(t)v_{LO}^2(t) + a_9 v_{LO}^3(t) \\
 & + \dots
 \end{aligned}$$

This suggests that signals appear at the **IF output** with precisely the **same frequencies** of the RF and LO signals (i.e.,  $\omega_{RF}$  and  $\omega_{LO}$ )!?!)



**A:** That's correct! Essentially the LO and RF signals "leak" across the mixer and are directly **coupled** into the **IF output**—no up-conversion or down-conversion occurs!

These "leaked" signal are yet another **spurious output** that we wish **weren't** there.

**Q:** Do these spurious **first-order** products actually cause any **problems**?

**A:** It **depends** on the application. Of course both the RF signal and the LO signal are generally much **higher in frequency** than the IF signal, so often we can easily **filter** them out. But, we will find for **wideband applications** that these leaked signals, if too large, can be **problematic**.

**Q:** *How large are these first-order signals? How much "leaks" across the mixer?*

**A:** The coupling of the RF/LO signal from the RF/LO port to the IF port is specified as **mixer isolation**.

Mixer isolation is simply the **ratio** of the RF/LO signal **power** leaving the IF mixer port to the RF/LO signal power incident on the RF/LO port. This value is almost **always** expressed in **dB**.

For example, say that an RF signal at 500MHz and power of -35 dBm is incident on the RF port of a mixer. Say this mixer has an **RF Isolation** of **30dB**. There will be then a 500MHz signal exiting the IF mixer port at 500MHz (i.e.,  $f_{RF}$ ).

The power of this 500MHz signal **exiting the IF** will be:

$$-35dBm - 30dB = -65dBm$$

In other words, the **"leaked"** signal will be 30 dB (i.e., 1000 times) **smaller** than the incident RF signal.

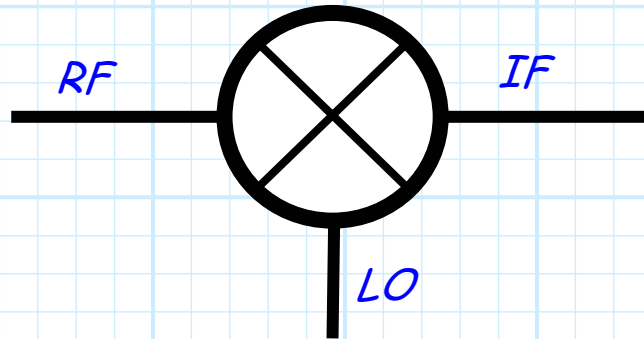
# The Mixer

## Specification Sheet

RF Bandwidth (Hz)

LO Bandwidth (Hz)

IF Bandwidth (Hz)



A mixer, like all other devices, can operate effectively only within a finite **bandwidth** (e.g., 2-5 GHz or 300-400 MHz).

We find that the **IF** operates over a frequency range that is much **lower** in frequency than either the LO or RF ports (Do **you** understand why?).

RF Port Impedance ( $\Gamma$ , return loss, VSWR)

LO Port Impedance ( $\Gamma$ , return loss, VSWR)

IF Port Impedance ( $\Gamma$ , return loss, VSWR)

Generally, the input impedance of all mixer ports is **poor**. This is particularly true of the **LO port**. Often, the port impedance is specified in terms of **VSWR** (an attempt to make the value seem better than it really is!).

**Typical VSWR values range for 1.5:1 to 2.5:1.**

### Conversion Loss (dB)

Typically 3 to 10 dB.

### 1 dB Compression Point (dBm)

Typically 0 to 15 dBm.

### 3<sup>rd</sup> Order Intercept (dBm)

Typically 10 to 20 dB **greater** than the 1 dB Compression Point.

### LO Isolation (dB)

### RF Isolation (dB)

Typically, isolation values range from 15 to 40 dB, depending on the mixer **design**.

