3. Mixers

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

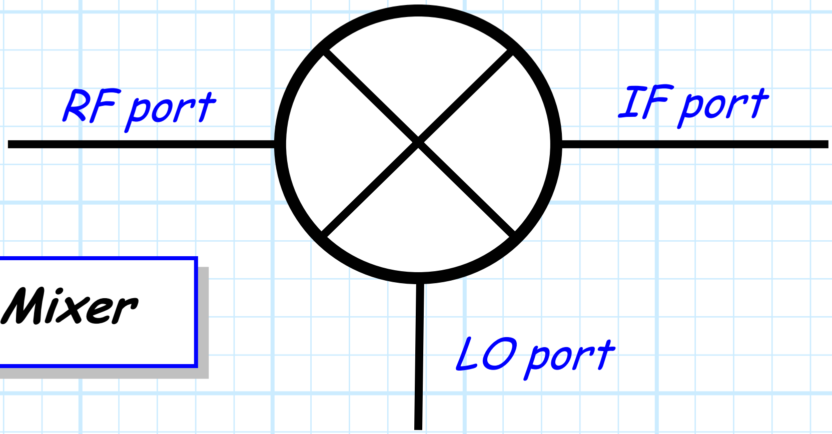
Q: *Are there any other important mixer performance specifications?*

A: HO:Mixer Isolation

HO: The Mixer Spec Sheet

Mixers

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



The Mixer

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:

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

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

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

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

Multiplying these signals, we get:

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

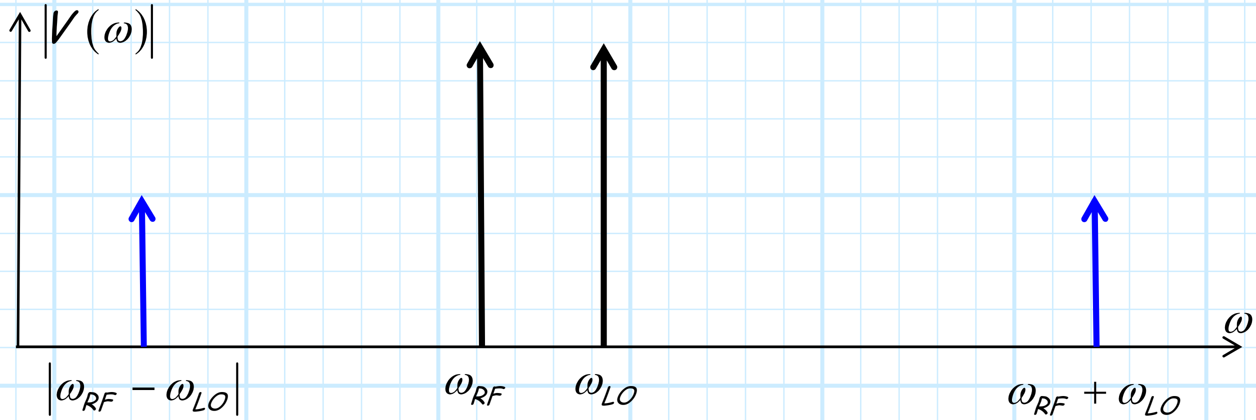
At the IF port we have created **two** signals with **new** frequencies!

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:

$$\frac{1}{2}\cos\left(\omega_{RF}+\omega_{LO}\right)t$$



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:

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

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

Just as with an amplifier, a mixer will produce **1st-order**, **2nd-order**, **3rd-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 ω_{RF} and ω_{LO}) are:

1st order: ω_{RF}, ω_{LO}

2nd order: $|\omega_{RF} - \omega_{LO}|, 2\omega_{RF}, 2\omega_{LO}, \omega_{RF} + \omega_{LO}$

3rd 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:

$$v_{IF}(t) = a_4 \, v_{RF}(t) v_{LO}(t) \qquad \textbf{(ideal mixer response)}$$

and thus the **only** signals created are the 2nd 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 $\left|\omega_{RF} - \omega_{LO}\right|$ and $\omega_{RF} + \omega_{LO}$.

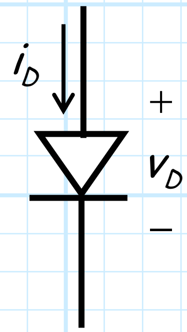
All **other** signals (meaning other than $\left|\omega_{RF} - \omega_{LO}\right|$ and $\omega_{RF} + \omega_{LO}$) at the IF are known as **spurious** signals—or in the vernacular of radio engineers, "**spurs**".

