Chapter 7

Microwave Mixers

INTRODUCTION

Most of the slides are from
http://rfic.eecs.berkeley.edu/~niknejad/ee142_fa05lects/pdf/lect15.pdf
https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/
https://www.qsl.net/va3iul/RF%20Mixers/RF_Mixers.pdf
https://web.ece.ucsb.edu/~long/ece145b/Mixer1.pdf
https://slideplayer.com/slide/6012717/

What is a Mixer?

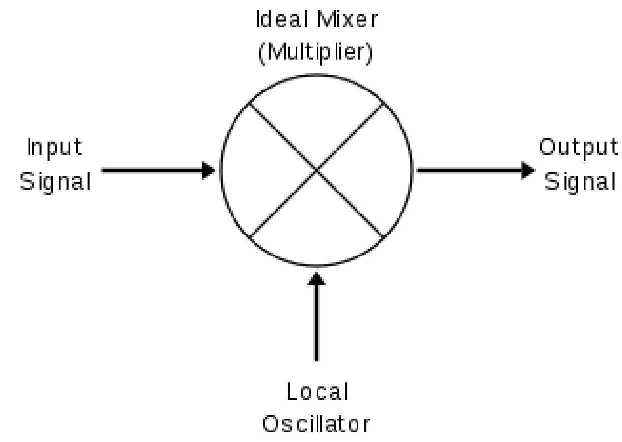
A Mixer is an Electronic circuit used to convert frequency up or down.

Why frequency needs to be down converted ?

- Easier to process signals
- Lower frequency leads to cost-effective components
- Easier to design.

How to convert frequency ?

→ Introduce a local Oscillator (LO).

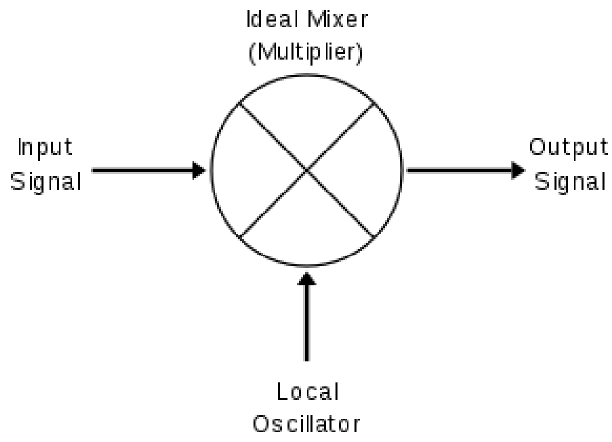


Mixer applications

The super-heterodyne receiver architecture often has several frequency translation stages (IF frequencies) to optimize image rejection, selectivity, and dynamic range.

The mixer can be used for demodulation, although the trend is to digitize following a low IF frequency and implement the demodulation function digitally. It can also be used as analog multipliers to provide gain control. In this application, one input is a DC or slowly varying signal, which when multiplied by the RF/IF signal, will control the degree of gain or attenuation.

In transmitter applications, the mixer is often used for up-conversion or modulation. In this application, the input signal level can be selected to optimize the overall signal-to-noise ratio at the output.



MIXER DESIGN PARAMETERS

Mixer Design specifications

- **Large signal performance:**
  - Conversion gain (> 1 or < 1)
  - Port-to-port isolation (most significant : Lo signal)
  - Gain compression P_{1dB}
  - Intermodulation distortion (IIP3, OIP3)
- **Small signal performance : noise figure**

Mixer Design specifications

Conversion gain – lowers noise impact of following stages

Noise Figure – impacts receiver sensitivity

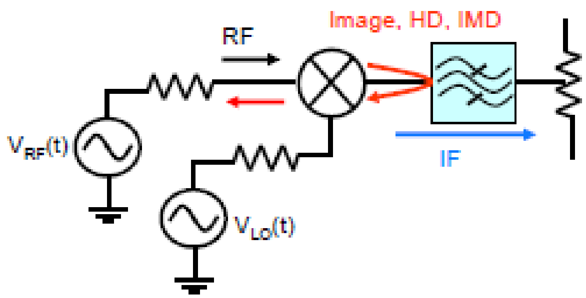
Port isolation – want to minimize interaction between the RF, IF, and LO ports

Linearity (IP3) – impacts receiver blocking performance and spurious response

Sensitivity to process / T° variations – need to make it manufacturable in high volume

Power match – target max voltage gain rather than power match for integrated designs

Power – target low power dissipation



Mixer Design specifications : Conversion gain (or conversion loss)

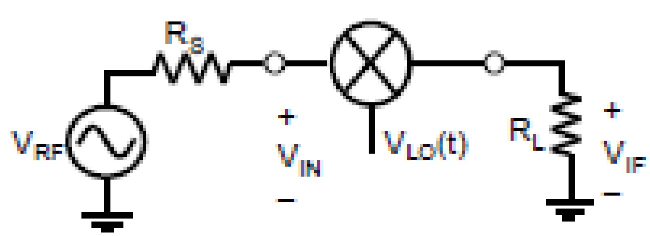
Conversion gain or loss is the ratio of the desired IF output (voltage or power) to the RF input signal value (voltage or power).

If the input impedance and the load impedance of the mixer are both equal to the source impedance, then the voltage conversion gain and the power conversion gain of the mixer will be the same in dB's

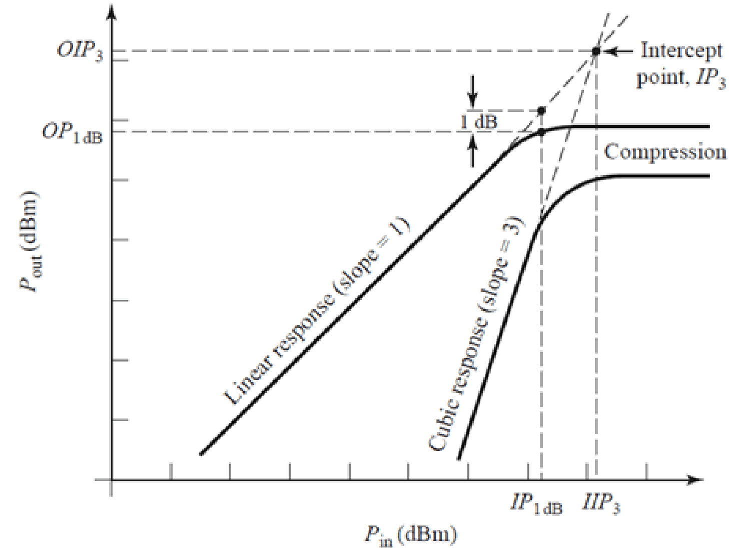
So, generally expressed as voltage gain or as transducer power gain

$$A_V = \frac{V_{IF}}{V_{IN}}$$

$$ConvGain = \frac{Output\ power\ at\ F_{IF}}{RF\ available\ input\ power} = \left(\frac{v_{IF}^2}{2R_L} \Big/ \frac{v_{RF}^2}{8R_S} \right)$$



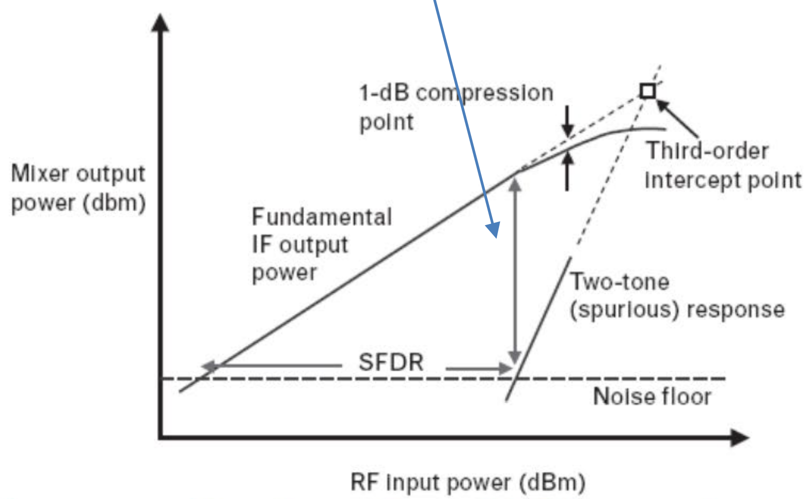
Dynamic range of a mixer

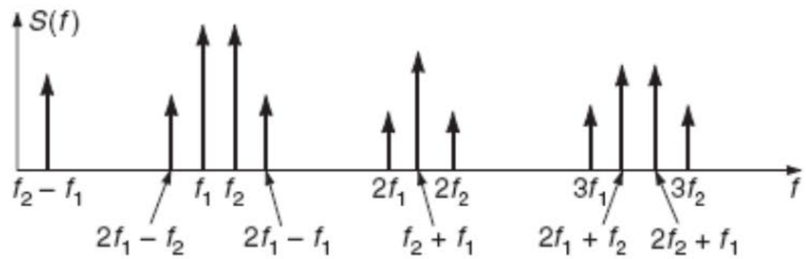


The dynamic range of a mixer is defined by 1-dB compression point at the higher end and the mixer noise figure at the lower end.

In RF Mixers, the P_{1dB} occurs at about ***5 to 10 dB*** below the LO power applied to the mixer. This enables to estimate the Dynamic Range based on the LO Power.

Similarly, if the IP3 of a mixer is given, we know that the P_{1dB} will be ***10 -12 dB*** lower than this (rule of thumb).





In any application where IIP3 is very important, a large LO power is required.

https://www.everythingrf.com/community/filter?topic=;Mixers;

Isolation in a mixer

There are three main types of isolations:

LO-RF Isolation: This is a measure of how much the LO signal is attenuated when traveling from the LO port to the RF port of the mixer (at the LO frequency). The LO-RF isolation can be seen as the leakage of the LO signal into the RF port.

This is of most importance when a mixer is being used to down-convert a signal as the LO power can leak into the RF circuits and cause interference in the amplifier and other RF circuits. This is also of importance in up-conversion mixers when the LO and RF Frequencies are close to each other - as the LO Signals that get though might not get filtered out and can cause interference.

LO-IF Isolation: This is a measure of how much the LO signal is attenuated when traveling from the LO port to the IF port of the mixer (at the LO frequency).

This type of isolation is most important when the LO Frequency and IF Frequency are close to each other (leakage of the LO signal to the IF circuitry can cause the IF amplifier to saturate).

RF-IF Isolation: This is a measure of how much the RF signal is attenuated when traveling from the RF port to the IF port.

Since the RF signal power levels are usually much smaller than the IF signal power levels, this Isolation does not matter as much as the other two types of isolations.

https://www.everythingrf.com/community/filter?topic=;Mixers;

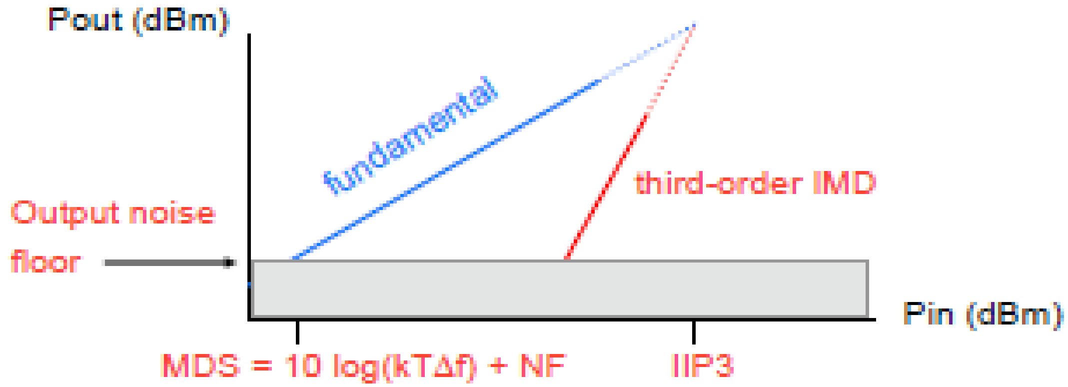
Noise in a mixer

- We have been concentrating on the large signal limitations of the mixer. Noise determines the other end of the mixer dynamic range.
- Spurious-free dynamic range:

$$NF = 10\log_{10}\left[\frac{(S/N)_{in}}{(S/N)_{out}}\right]$$

$$SFDR = \frac{2}{3}[IIP3 - (10\log kT\Delta f + NF)]$$

The *minimum detectable signal* (MDS) power is determined by noise and corresponds to a signal whose strength just equals the noise.

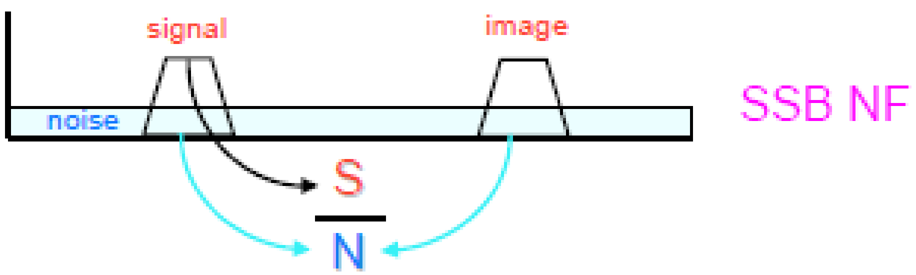


The *maximum signal power* is limited by distortion (IIP3).

