EEEN3006J

Wireless Systems

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Purpose of this lecture

- We will discuss mixers, another key part of wireless systems.
- A mixer is a three-port device that uses a non-linear or time-varying element to achieve frequency conversion.
- Operation of practical radio frequency and microwave mixers are usually based on the non-linearity provided by a diode or a transistor.

Non Linear Devices

- Remember the small signal analysis of a non linear device.

We can explain the process of small-signal analysis for a general element as follows:

A nonlinear element has characteristic $i_D = f(v_D)$

i.e. $I_D + i_d = f(V_D + v_d)$

$= f(V_D) + f'(V_D).v_d + \frac{1}{2} f''(V_D).\ v_d^2 + \ldots$ (Taylor series)

$\cong f(V_D) + f'(V_D).v_d$ for small v_d

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DC part

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Signal part

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Later, we will see how this characteristic is used for mixers!

Mixers

- Mixer circuits are used extensively in radio frequency electronics. Applications include
  - frequency translators (including in radio receivers),
  - demodulators,
  - limiters,
  - attenuators,
  - phase detectors and
  - frequency doublers.
- We will focus on their ability to translate a signal in frequency.

Mathematics of a multiplicative mixer

- Given inputs v1 and v2

$$v_1 = A_1 \sin(2\pi f_1 t)$$
$$v_2 = A_2 \sin(2\pi f_2 t)$$

- An ideal mixer multiplies them

$$v_1 v_2 = \frac{A_1 A_2}{2}\{\cos[2\pi(f_1 - f_2)t] + \cos[2\pi(f_1 + f_2)t]\}$$

- Note terms at two frequencies: the sum and the difference.
  - Remember: Any signal can be written as a weighted sum of sinusoids (using the Fourier transform), so this analysis applies generally.