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:

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

And if, for example:

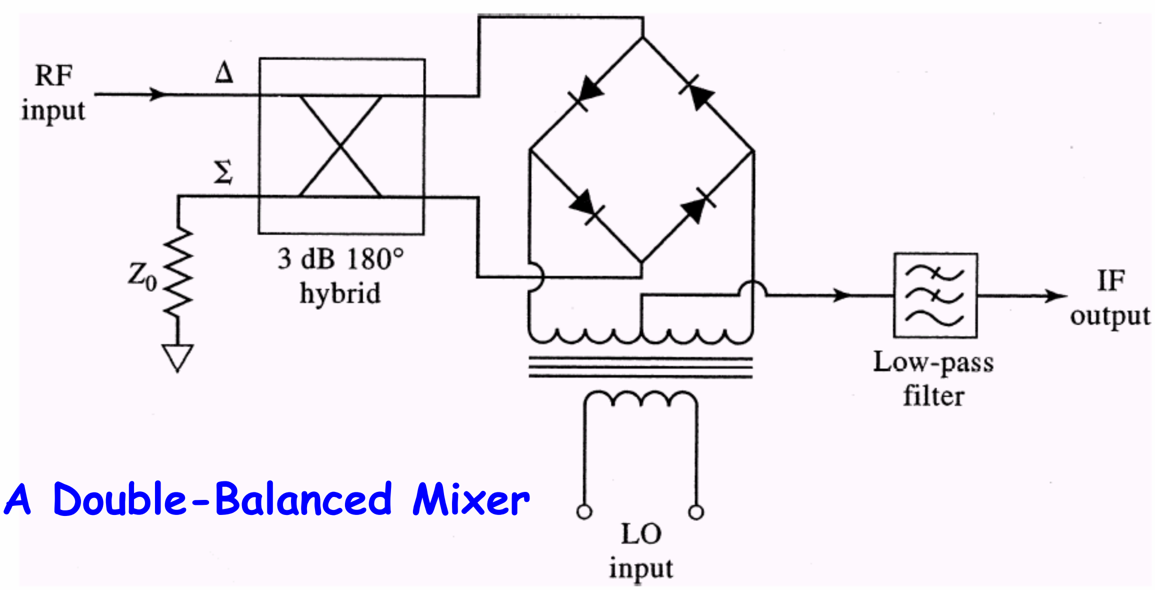
$$v_D(t) = v_{RF}(t) + v_{LO}(t)$$

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

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

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 2nd order term $v_{RF}(t)v_{LO}(t)$, while somehow **suppressing** the rest.

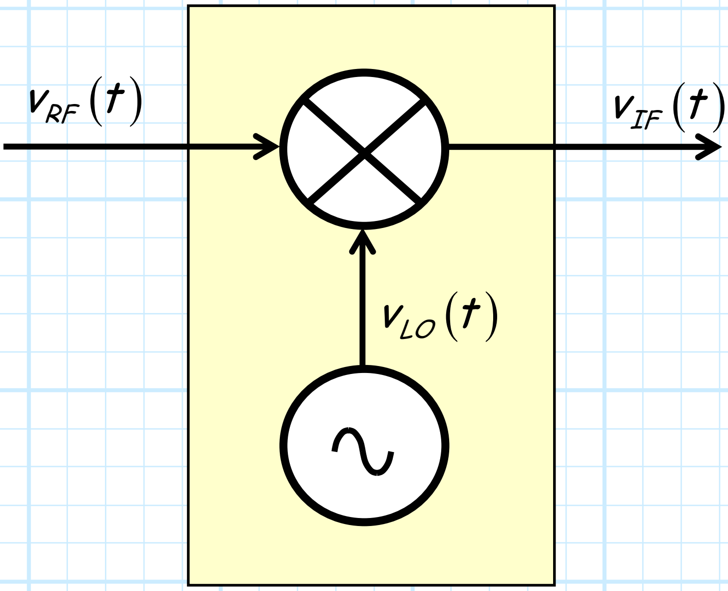
Thus, mixer design is as much **art** as it is science! Popular designs include the **balanced mixer** (with 2 junction diodes), and the **double balanced mixer** (with 4 junction diodes).



A Double-Balanced Mixer

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 ω_{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 ω_{RF} that is relatively large—it's a **received** signal!

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

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

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

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

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:

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

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 ω_{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:

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

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.

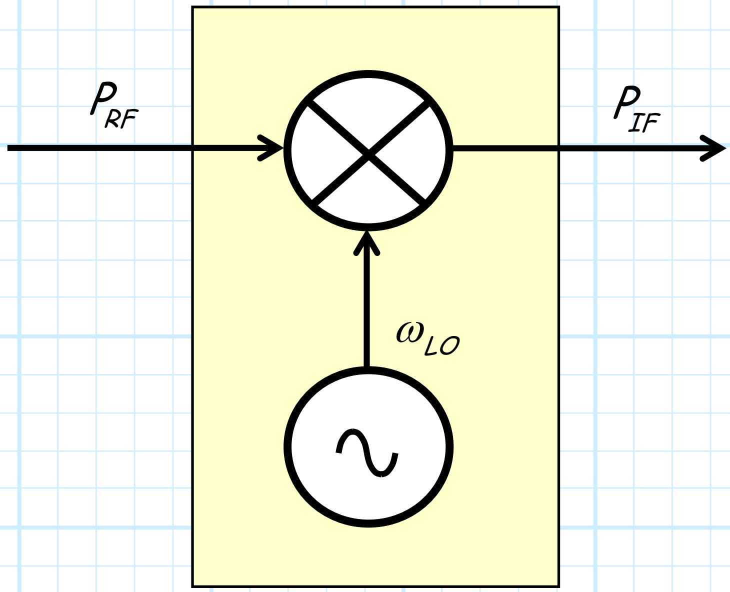
For example, at the RF port of a mixer in an **FM radio** receiver, **all** of the radio stations within the FM band (88 MHz to 108 MHz) will be present! As a result, **each** of these stations will be down-converted, **each** of these stations will appear at the IF output, and each will create there own set of **spurious** signals!