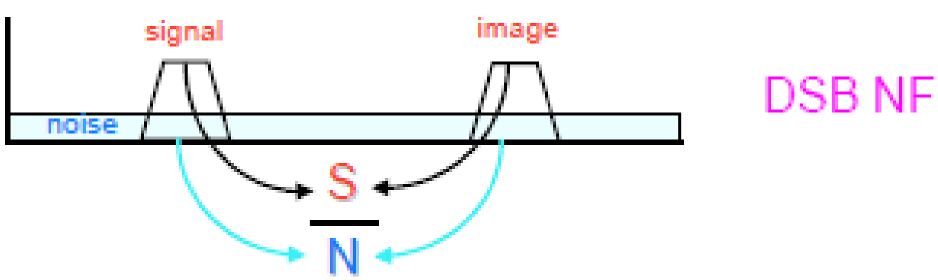
The *spurious-free dynamic range* (SFDR) is a commonly used figure of merit to describe the dynamic range of an RF system. If the signal power is increased beyond the point where the IMD rises above the noise floor, then the signal-to-distortion ratio dominates and degrades by 3 dB for every 1 dB increase in signal power.

Noise in a mixer

- There are two definitions used for noise figure with mixers - often a source of confusion.
- SSB NF assumes signal input from only one sideband, but noise inputs from both sidebands.
- Relevant for heterodyne architectures



- DSB NF includes both signal and noise inputs from both sidebands. Appropriate for direct conversion architectures.



Noise figure is generally measured with a wideband noise source switched on and off.

Measuring SSB noise figure is relevant for superheterodyne receiver architectures in which the image frequency is removed by filtering or cancellation.

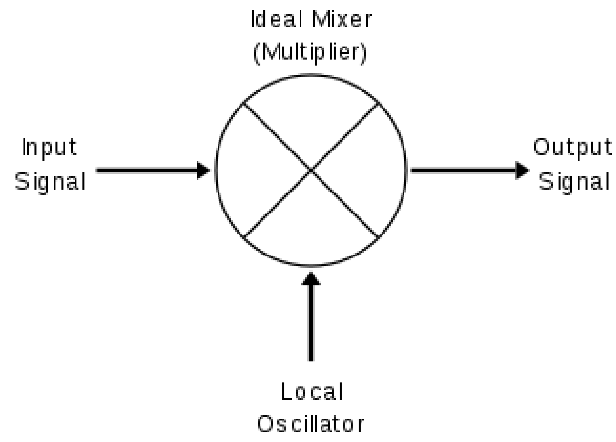
With a SSB measurement, the mixer internal noise shows up at the IF output from both signal and image inputs, but the excess noise is only introduced in the signal frequency band.

A DSB NF is easier to measure; wideband excess noise is introduced at both the signal and image frequencies. It will be 3 dB less than the SSB noise figure in most cases. This is perhaps more relevant for direct conversion receivers where the image cannot be filtered out from the signal

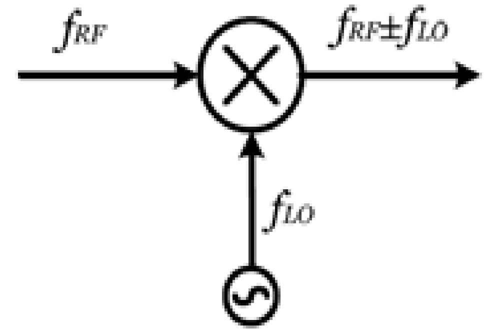
OPERATION

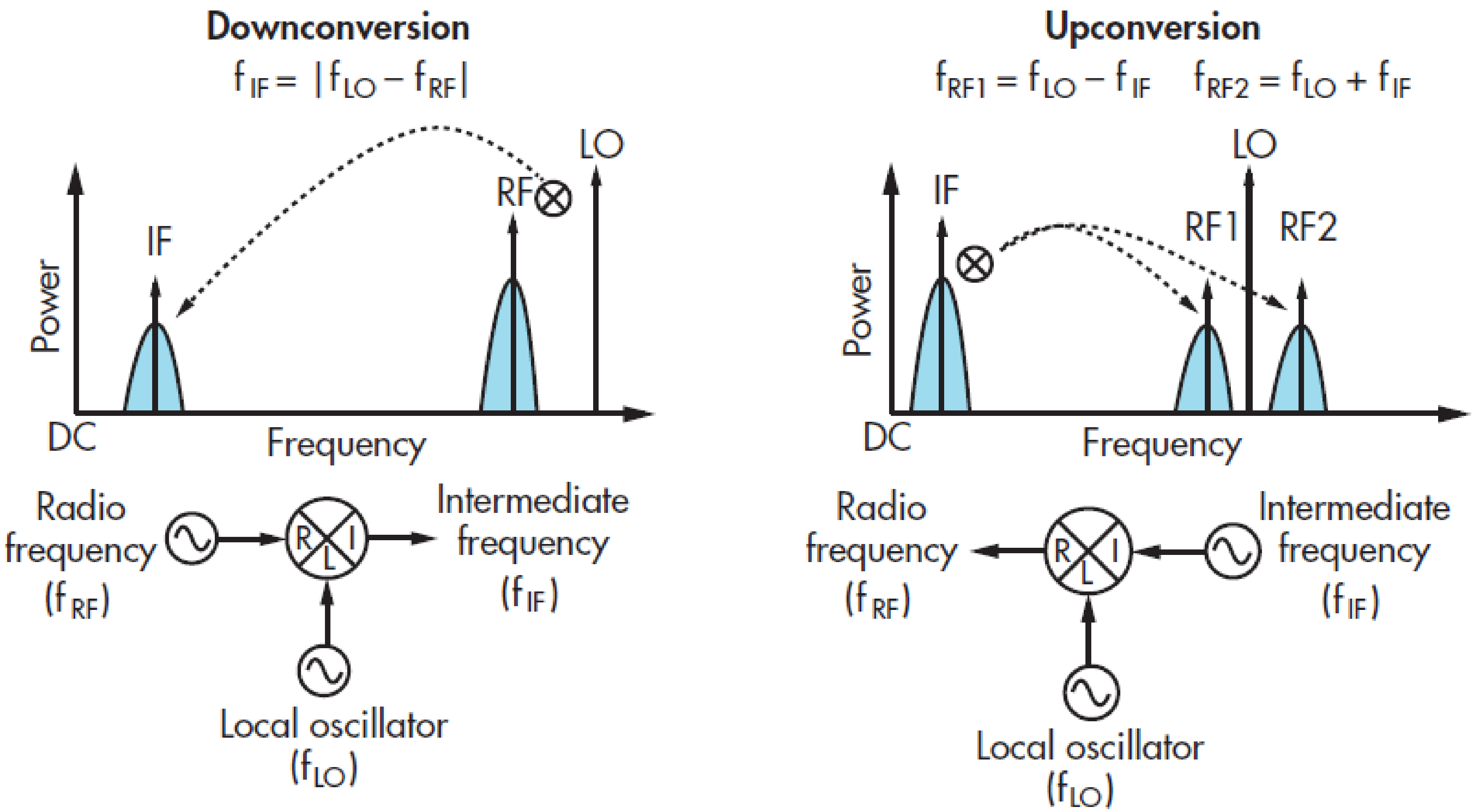
Mixer operation

- Mixer is used as one of the building blocks for frequency translation of an input signal.
- Converts an input signal to a higher (Up-conversion) or lower (Down-conversion) frequency by combining the input RF frequency with LO.
- The output has both up-converted and down-converted frequencies. The up-converted deals with the transmitter, while the down-converted deals with the receiver side.



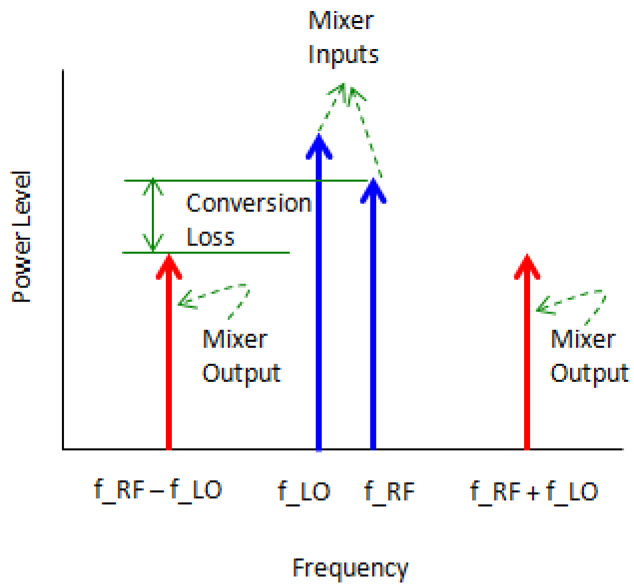
Mixer operation

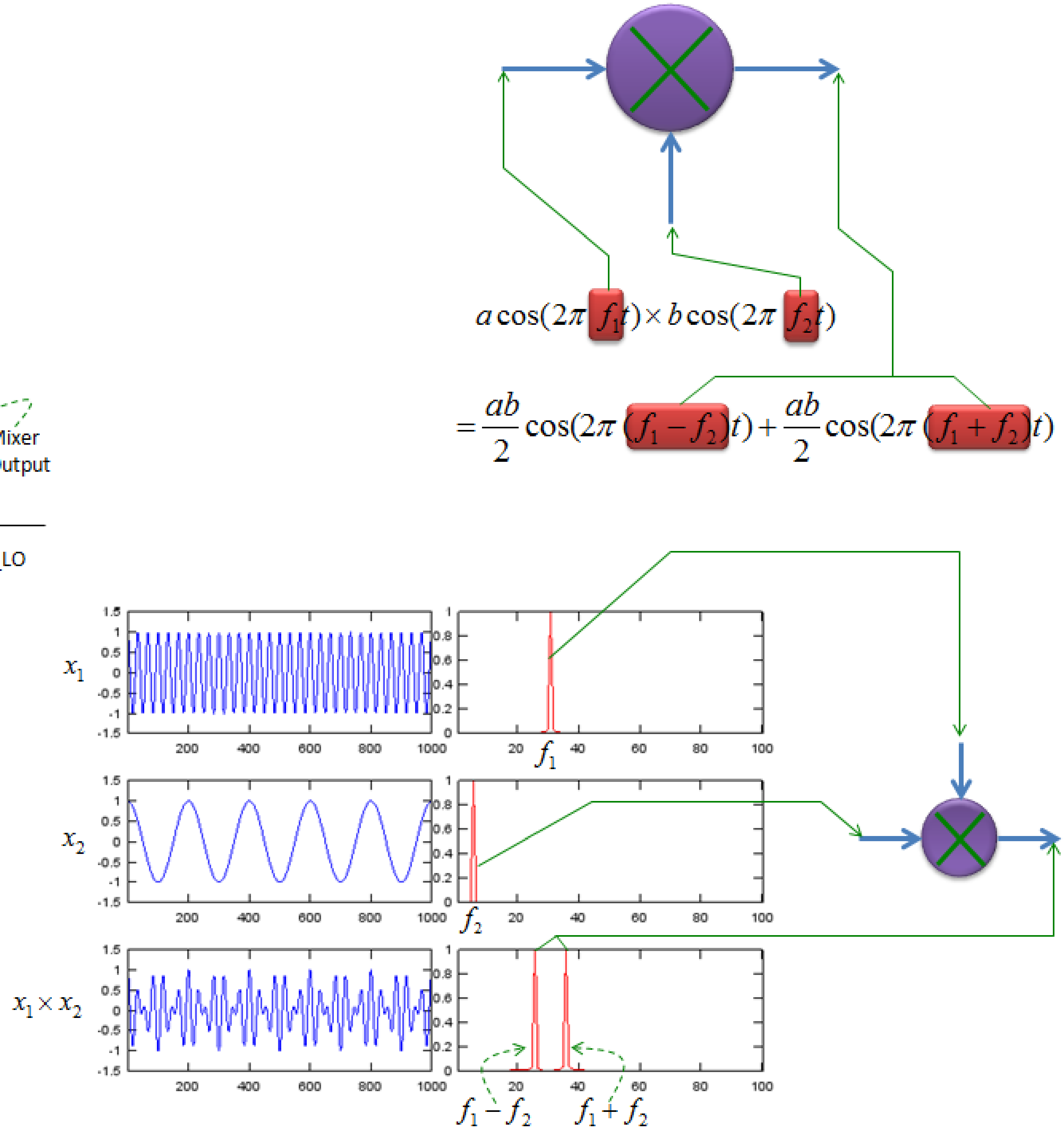




https://www.mwrf.com/technologies/active-components/article/21845701/rf-mixers-pine-for-linearity-and-dynamic-range