Example 1

20 Hz signal

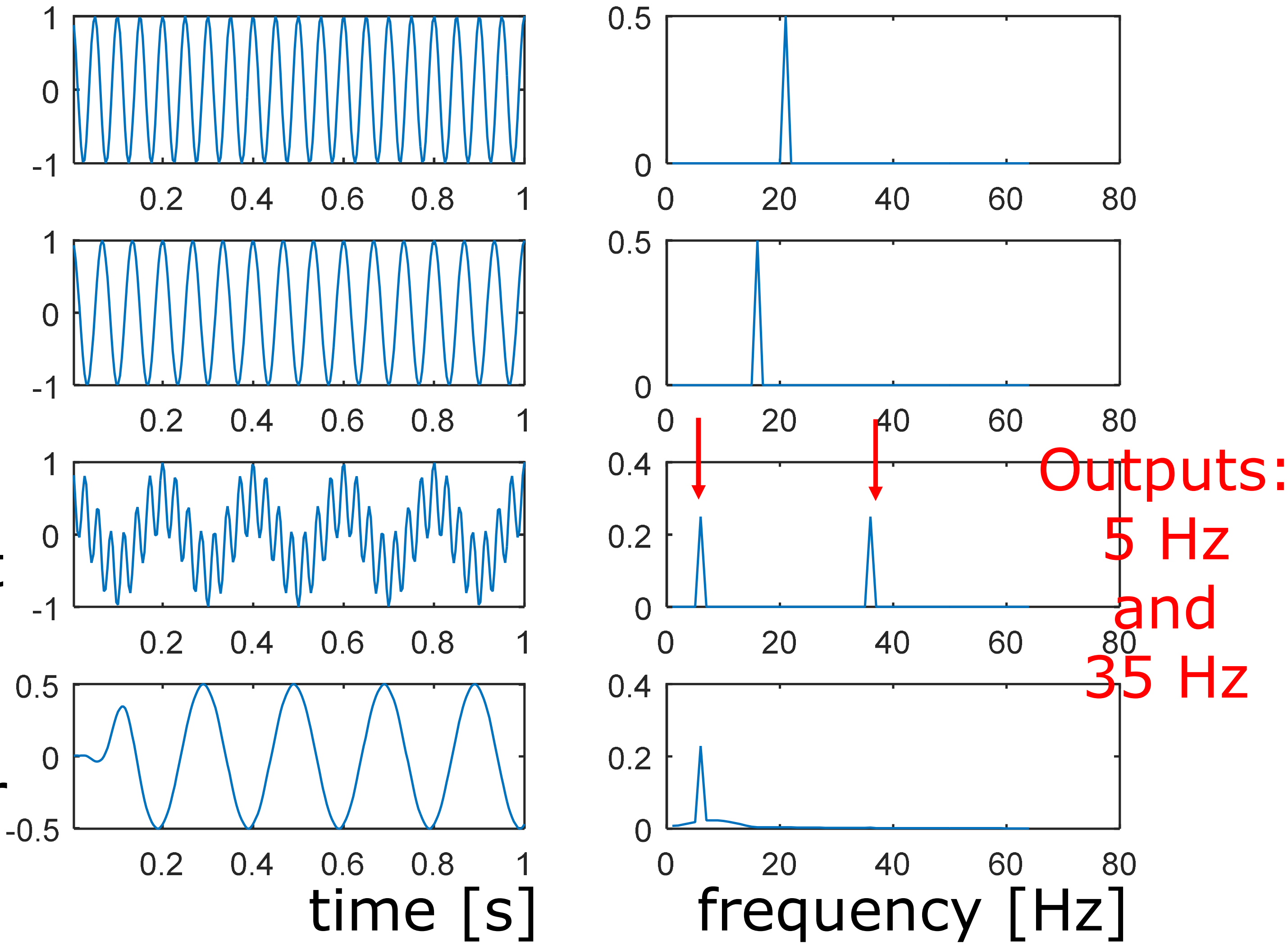
x

15 Hz signal

=

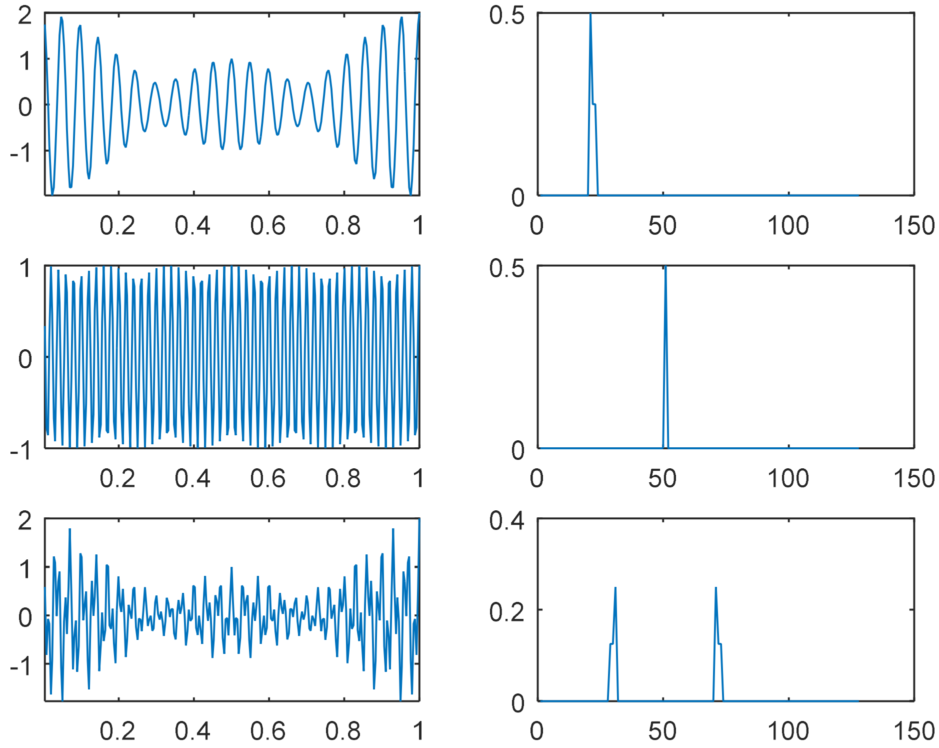
Mixer output

After low pass filter



Example 2

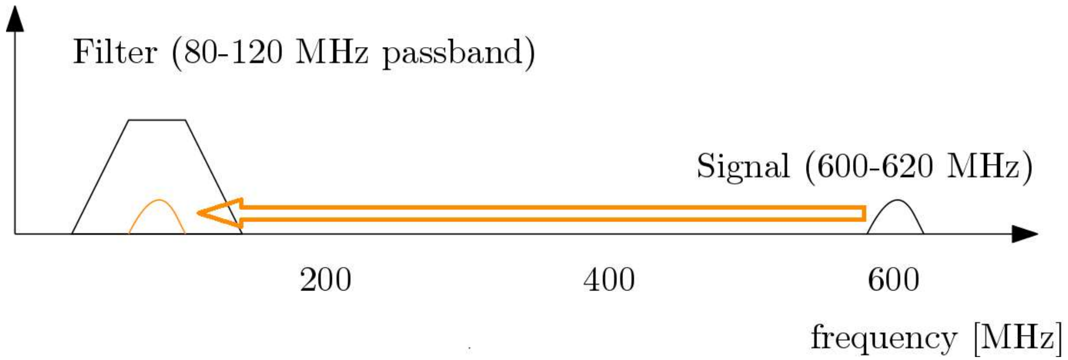
~21 Hz signal
x
50 Hz signal
=
Mixer output



Notice how the spectrum of the lower frequency product (at $f_1 - f_2$) is reversed. Can you explain this?

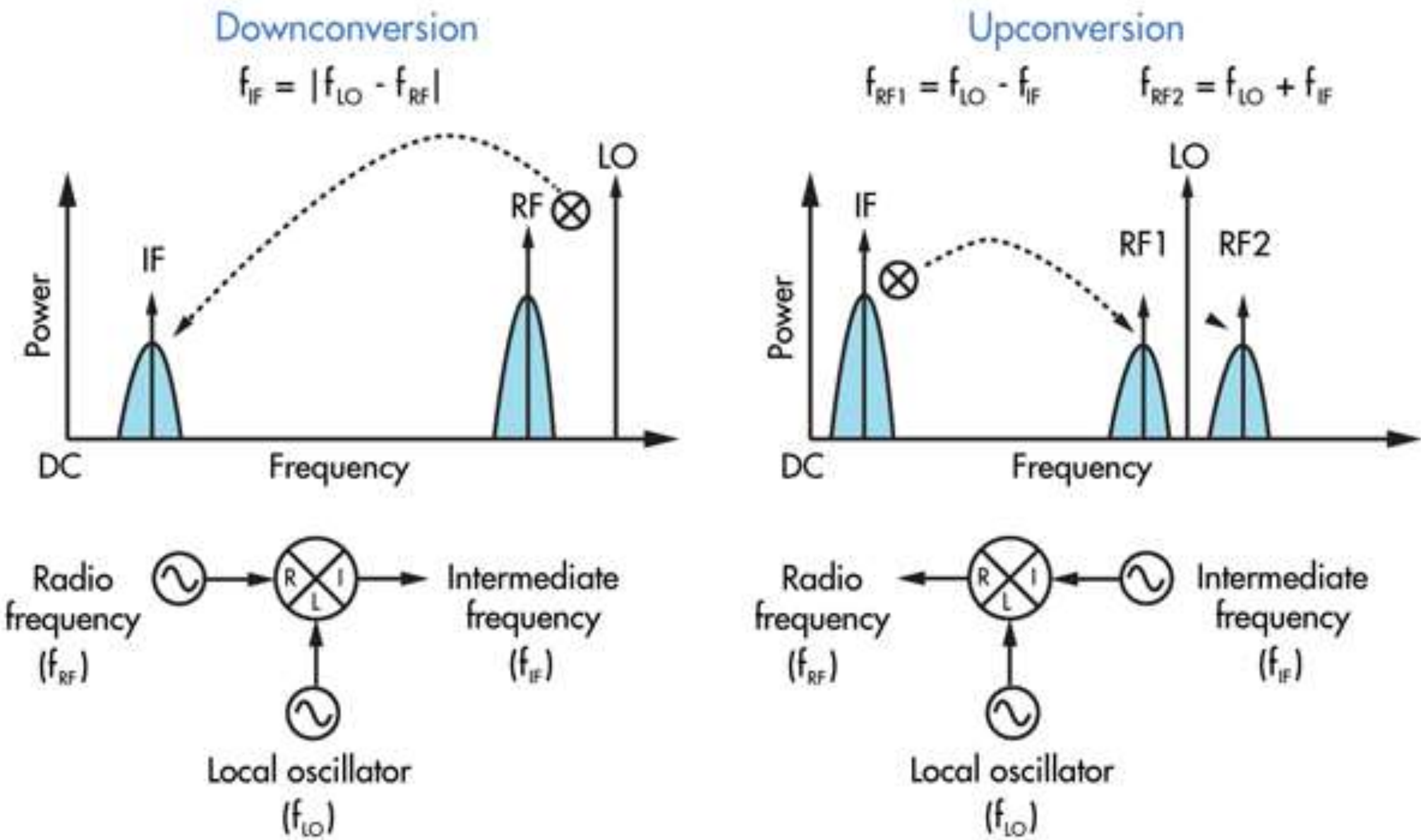
Frequency sifting by mixing

- Common problem at RF: want to shift signal.
  - example: signal at 610 MHz, filter at 100 MHz