Mixer Compression and Intercept Points

Recall we discussed the **1 dB compression point** and the **3rd 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:

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

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

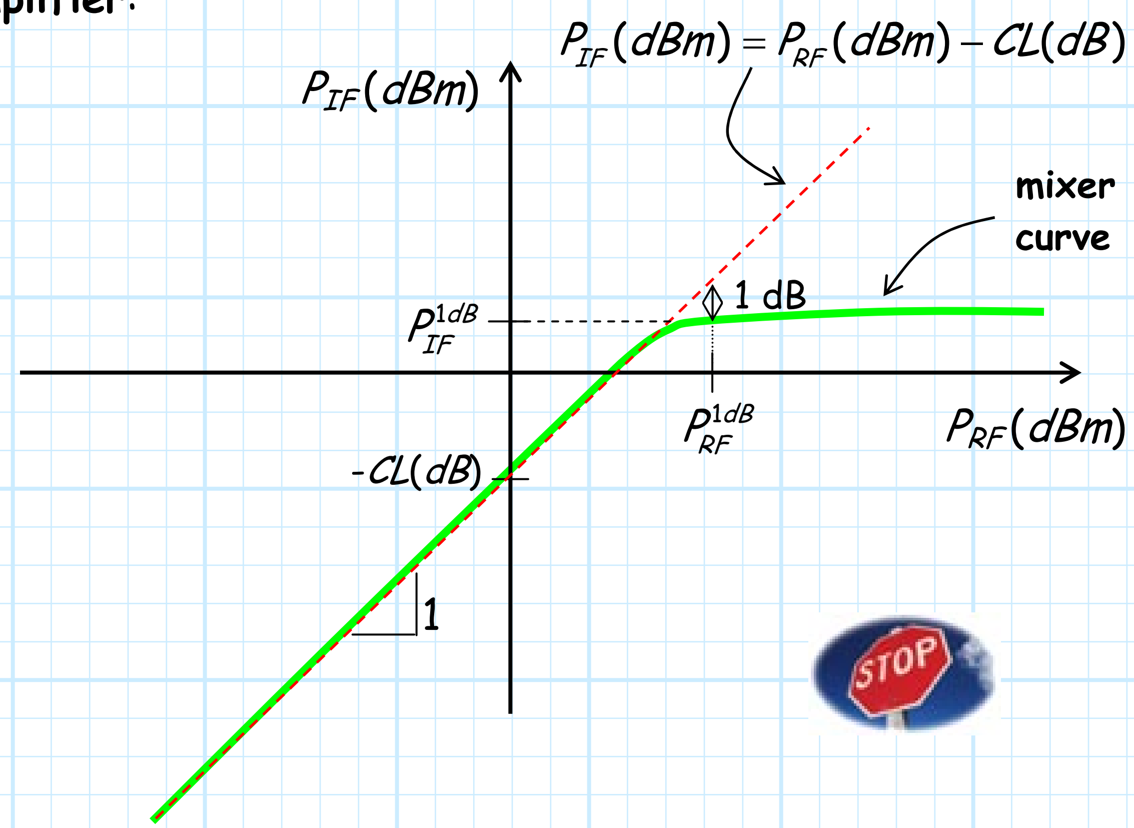
For **small** values of P_{RF}, this gain (conversion loss) is **constant** with respect to RF power.

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.:

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

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:

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

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_{RF}^{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^{rd} Order Intercept Point

Manufactures 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^{rd} order intercept point is a **theoretical** value, as the mixer IF output will **saturate** before the 3^{rd} order intermodulation terms can get that large.

* However, the mixer 3^{rd} order intercept power does provide an indication of the mixers intermodulation **distortion performance**.

* Just like an amplifier, the **higher** the two-tone 3^{rd} order intercept point, the **better**.

* **Typically**, the two-tone 3^{rd} 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**:*

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

*This suggests that signals appear at the **IF output** with precisely the **same frequencies** of the RF and LO signals (i.e., ω_{RF} and ω_{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 (Γ, return loss, VSWR)

LO Port Impedance (Γ, return loss, VSWR)

IF Port Impedance (Γ, 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.

3rd 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**.