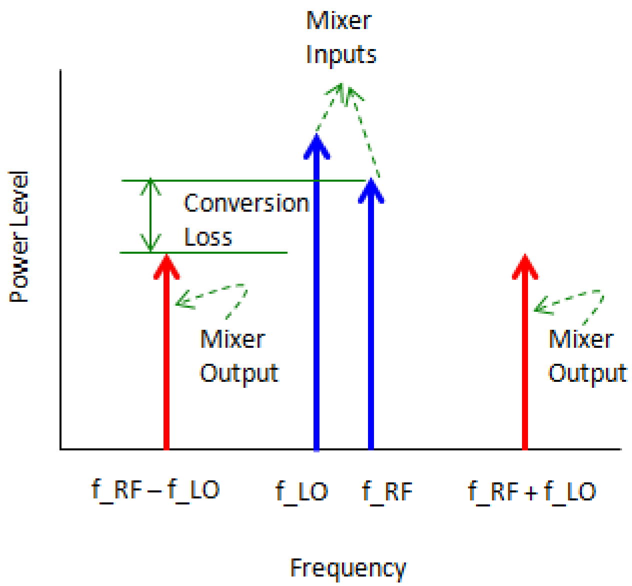
Mixer operation



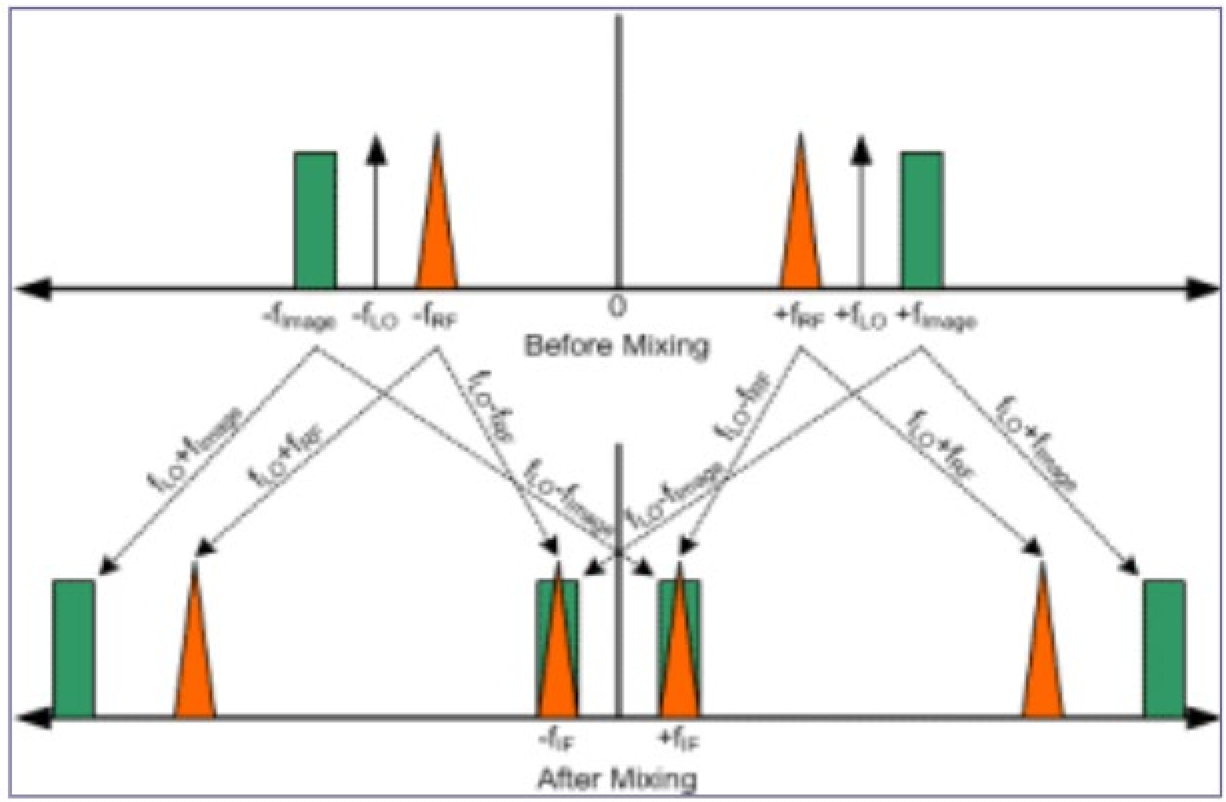


http://www.sharetechnote.com/html/RF_Mixer.html

Mixer operation: Image issue !

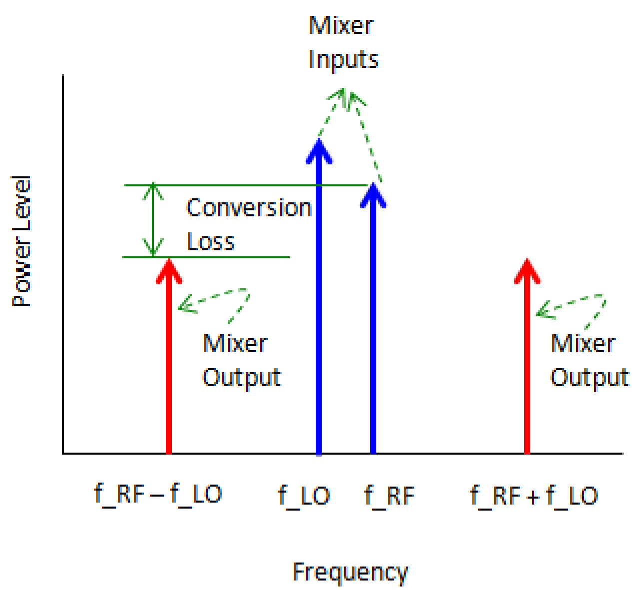


An image frequency is one which lies equidistant from the LO frequency, but on the opposite side.



http://www.sharetechnote.com/html/RF_Mixer.html
https://www.rfcafe.com/references/electrical/image-frequency.htm

Mixer operation: Image issue !



An image frequency is one which lies equidistant from the LO frequency, but on the opposite side.

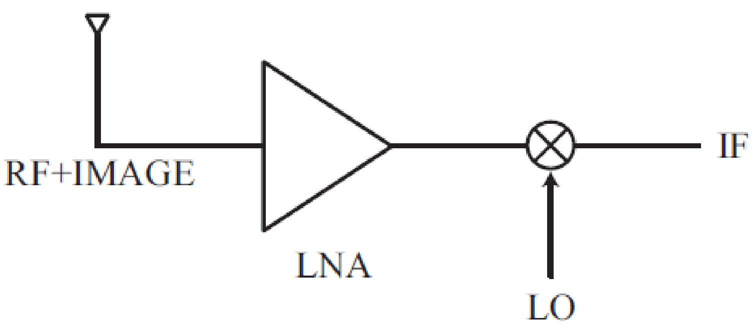
Example: Down-conversion

RF = 1000 MHz IF = 100 MHz

Let's say we choose a low-side injection:

LO = 900 MHz

That means that any signal or noise at 800MHz will also be down-converted to the same IF.

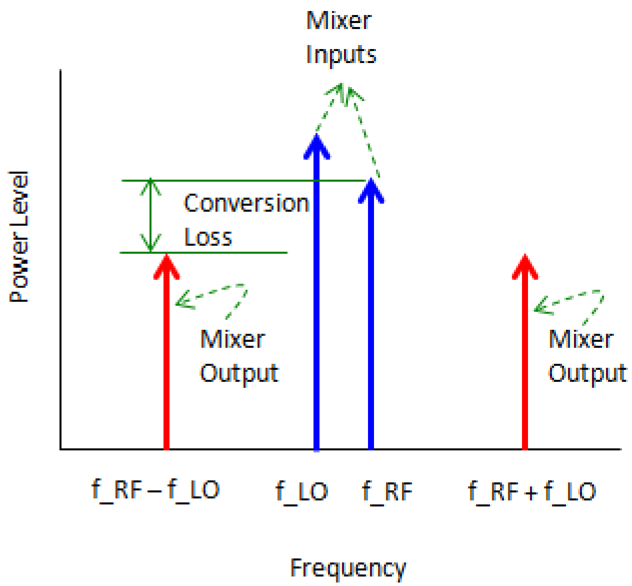


IF = 800 MHz = RF – LO

Image = 800 MHz = LO – IF

http://www.sharetechnote.com/html/RF_Mixer.html

Mixer operation: Image issue !



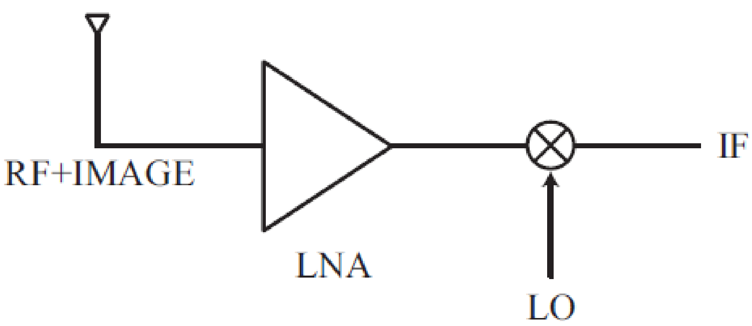
Example: Down-conversion

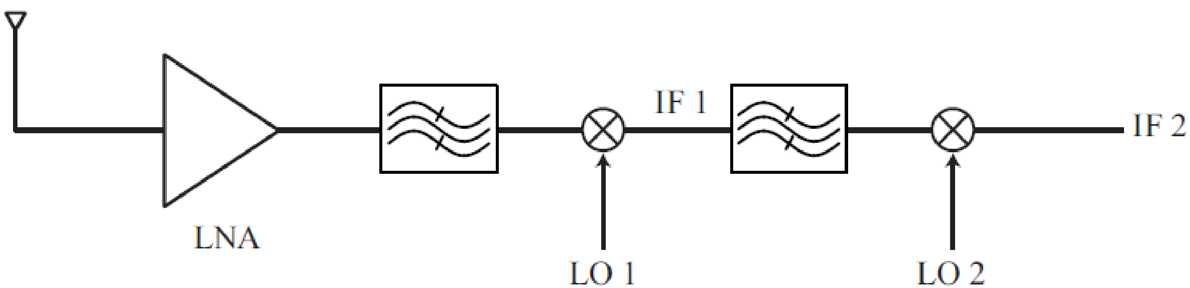
RF = 1000 MHz IF = 100 MHz

LO = 900 MHz Image Image = 800 MHz

Filtering leads to a too high filter Q-factor !

The image filtering problem can be relaxed by using multi-IF stages. Instead of moving to such a low IF where the image filtering is difficult (or expensive/bulky), we down-convert twice, using successively lower IF frequencies.



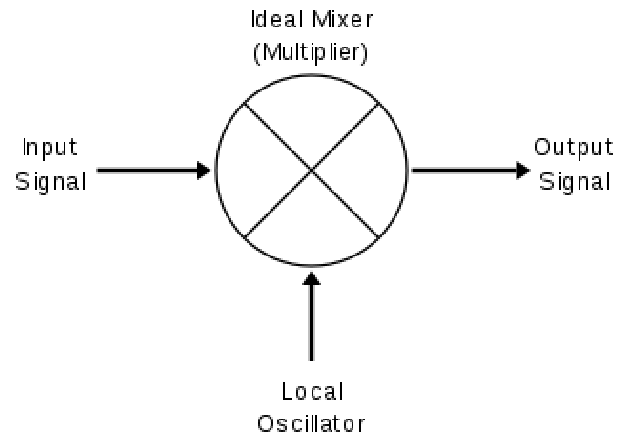


http://www.sharetechnote.com/html/RF_Mixer.html

Mixer operation

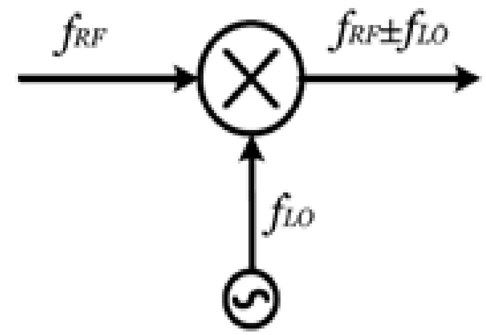
Three operations mechanisms

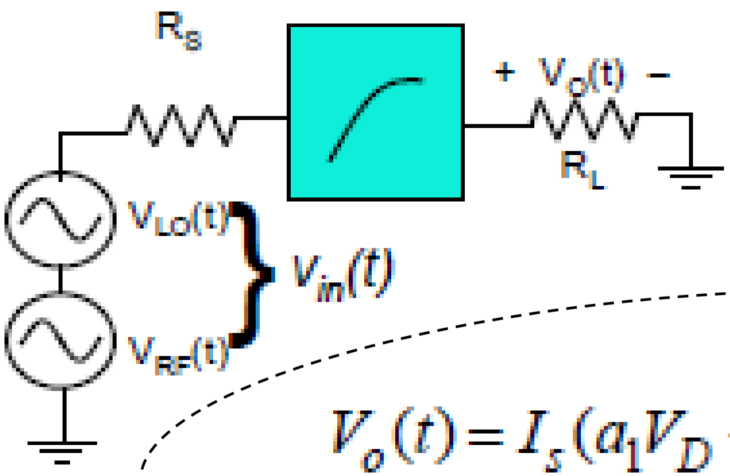
- ❑ ***Nonlinear transfer function***
  - ❑ Use the nonlinearity characteristics of active device(s)
  - ❑ High-performance mixers
    - ❑ Generate lots of undesired output frequencies
- ❑ ***Switching or sampling***
  - ❑ Time-varying process
  - ❑ Fewer spurious signals at the output
    - ❑ Good when lower frequencies are involved
- ❑ ***Direct-conversion receiver***