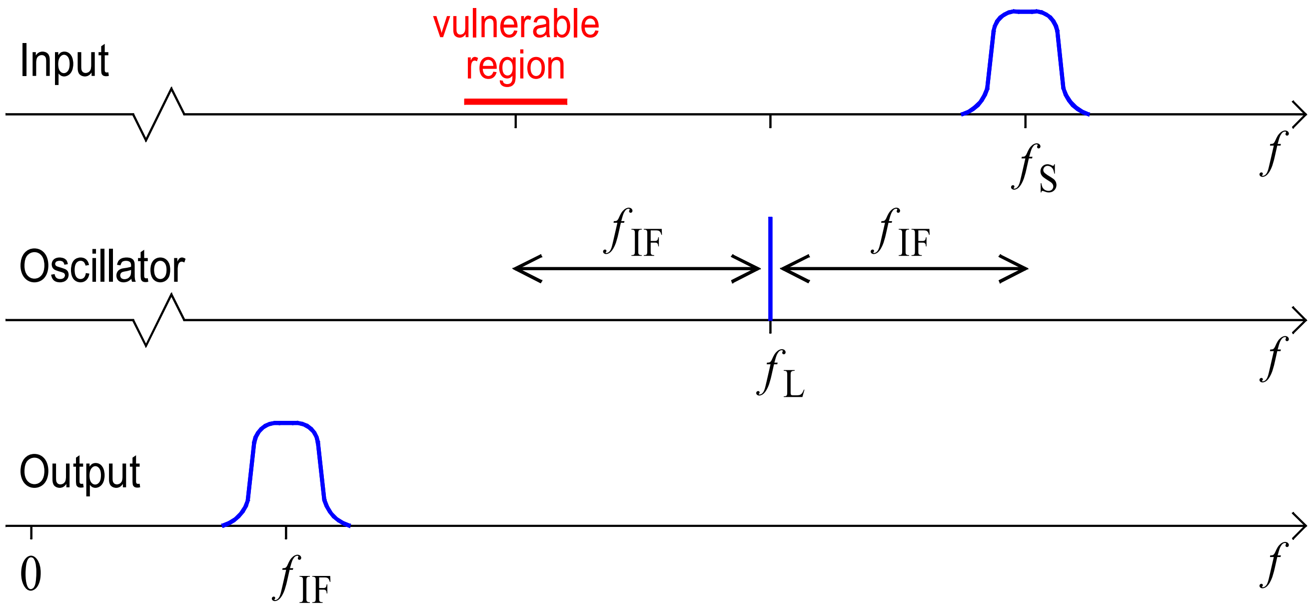
- We use a mixer
  - one input is the received signal
  - one input is a *local oscillator* – set at 510 MHz
- Outputs at sum and difference of frequencies
  - sum at 1120 MHz is easily blocked by filter.
  - difference at 100 MHz passes through filter.

Upconversion and downconversion

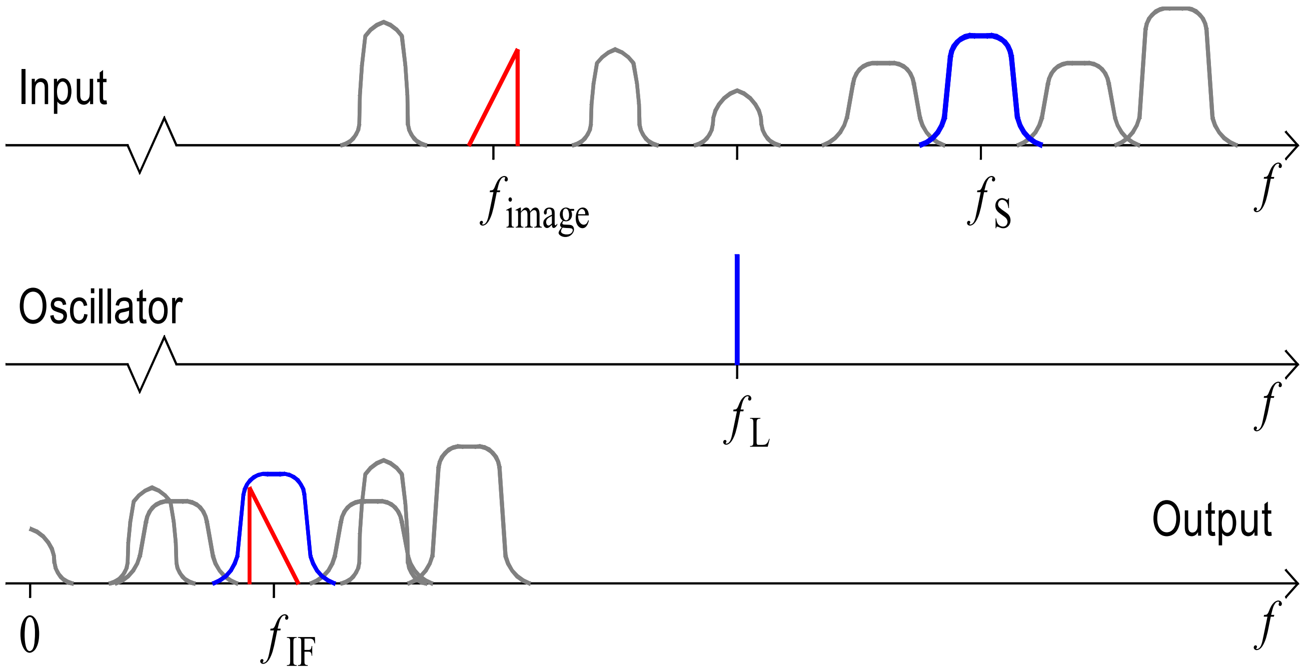


- Mixers have **two** input frequencies that would shift to the desired output frequency.
  - This means we can use a local oscillator above <u>or</u> below the signal.
- Example:
  - signal at 610 MHz
  - filter at 100 MHz.
  - We can use a local oscillator at either 510 MHz or 710 MHz.

Image Frequency Problem

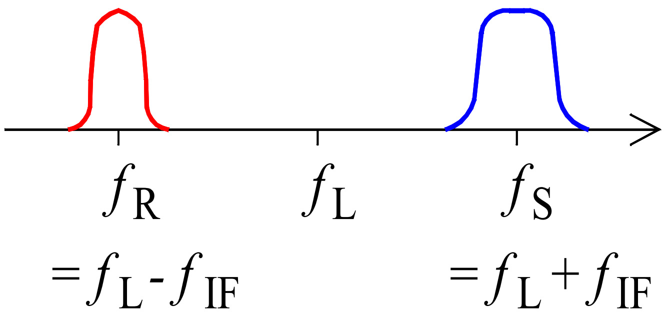


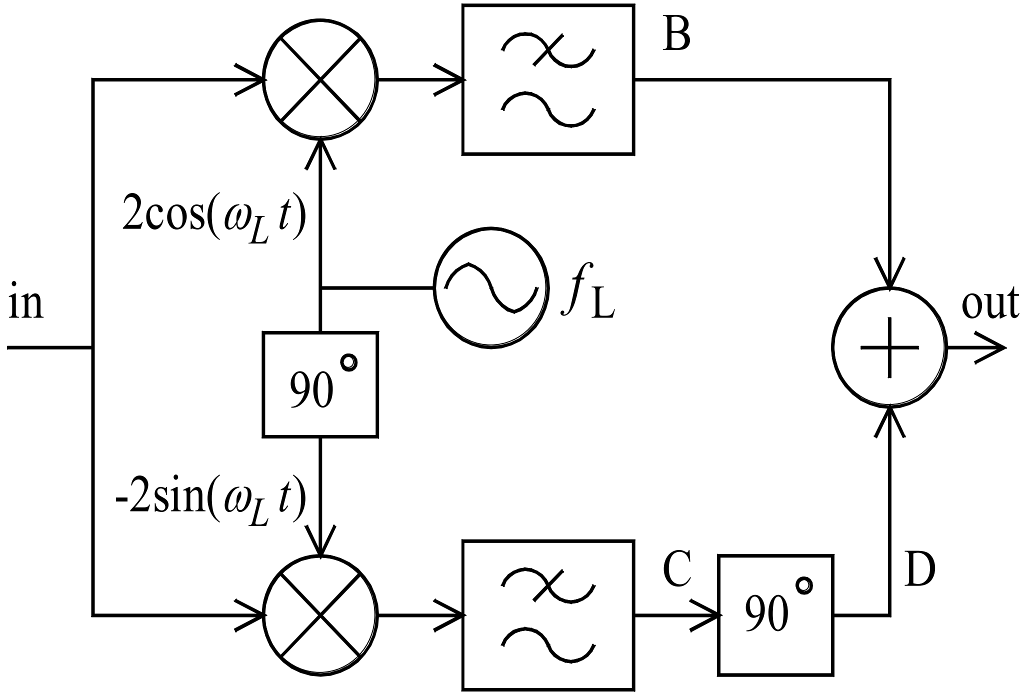
- Mixers are vulnerable to interference
  - In our example, an unwanted input at ~410 MHz would give a mixer output at ~100 MHz.
  - This unwanted output would also pass through our filter.
  - We call this problem frequency (410 MHz in the example) the image frequency.



- This more realistic scenario shows many signals present at input to mixer
  - all frequencies above LO shifted down by f_L
  - all frequencies below LO shifted to $f_L - f_{signal}$ with their frequency spectrums reversed.

Image-Rejecting Frequency Shift





- More complicated frequency shift circuit
  - designed to reject signals at image frequency
  - if multiply by either $\cos(2\pi f_L t)$ or $\sin(2\pi f_L t)$
    - cannot distinguish between signals above or below f_L
  - but multiply by both, can see difference
    - phase shift and combine to select whichever wanted

Simple Analysis

$\omega_L = 2\pi f_L \qquad \omega_{IF} = 2\pi f_{IF}$

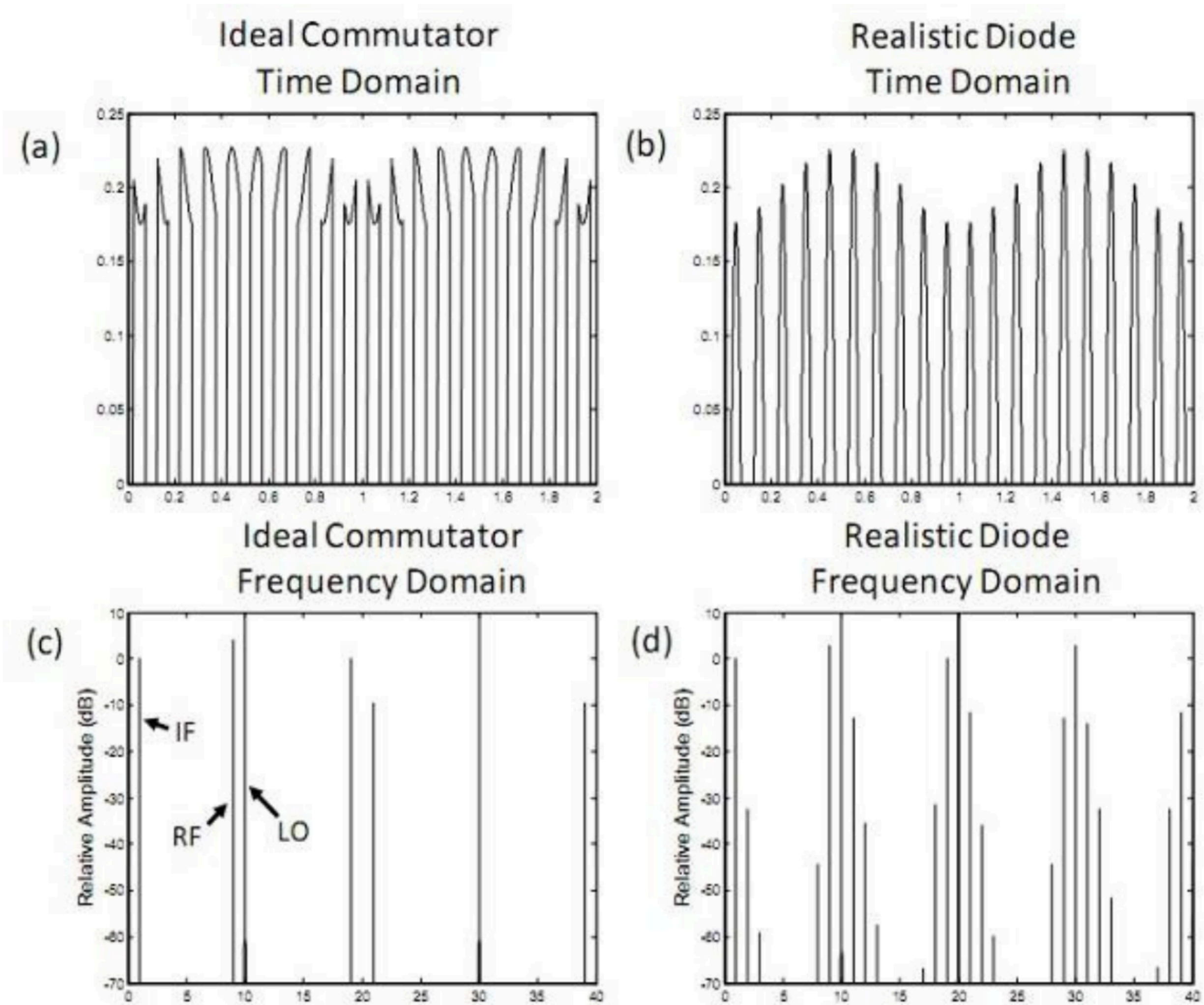
$f_S = f_L + f_{IF} \qquad f_R = f_L - f_{IF} \qquad \omega_S = 2\pi f_S \qquad \omega_R = 2\pi f_R$