NONLINEAR TRANSFER MIXER

Nonlinear Mixer





second-order product term

$$V_o(t) = I_s(a_1 V_D + a_2 V_D^2 + a_3 V_D^3 + \cdots) R_L$$

$$a_2 V_D^2 = a_2 \left[V_R^2 \sin^2(\omega_R t) + V_L^2 \sin^2(\omega_L t) + 2 V_R V_L \sin(\omega_R t) \sin(\omega_L t) \right]$$

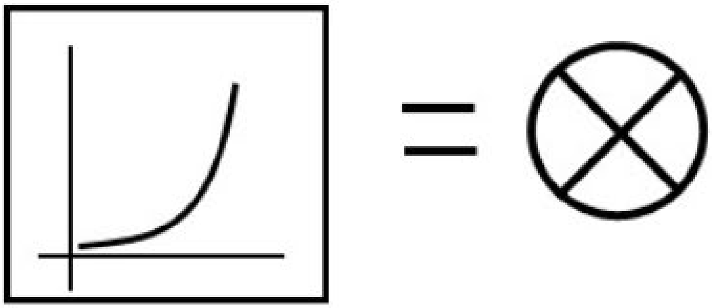
The product term produces the desired mixer output:

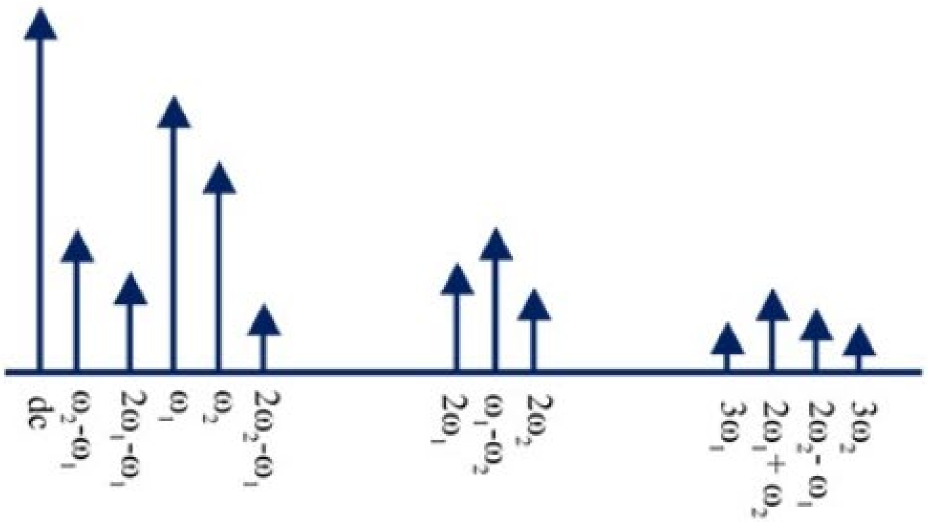
$$V_R V_L \left[\cos(\omega_R + \omega_L) t - \cos(\omega_R - \omega_L) t \right]$$

Down conversion

Up-conversion

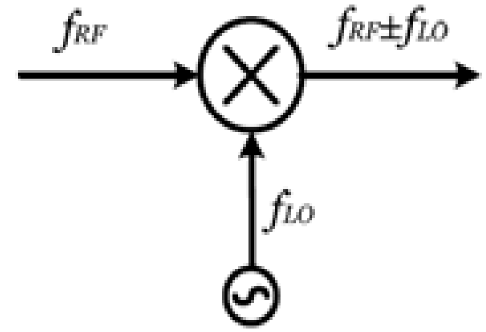
Nonlinear Mixer : lot of intermodulations !

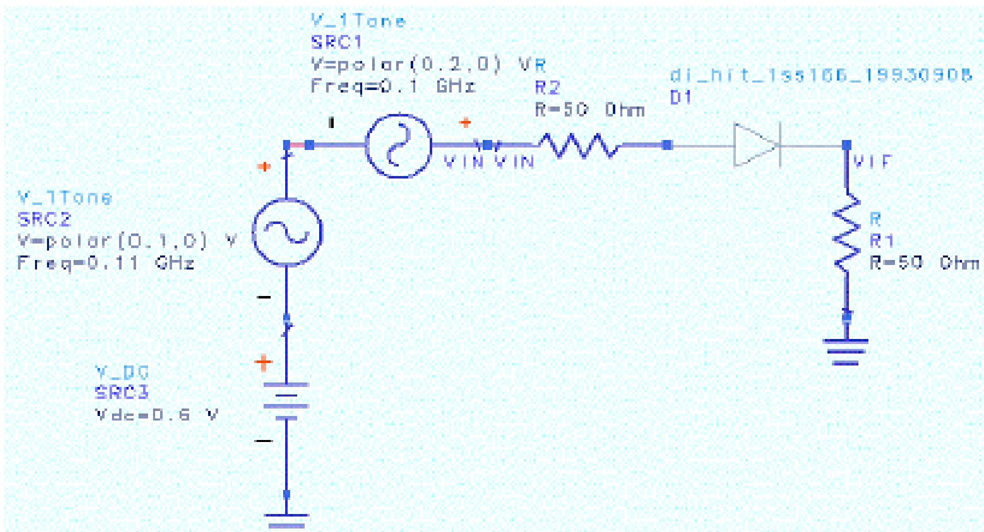




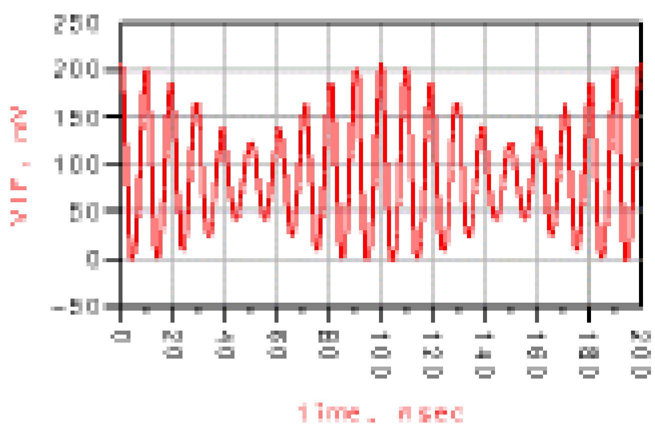
$$\alpha_1(A_1 \text{ Cos } \omega_1 t + A_2 \text{Cos } \omega_2 t)$$
$$+ \alpha_2(A_1 \text{ Cos } \omega_1 t + A_2 \text{Cos } \omega_2 t)^2$$
$$+ \alpha_3(A_1 \text{ Cos } \omega_1 t + A_2 \text{Cos } \omega_2 t)^3$$
$$= \tfrac{1}{2}\alpha_2 \,(A^2{}_1 + A^2{}_2)$$
$$+ [\alpha_1 + \tfrac{3}{4}\alpha_3 \, A^2{}_1 + \tfrac{3}{2}\alpha_3 \, A^2{}_2 \,] \, A_1 \text{Cos}\omega_1 t$$
$$+ [\alpha_1 + \tfrac{3}{4}\alpha_3 \, A^2{}_2 + \tfrac{3}{2}\alpha_3 \, A^2{}_1 \,] \, A_2 \text{Cos}\omega_2 t$$
$$+ [\alpha_2 A_1 A_2] \text{ Cos } (\omega_1 \pm \omega_2) t$$
$$+ [\tfrac{1}{2}\alpha_2 \, A^2{}_1 \,] \text{ Cos } 2\omega_1 t$$
$$+ [\tfrac{1}{2}\alpha_2 \, A^2{}_2 \,] \text{ Cos } 2\omega_2 t$$
$$+ [\tfrac{3}{4}\alpha_3 \, A^2{}_1 A_2] \text{ Cos } (2\omega_1 + \omega_2) t$$
$$+ [\tfrac{3}{4}\alpha_3 \, A^2{}_2 A_1] \text{ Cos } (2\omega_2 + \omega_1) t$$
$$+ [\tfrac{3}{4}\alpha_3 \, A^2{}_1 A_2] \text{ Cos } (2\omega_1 - \omega_2) t$$
$$+ [\tfrac{3}{4}\alpha_3 \, A^2{}_2 A_1] \text{ Cos } (2\omega_2 - \omega_1) t$$
$$+ [\tfrac{1}{4}\alpha_3 \, A^3{}_1 \,] \text{ Cos } 3\omega_1 t$$
$$+ [\tfrac{1}{4}\alpha_3 \, A^3{}_2 \,] \text{ Cos } 3\omega_2 t$$

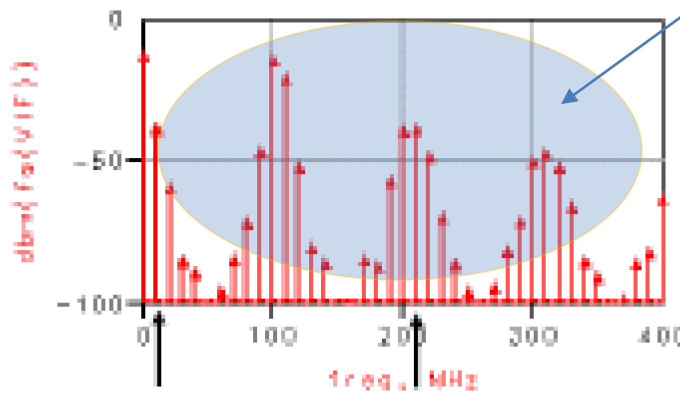
Nonlinear mixer - Example





Lot of undesired frequencies at the output





$f_{RF}-f_{LO}$ $f_{RF}+f_{LO}$

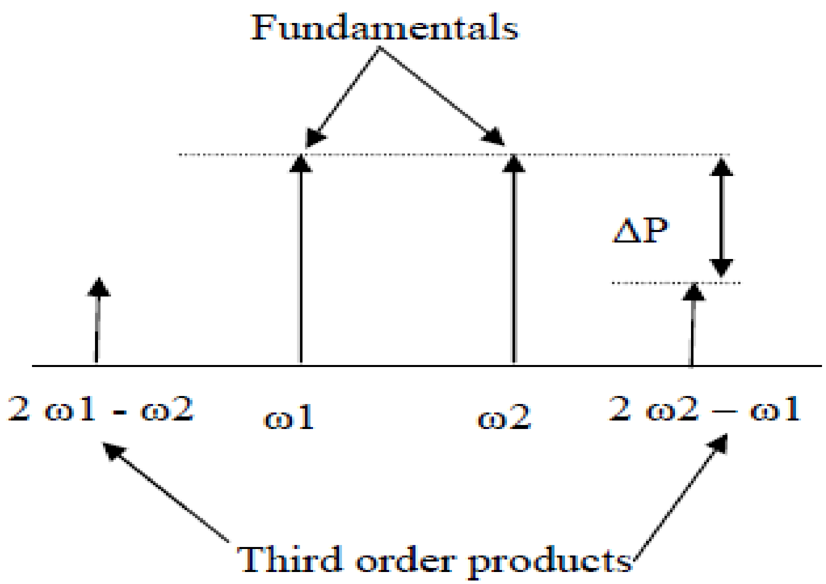
F_{RF} = 110 MHz $|V_{RF}|$ = 0.1V

F_{LO} = 100 MHz $|V_{LO}|$ = 0.2V

V_{DC} = 0.6V

Nonlinear Mixer

Intermodulation and harmonic spectrum representations



Let's consider the 3rd order nonlinearity: $a_3 v_{in}^3$

– two inputs: $v_{in} = V_1 \sin(\omega_1 t) + V_2 \sin(\omega_2 t)$

$$V_{out3} = a_3[V_1^3 \sin^3(\omega_1 t) + V_2^3 \sin^3(\omega_2 t) + 3V_1^2 V_2 \sin^2(\omega_1 t)\sin(\omega_2 t) + 3V_1 V_2^2 \sin(\omega_1 t)\sin^2(\omega_2 t)]$$

$$\underbrace{\frac{3V_1^2 V_2 a_3}{2}\{\sin(\omega_2 t)}_{\text{Cross-modulation}} - \underbrace{\frac{1}{2}[\sin(2\omega_1-\omega_2)t - \sin(2\omega_1+\omega_2)t]\}}_{\text{Third-order IMD}}$$