- Consider two sinusoidal signals at input
  - $v_{in}(t) = A_S \cos(\omega_S t) + A_R \cos(\omega_R t)$
- After multiplication and filtering
  - $v_B(t) = A_S \cos\{(\omega_S - \omega_L)t\} + A_R \cos\{(\omega_R - \omega_L)t\}$
    $= A_S \cos(\omega_{IF} t) + A_R \cos(\omega_{IF} t)$
  - $v_C(t) = A_S \sin\{(\omega_S - \omega_L)t\} + A_R \sin\{(\omega_R - \omega_L)t\}$
    $= A_S \sin(\omega_{IF} t) - A_R \sin(\omega_{IF} t)$
- With 90° phase lead and adder
  - $v_D(t) = A_S \cos(\omega_{IF} t) - A_R \cos(\omega_{IF} t)$
  - $v_{out}(t) = 2A_S \cos(\omega_{IF} t)$
  - get wanted signal only, other rejected…

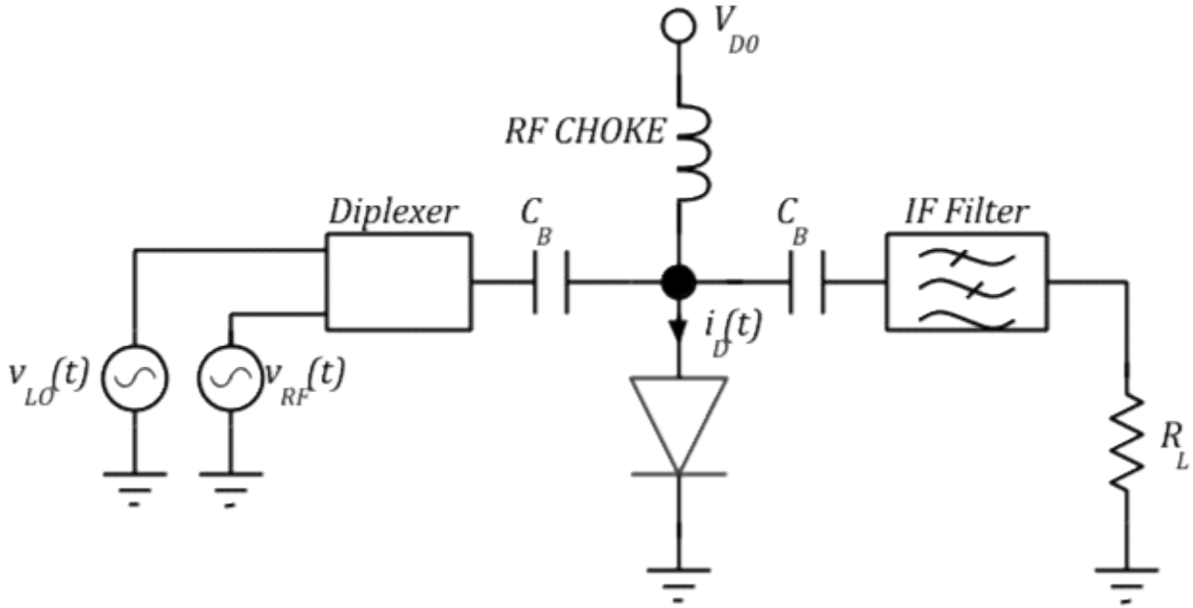
Balance

- Unbalanced mixers
  - F_{RF} and F_{LO} appear in output spectrum
  - Poor LO–RF and RF–LO port isolation.
  - Low cost.
- Single balanced mixers.
  - Either F_{RF} or F_{LO} suppressed in output.
    - Also suppresses even-order LO harmonics.
  - High LO–RF isolation is provided, but external filtering must provide LO–IF isolation.
- Double balanced mixers
  - Both F_{RF} and F_{LO} are suppressed in the output.
    - Also suppresses even-order LO and RF harmonics.
  - High port-to-port isolation.

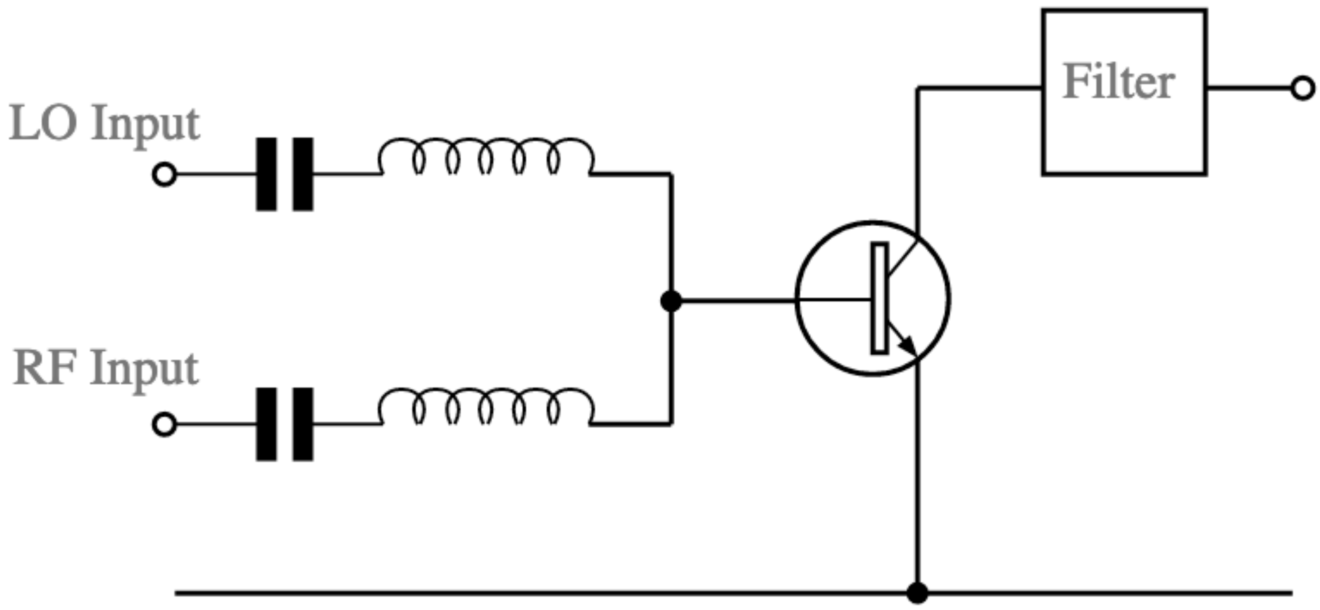
Unbalanced Single Diode Mixer



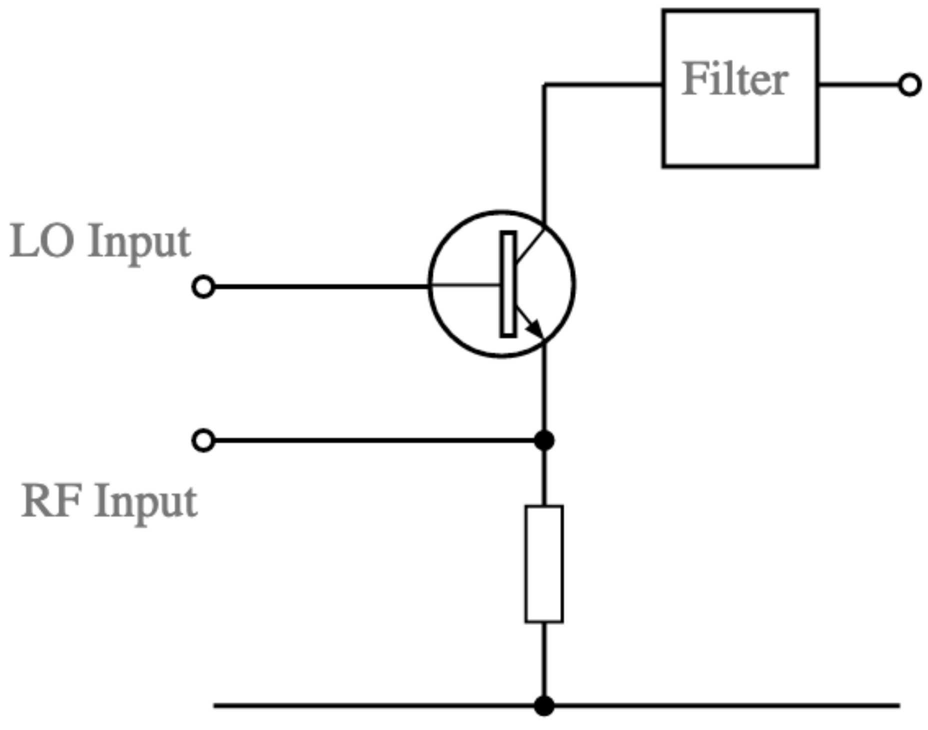
Diode mixers



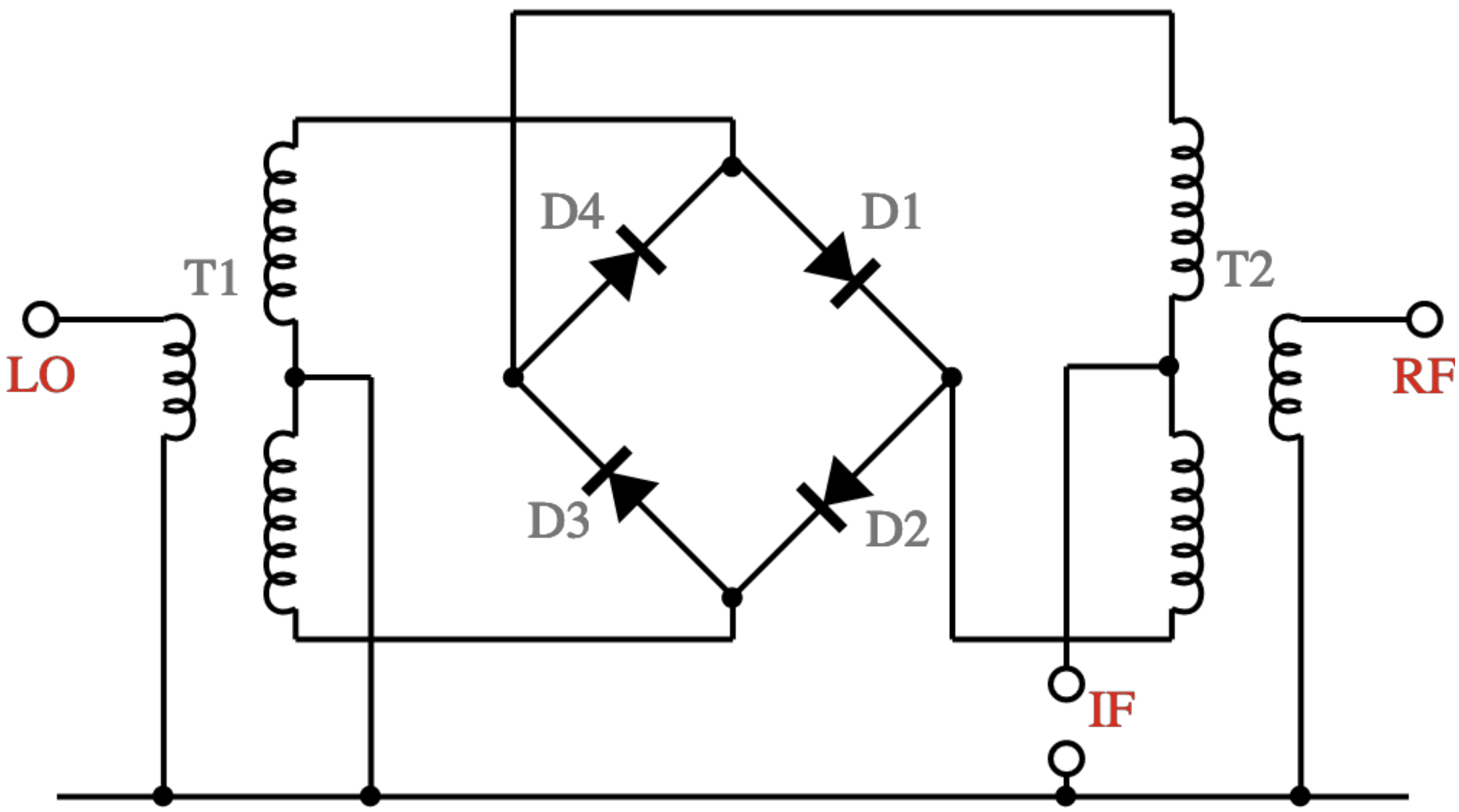
Transistor mixers



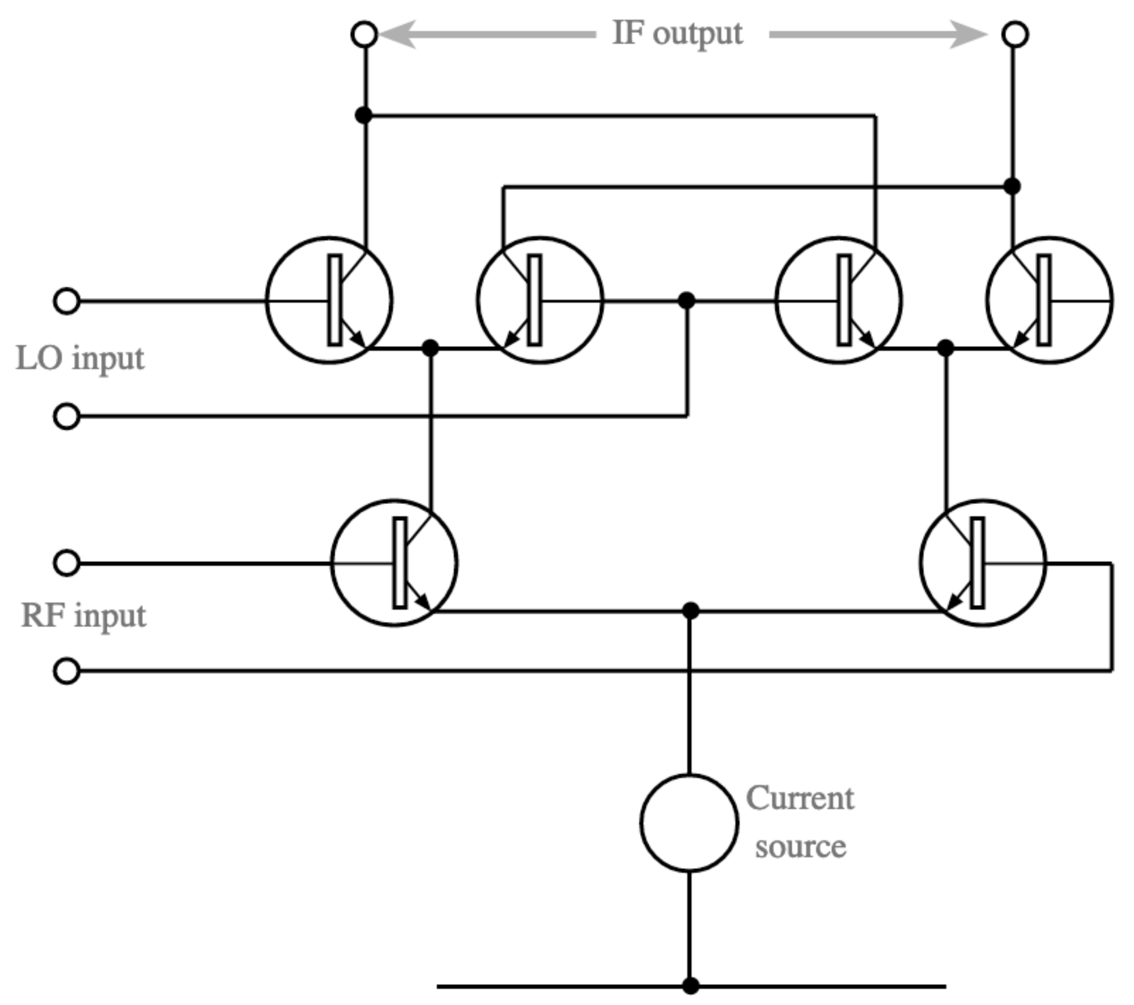
Transistor mixers



Double Balanced Mixer



Gilbert Cell Mixer



Diode mixers

- Let $v_{LO}(t) = V_{LO}\ \cos(\omega_{LO} t)$ and $v_{RF}(t) = V_{RF} \cos(\omega_{RF} t)$.
- Using the small signal approximation, the diode current is $I_0 + G_d v(t) + \frac{1}{2} G'_d v^2(t) + \cdots$
- We substitute $v(t) = v_{LO}(t) + v_{RF}(t)$.
  - The DC term will be blocked by the capacitor.
  - The $v(t)$ terms will be blocked by the filter.

- This leaves us with

$$i(t) = \frac{G_d'}{2}[v_{LO}(t) + v_{RF}(t)]^2$$