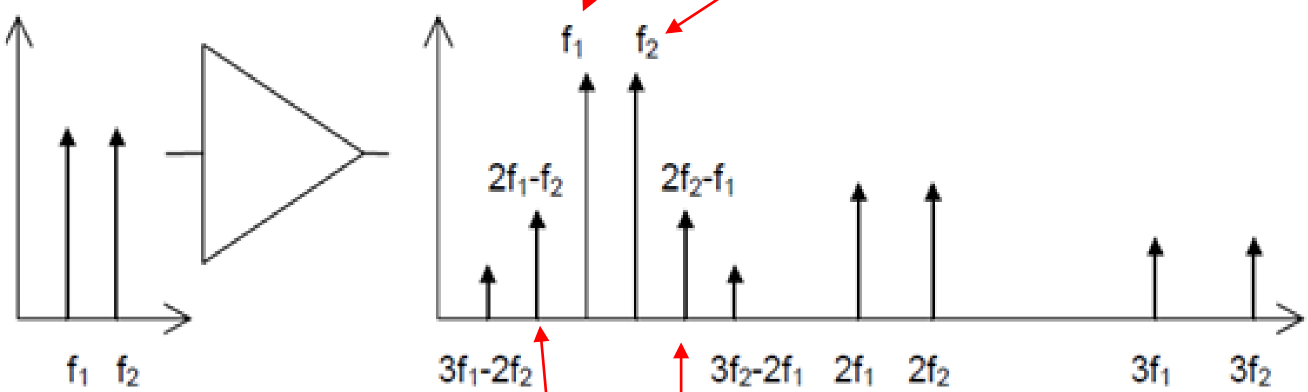
3rd order : the most significant !!

WHY?

Nonlinear Mixer

Intermodulation and harmonic spectrum representations

Suppose we have 2 input frequencies at 8.9 GHz and 9.1 GHz.



$2*f_1 - f_2 = 8.7$ GHz

Third order products:

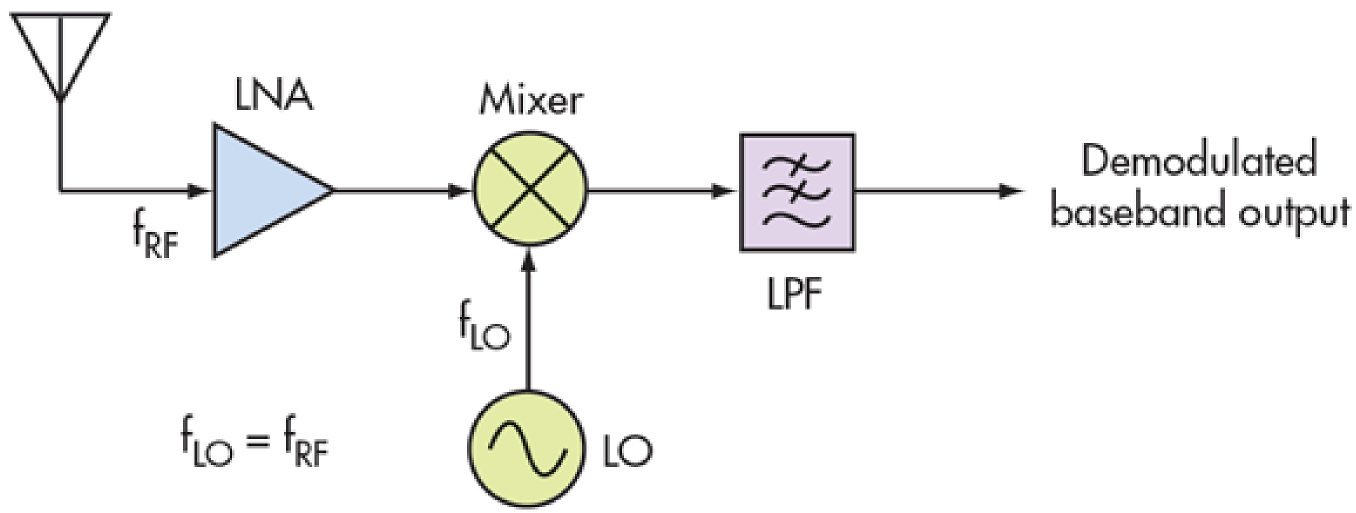
$2*f_2 - f_1 = 9.3$ GHz

How to filter them?

DIRECT-CONVERSION MIXER

Direct-conversion Mixer

A **direct-conversion receiver** (**DCR**), also known as **homodyne**, **synchrodyne**, or **zero-IF receiver**, is a radio receiver that demodulates the incoming radio signal using synchronous detection driven by a local oscillator whose frequency is identical to, or very close to the carrier frequency of the intended signal.

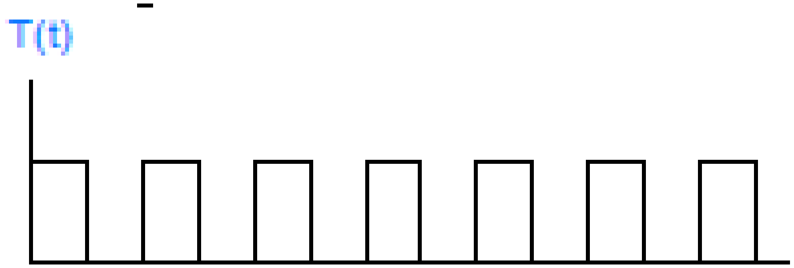


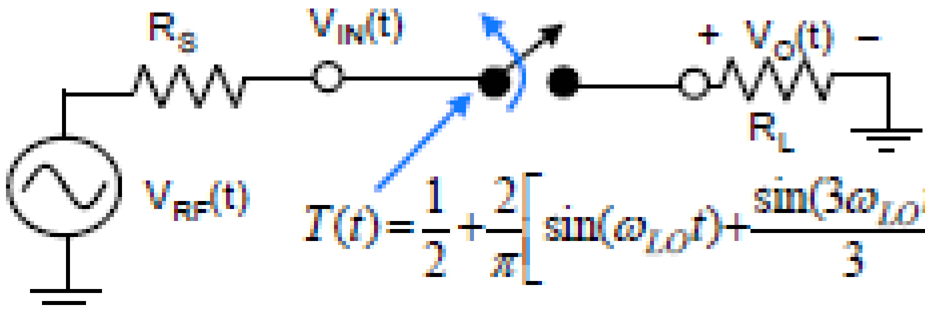
Direct conversion receiver architectures such as used in pagers use mixers at the input to both down-convert and demodulate the digital information. Mixers are thus widely used in the analog/RF front end of receivers. In these applications, often the mixer must be designed to handle a very wide dynamic range of signal powers at the input.

SWITCH MIXER

Switch mixer with ***one*** active device

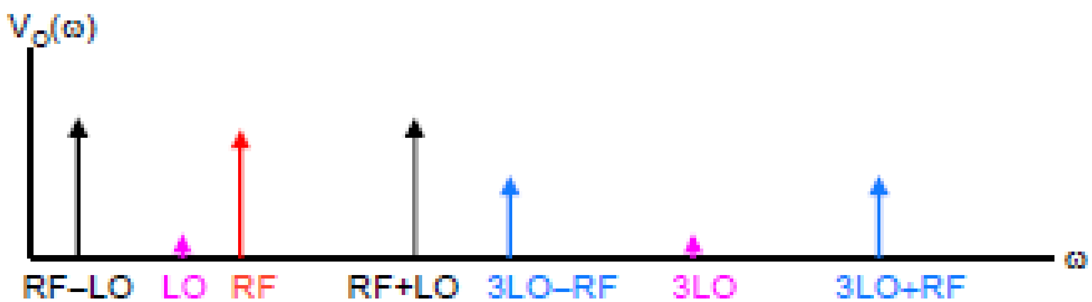
- Let $V_{IN}(t) = V_R \cos(\omega_{RF} t)$
- Multiply by the LO switching function T(t)





$$T(t) = \frac{1}{2} + \frac{2}{\pi}\left[\sin(\omega_{LO} t) + \frac{\sin(3\omega_{LO} t)}{3} + \frac{\sin(5\omega_{LO} t)}{5} + \cdots\right]$$

no even order harmonics



Switch mixer with ***one*** active device

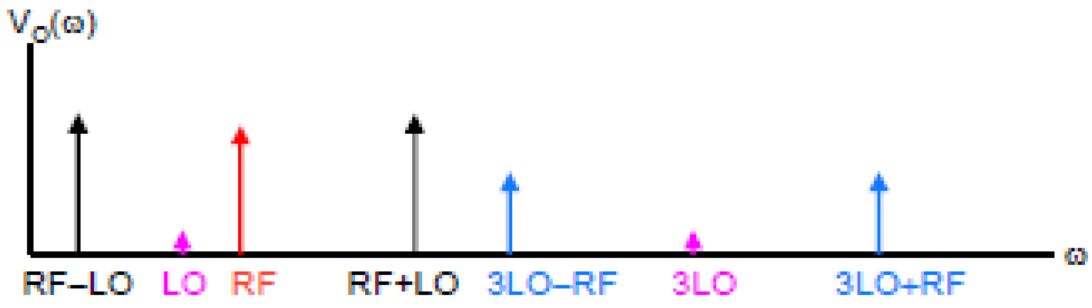
Intermodulation and harmonic spectrum representations

$$V_o(t) = \underbrace{\frac{V_R}{2}\cos(\omega_{RF}t)}_{\text{RF feedthrough}} + \frac{2V_R}{\pi}\left[\underbrace{\cos(\omega_{RF}t)\sin(\omega_{LO}t)}_{\text{2nd-order product}} + \underbrace{\frac{\cos(\omega_{RF}t)\sin(3\omega_{LO}t)}{3}}_{\text{4th-order spurs}} + \cdots\right]$$

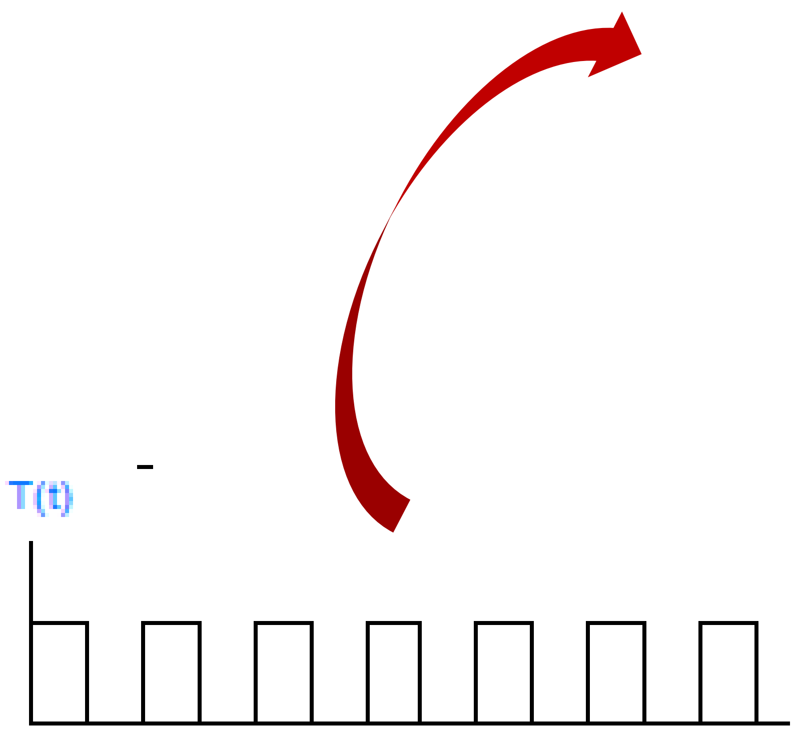
Advantage: None of the LO signal should appear in the output if the mixer behaves according to this equation.

Disadvantage: We get *RF feedthrough* directly to the output.

Also, if there is a DC offset on the RF input, there will be a LO frequency component in the output as well.



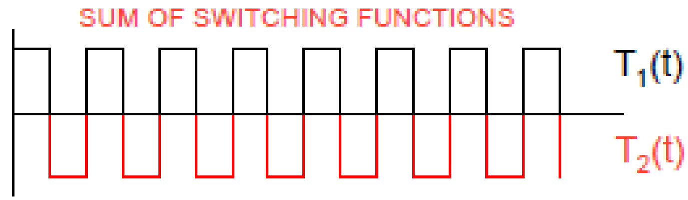
Change to a switch mixer with ***two*** active devices



LO Switching Function T(t)

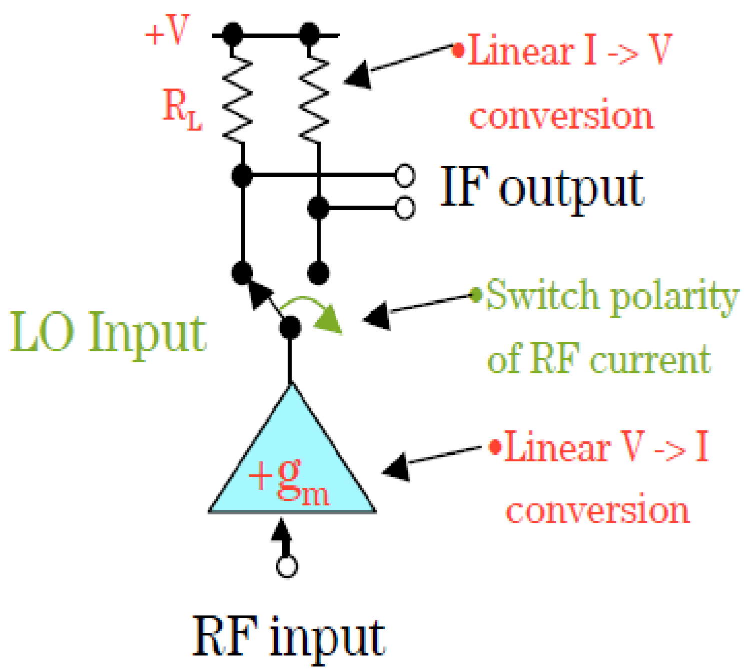
$$T_1(t) = \frac{1}{2} + \frac{2}{\pi}\left[\sin(\omega_{LO}t) + \frac{1}{3}\sin(3\omega_{LO}t) + \ldots\right]$$

$$T_2(t) = -\frac{1}{2} + \frac{2}{\pi}\left[\sin(\omega_{LO}t) + \frac{1}{3}\sin(3\omega_{LO}t) + \ldots\right]$$



$T(t) = T_1(t) + T_2(t)$

Change to a switch mixer with ***two*** active devices



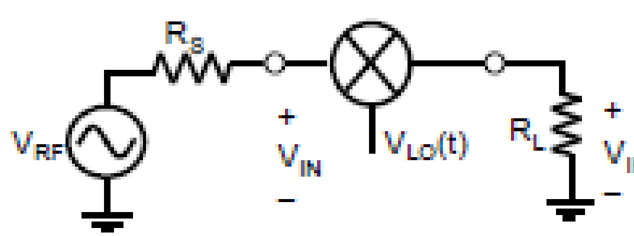
Advantage : the **RF feedthrough** can be eliminated using a differential input.

Disadvantage: we can still get **LO feedthrough** if we take a single-ended output or if there is a DC current in the signal path.

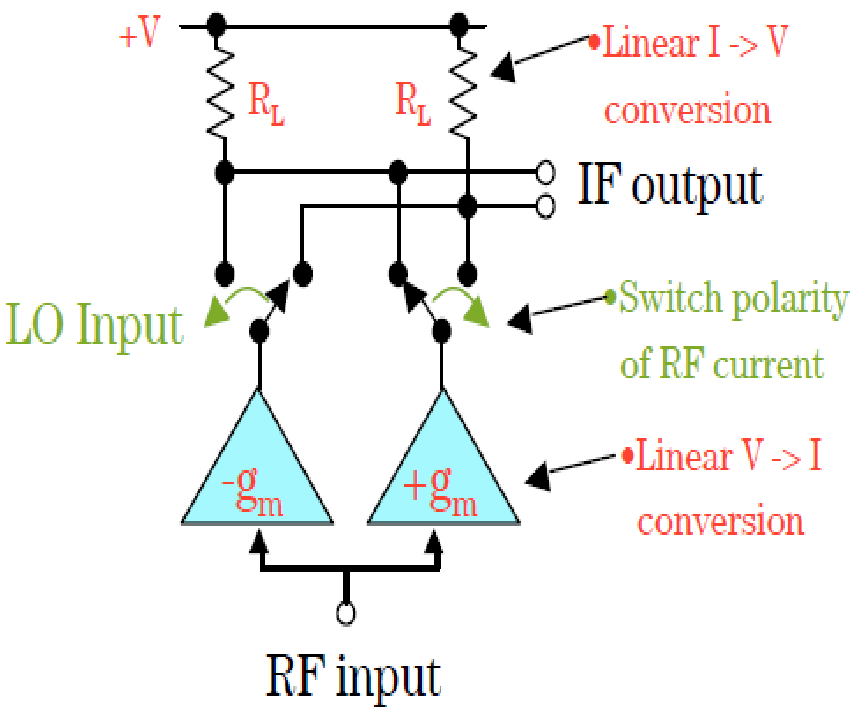
$$V_{IF}(t) = R_L[I_{DC} + g_m V_R \cos(\omega_{RF} t)] \times \frac{4}{\pi}\left[\sin(\omega_{LO} t) + \frac{1}{3}\sin(3\omega_{LO} t) + \frac{1}{5}\sin(5\omega_{LO} t) + \ldots\right]$$

$$= \frac{4R_L}{\pi}\{I_{DC}\sin(\omega_{LO} t) + \frac{1}{2} g_m V_R[\sin(\omega_{RF} + \omega_{LO})t + \sin(\omega_{RF} - \omega_{LO})t]\}$$

Present even with no RF input



Change to a switch mixer with ***four*** active devices



Changing the number of active devices ?

An ideal double balanced mixer consists of a switch driven by the local oscillator that reverses the polarity of the RF input at the LO frequency and a differential amplifier stage. The polarity reversing switch and differential IF cancels any output at the RF input frequency since the DC term cancels as was the case for the single balanced design.

The double LO switch cancels out any LO frequency component, even with currents in the RF to IF path.

The LO is typically suppressed by 50 or 60 dB if the components are well matched/balanced.

CONFIGURATIONS

It exists different configurations of mixers based on the number of active devices involved:

Lowest gain / Highest loss	Simplest design	Lowest cost	Lowest Input power	Poorest Isolation	Highest IMD

- Single-ended : 1 active device
- Balanced : 2 active devices
- Double-balanced : 4 active devices
- Double double-balanced : 8 active devices

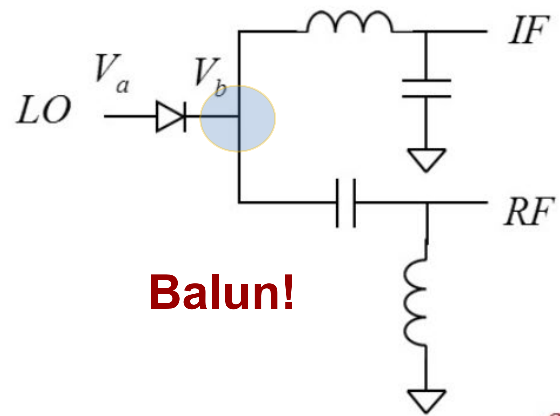
Highest gain / Lowest loss	Highest complexity	Highest cost	Highest Input power	Highest Isolation	Lowest IMD

DIODE MIXERS

Single-diode mixer

$$I_{D1} = \alpha_0 + \alpha_1 (V_a - V_b) + \alpha_2 (V_a - V_b)^2 + \alpha_3 (V_a - V_b)^3 + \dots$$

$$I_{D1} = \alpha_0 + \alpha_1 V_a - \alpha_1 V_b + \alpha_2 V_a^2 - 2\alpha_2 V_a V_b + \alpha_2 V_b^2 + \alpha_3 (V_a - V_b)^3 + \dots$$



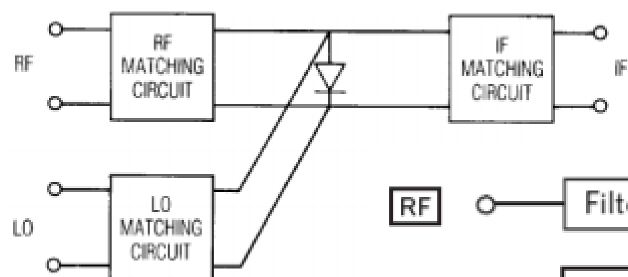
$$\cos^2 \omega t = \frac{1}{2} + \frac{1}{2}\cos 2\omega t$$

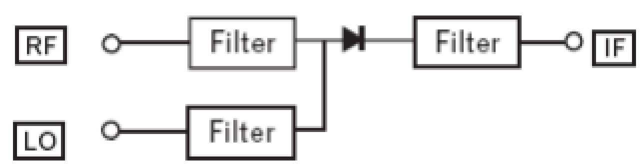
Single-Diode mixer is extremely useful at very high frequency (mm-wave band).

The diode used for mixing can be modeled at the RF frequency as a ***resistor*** and ***capacitor*** in parallel.

At low IF frequencies the output impedance is almost pure resistive.

The ***resistor*** is usually in a range of 50 to 150 ohms and the ***capacitor*** between 1x and 1.5x the junction capacitance. The IF output impedance is usually between 75Ω and 150Ω.





https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/

Baluns

Balun Transformers transfer the signals from an unbalanced impedance input to a balanced impedance output, or vice versa.

An unbalanced impedance input is a **two** terminal transmission device **with one** of the terminals connected to ground. Signal must transmit and receive from the center conductor but not the outside shielding.

Coaxial cables are considered as unbalanced impedance cables.

A balanced impedance output is a two terminal reciprocal device with neither one of its terminals connected to the ground. Signals can transmit or receive from either one or both terminals.

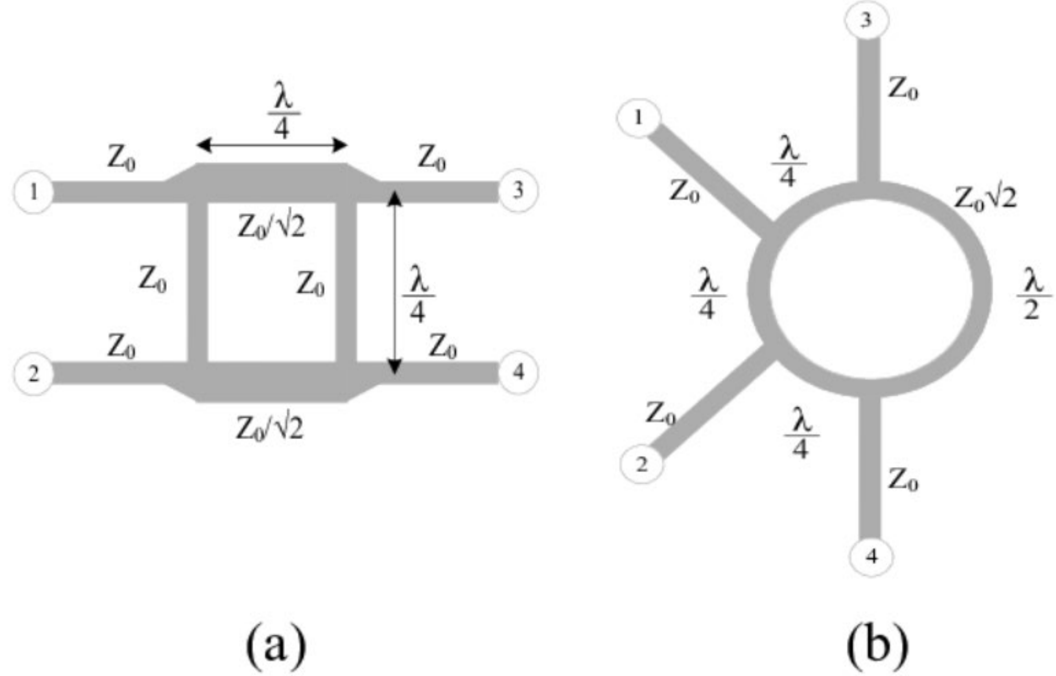
Twisted pair cables are considered as balanced impedance cables.