$$= \frac{G_d'}{2}\Big[V_{RF}^2(1 + \cos(2\omega_{RF}t)) + V_{LO}^2(1 + \cos(2\omega_{LO}t))$$
$$+ 2V_{RF}V_{LO}\cos\big((\omega_{RF} - \omega_{LO})t\big) + 2V_{RF}V_{LO}\cos\big((\omega_{RF}$$
$$+ \omega_{LO})t\big)\Big]$$

- This result contains components at several frequencies. The DC terms will again be blocked. The terms at $2\omega_{RF}$ and $2\omega_{LO}$ will be filtered out.

Metrics: Insertion/Conversion loss

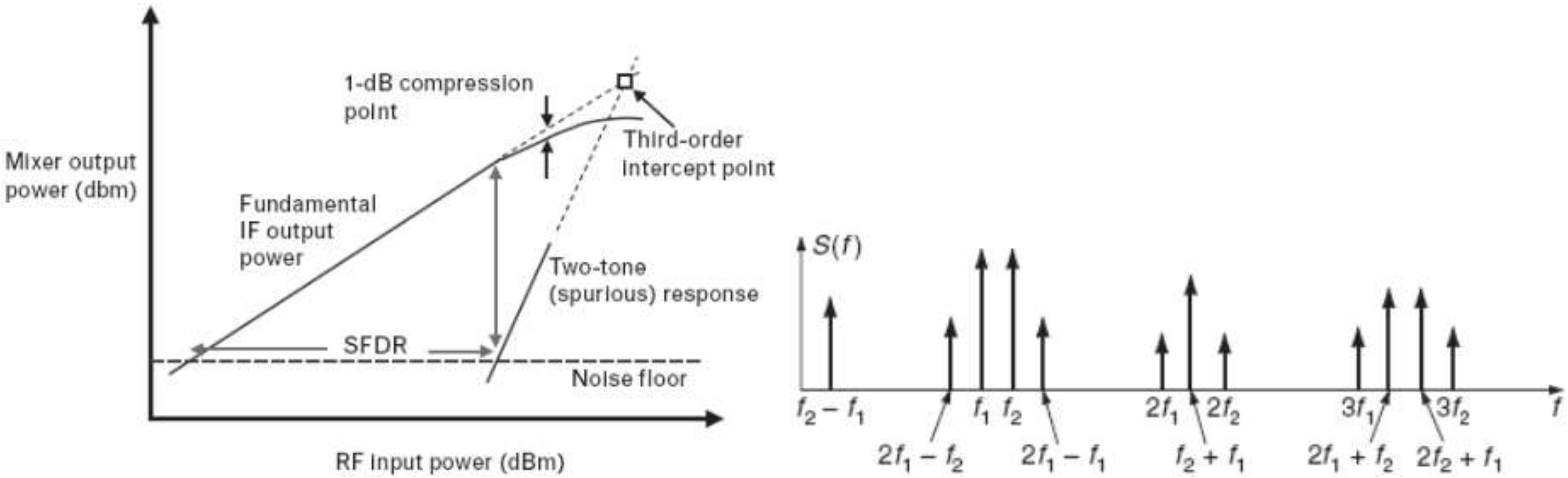
- The conversion loss (or gain) is the ratio of the desired IF output to the RF input signal value. It is measured in dB.

$$InsertionLoss = 10\ \log_{10} \frac{P_T}{P_R}$$

- Conversion loss depends on the type of mixer (active/passive), the load of the input RF circuit, the output impedance at the IF port, and the level of the LO.