General uses of Balun Transformer:

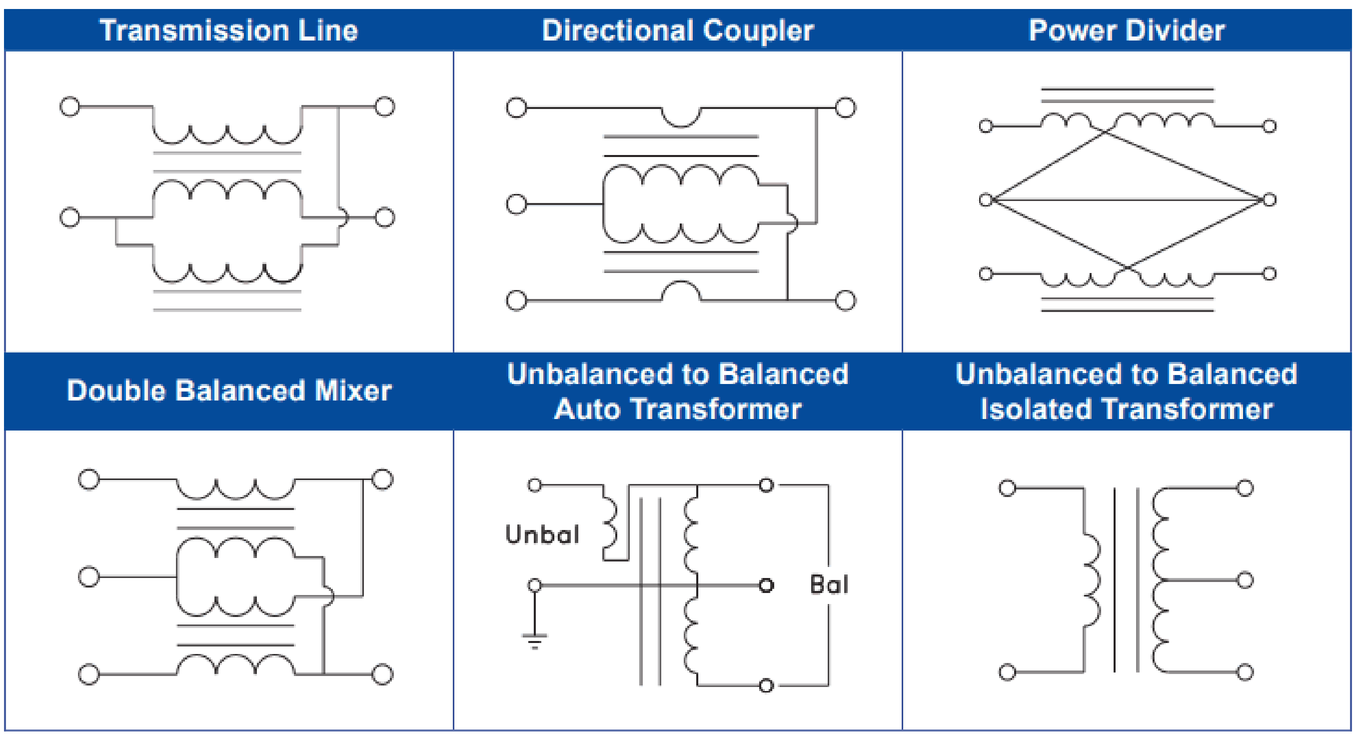
1. Impedance matching to achieve maximum power transfer
2. Step up or step down of signal amplitude
3. DC Isolation
4. Splitter / Combiner / Coupler
5. Double Balanced Mixer

https://www.mpsind.com/product-resources/balun-product-application-notes/
https://www.researchgate.net/figure/a-Model1-branch-line-coupler-b-Model-2-Ring-Hybrid-coupler_fig1_282711663

Baluns

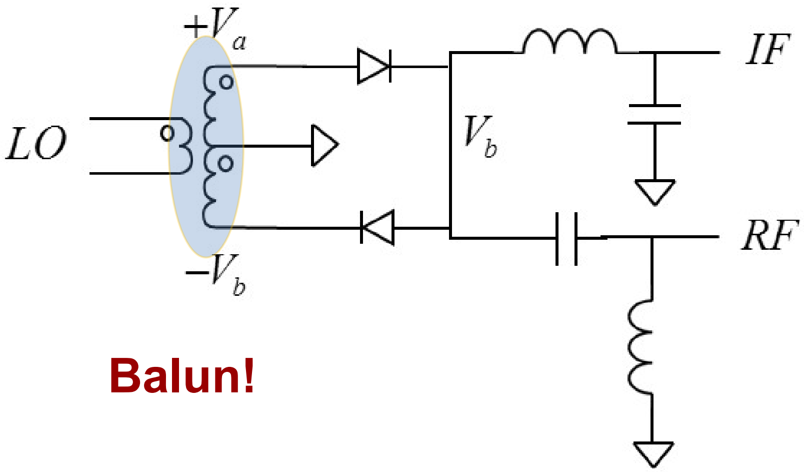


(a) Model.1: branch line coupler, (b) Model. 2: Ring Hybrid coupler



https://www.mpsind.com/product-resources/balun-product-application-notes/
https://www.researchgate.net/figure/a-Model1-branch-line-coupler-b-Model-2-Ring-Hybrid-coupler_fig1_282711663

Balanced diode mixer



Balun!

$$\alpha_0 + \alpha_1(V_a + V_b) + \alpha_2(V_a + V_b)^2 + \alpha_3(V_a + V_b)^3 + \dots$$

$$I_{D1} = \alpha_0 + \alpha_1 V_a + \alpha_1 V_b + \alpha_2 V_a^2 + 2\alpha_2 V_a V_b + \alpha_2 V_b^2 + \alpha_3(V_a - V_b)^3 + \dots$$

$$I_{D2} = \alpha_0 + \alpha_1(V_a - V_b) + \alpha_2(V_a - V_b)^2 + \alpha_3(V_a - V_b)^3 + \dots$$

$$I_{D2} = \alpha_0 + \alpha_1 V_a - \alpha_1 V_b + \alpha_2 V_a^2 - 2\alpha_2 V_a V_b + \alpha_2 V_b^2 + \alpha_3(V_a - V_b)^3 + \dots$$

- ❖ Poor gain
- ❖ Good LO-IF isolation
- ❖ Good LO-RF isolation
- ❖ Poor RF-IF isolation.

$$\cos^2 \omega t = \frac{1}{2} + \frac{1}{2}\cos 2\omega t$$

$$I_{D1} - I_{D2}$$

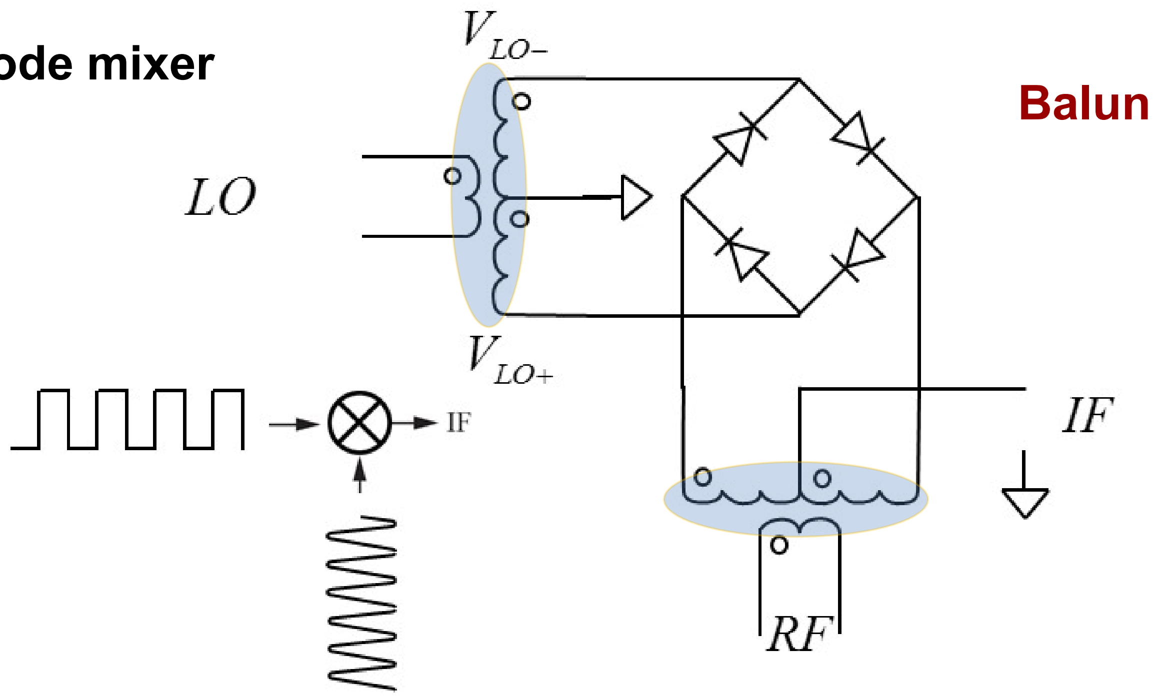
$$I_{D1} = +\alpha_0 + \alpha_1 V_a + \alpha_1 V_b + \alpha_2 V_a^2 + 2\alpha_2 V_a V_b + \alpha_2 V_b^2 + \alpha_3(V_a - V_b)^3 + \dots$$

$$-I_{D2} = -\alpha_0 - \alpha_1 V_a + \alpha_1 V_b - \alpha_2 V_a^2 + 2\alpha_2 V_a V_b - \alpha_2 V_b^2 - \alpha_3(V_a - V_b)^3 + \dots$$

$$= 2\alpha_1 V_b + \boxed{4\alpha_2 V_a V_b} + 6\alpha_3 V_a^2 V_b + 2V_b^3 + \boxed{8\alpha_4\left(V_a^3 V_b + V_a V_b^3\right)} + \dots$$

https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/

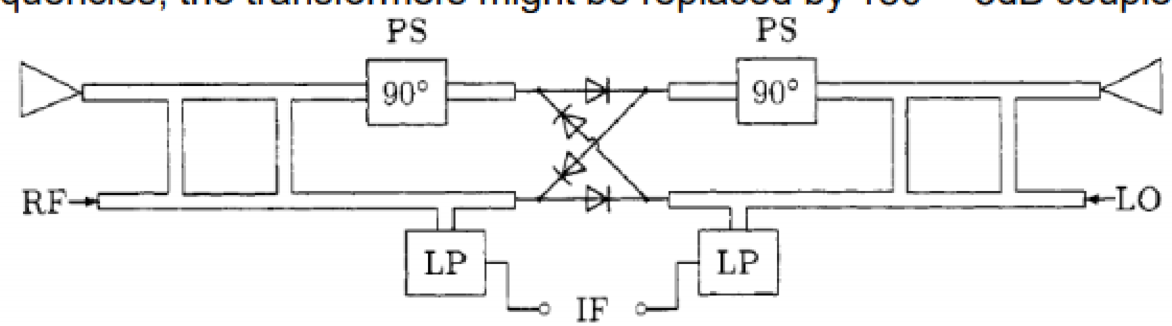
Double-balanced diode mixer



- Poor gain (typically -6dB)
- Good LO-IF isolation
- Good LO-RF isolation
- Good RF-IF isolation
- Good linearity
- Good dynamic range

$$V_{RF}(t)\cdot V_{LO}(t) = A_{RF}\sin\left(\omega_{RF}t\right)\times sq\left(\omega_{LO}t\right)$$
$$= \frac{2}{\pi}A_{RF}\left[\cos(\omega_{RF}-\omega_{LO})t + \frac{1}{3}\cos\left(3(\omega_{RF}-\omega_{LO})t\right) + \ldots\right]$$

At higher frequencies, the transformers might be replaced by 180° - 3dB couplers:



https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/

Double-balanced diode mixer

Since the LO signal must switch the diodes on and off, a large LO power is required, typically 7 dBm when one diode is placed in each leg, 17 dBm with two diodes per path!

With this high LO power, even with good isolation, there may be significant LO in the IF output.

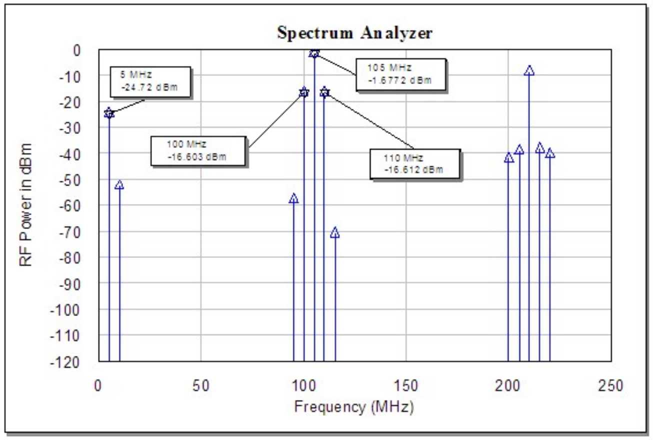
When the diodes are conducting with $I_{LO} >> I_{RF}$ the mixer should behave linearly.

At large RF signal powers, the RF voltage modulates the diode conduction, so lots of distortion will result in this situation. The diodes are also sensitive to RF modulation when they are biased close to their threshold current/voltage.