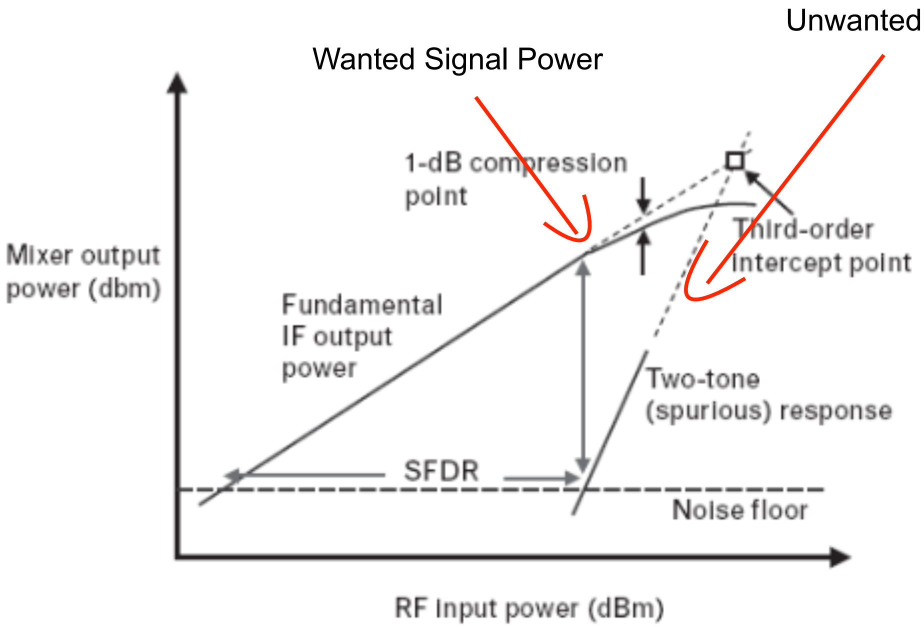
- We can specify conversion loss in terms of the voltage or the power.
- If the input and load impedances of the mixer are both matched to the source impedance, the voltage conversion gain and the power conversion gain will be the same.
- A typical conversion gain of an active mixer is 10dB.
- The conversion loss of a typical diode mixer is approximately 6dB.

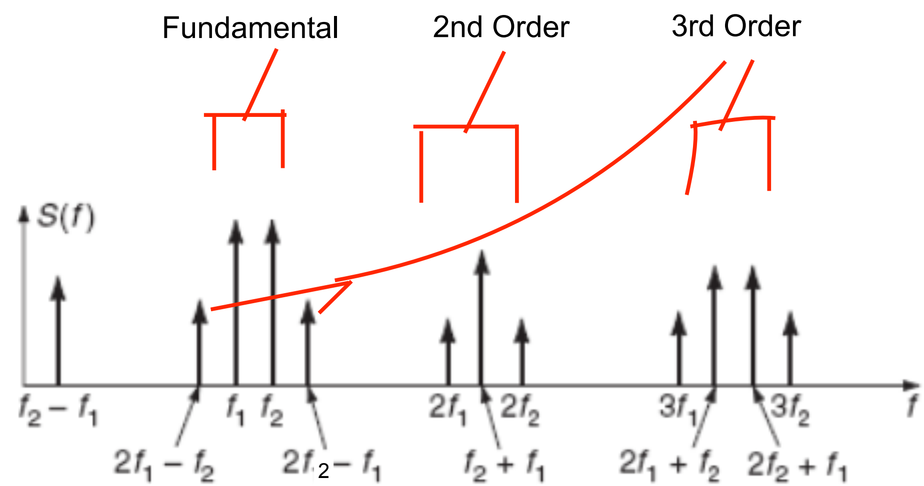
Input intercept points



- The most damaging distortion products are odd-order - more likely within the passband.
- The largest of these is the 3rd order products. The most common figure of merit for intermodulation distortion (IMD) is third order intercept (TOI or IIP3).

Input intercept points





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- In a well designed passive Diode Mixer should get:

IIP3[dB] ~= LO[dBm] + 9dB.

- Because the LO voltage is applied from the gate to the source-drain, and the signal flows from source to drain, there is an independence that allows FETs to have a higher IIP3 for a given LO drive than a diode mixer. The gate to channel impedance is very high, while the channel drain to source resistance is low.

- In passive FET mixers, the gate input which is driven by the LO looks like a high-Q, capacitor.
- For FET mixers:

IIP3[dBm] ~= LO[dBm] + 9dB + 20LOG(GMAX)

Where GMAX = Maximum available Gain at Frequency F.

- This is why FETs make better passive mixers than diodes.

- The amount of local oscillator power that leaks into either the IF or the RF ports is called the isolation.
- There are multiple types of isolation:
  - LO-to-RF,
  - LO-to-IF and
  - RF-to-IF isolation.
- LO to RF port isolation is by far the biggest short coming

Metrics: noise figure

- The noise figure is a measure of the noise added by the mixer itself.
  - We care about any noise that appears at the IF output.
- For a passive mixer (no gain), the noise figure is almost equal to the insertion loss.
- In a mixer, noise is replicated and translated by each harmonic of the LO. This is referred to as noise folding.

- The noise figure may depend on
  - Conversion loss of the mixer
  - Noise sources within the mixer itself.
    - E.g. 1/f noise in MESFETs can be large if the IF is below the corner frequency of the flicker noise (typically <1 MHz).
- Any mixer that doesn't reject the image frequency will add the broadband noise from both the desired and image frequencies, and so will increase the noise figure at the IF port by 3dB.

- A mixer’s linearity is more critical than its noise figure.
- In any application where IIP3 is very important, a large LO power is required.
- Typically Mixers are noisier than amplifiers due to the noise folding nature of Mixers.

- http://www.radio-electronics.com/info/rf-technology-design/mixers/rf-mixers-specifications.php
- http://www.radio-electronics.com/info/rf-technology-design/mixers/double-balanced-mixer-tutorial.php
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