For both reasons, we prefer **high LO drive** with a fast transition (high slew rate - a square wave LO is better than sine wave) between on and off : The IMD performance is very poor with small LO power.

https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/

single diode mixer



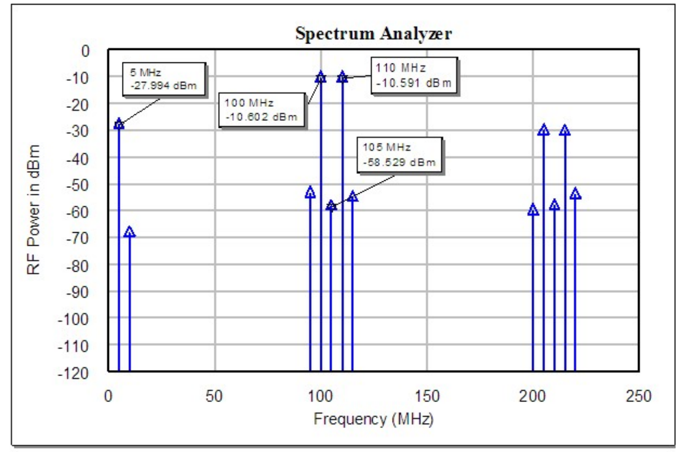
LO-RF Isolation

$7-(-1.67)=8.67\,\text{dB}$

Conversion Gain (Loss)

$-16.6-(-5)=-11.6\,\text{dBm}$

Balanced diode mixer



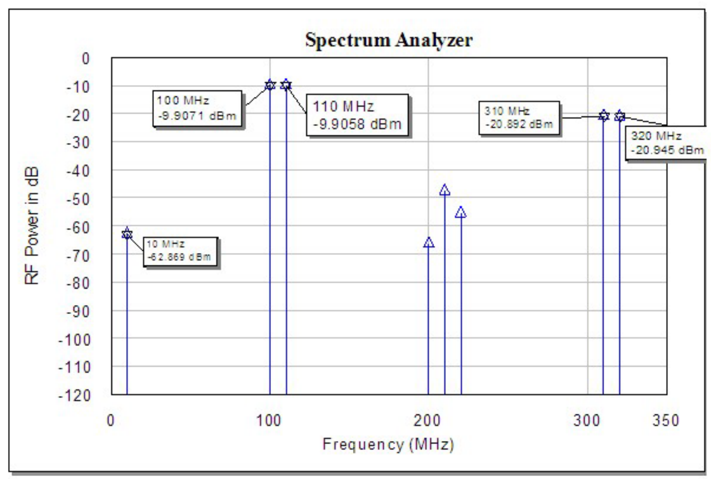
LO-RF Isolation

$7-(-58.5)=65.5\,\text{dB}$

Conversion Gain (Loss)

$-10.6-(-5)=-6.6\,\text{dBm}$

Double-balanced diode mixer



LO-RF Isolation

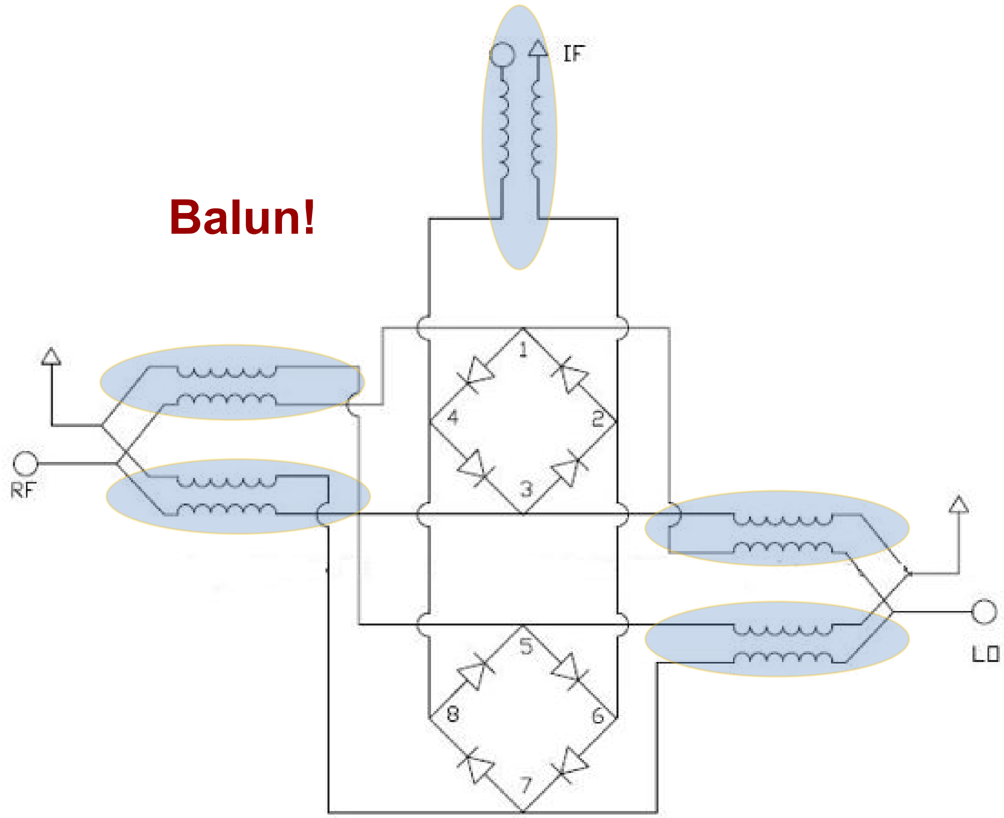
$\sim\infty$

Conversion Gain (Loss)

$-9.9-(-5)=-4.9\,\text{dBm}$

https://rickettslab.org/bits2waves/design/mixer-discrete/mixer-discrete-theory/

Double Double-balanced diode mixer or Triple-balanced diode mixer



Triple-balanced mixers enable low intermodulation distortion, up-conversion and down-conversion over very wide bandwidths, even into the high microwave/mm-wave frequencies.

Double-balanced mixers, on the other hand, are less complex and lower cost circuits that are fit for applications where moderate LO power is available and there are no concerns over overlapping RF and IF frequencies.

Generally, triple-balanced mixers also require about 3 dB more LO power, as the LO power is divided between the two diode quads.

https://www.everythingrf.com/community/filter?topic=;Mixers;

Diode Mixers : Comparison between Single- and double-balanced configurations

- DBM: Even order products canceled in O/P the double-balanced.
- SBM: only even products of the RF are canceled

- DBM: requires 3 dB more LO power.
- SBM: requires less power.

- DBM: more complex circuit configuration with higher efficiency.
- SBM: less efficient compared to DBM.

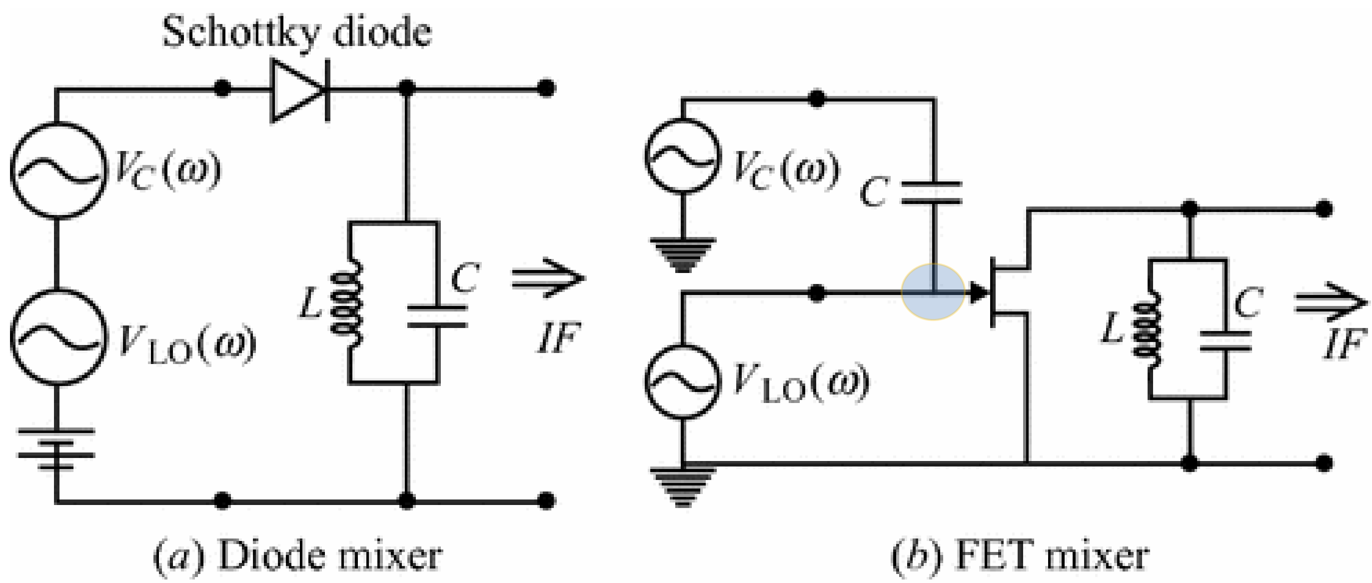
Performance comparison of diode mixers

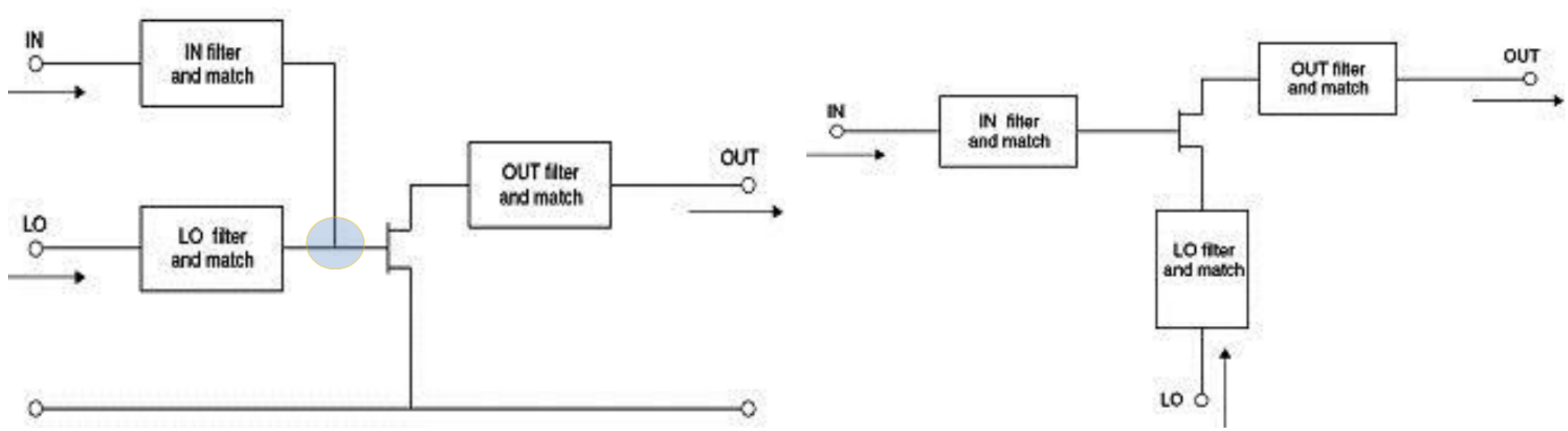
	Design complexity	Conversion gain	Conversion loss	Noise Figure	LO Rejection	RF Rejection	Spurious rejection	Linearity	LO level	Comments
single ended diode	+	No	-10 dB (ideal)	Low	No	No	No	+	+	Barely used. Need filters
Balanced diode	++	No	-4 dB (ideal)	Low	Either LO or RF	Either LO or RF	+	++	++	For simple application purposes
Double balanced diode mixer	4 diodes 2 baluns	No	Better than -4dB (ideal)	Higher	Yes	Yes	++	+++	+++	Two diode pairs need to be well ”matched”
Double double balanced diode mixer	8 diodes 3 baluns	No	Even better	Highest	Yes	Yes	+++	++++	++++	Very complex (in biasing all diodes + equal RF/LO signal distribution). Requires very well matched diodes

TRANSISTOR MIXERS

Single transistor mixer

Balun!



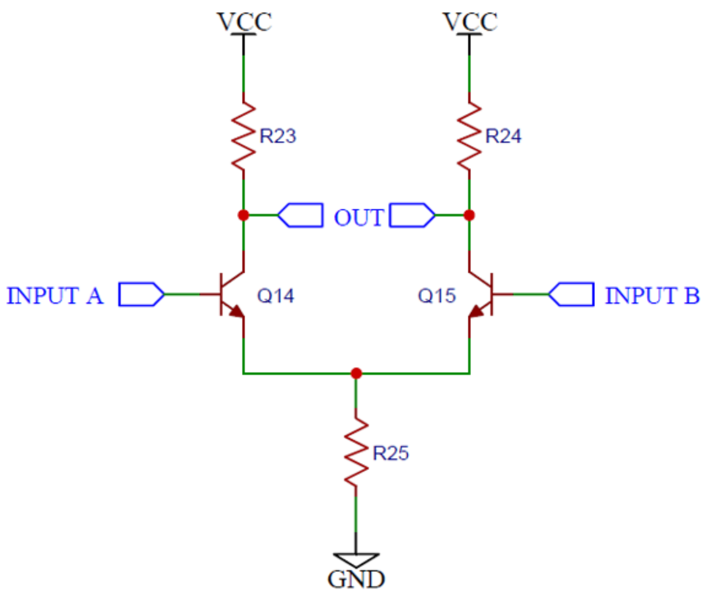


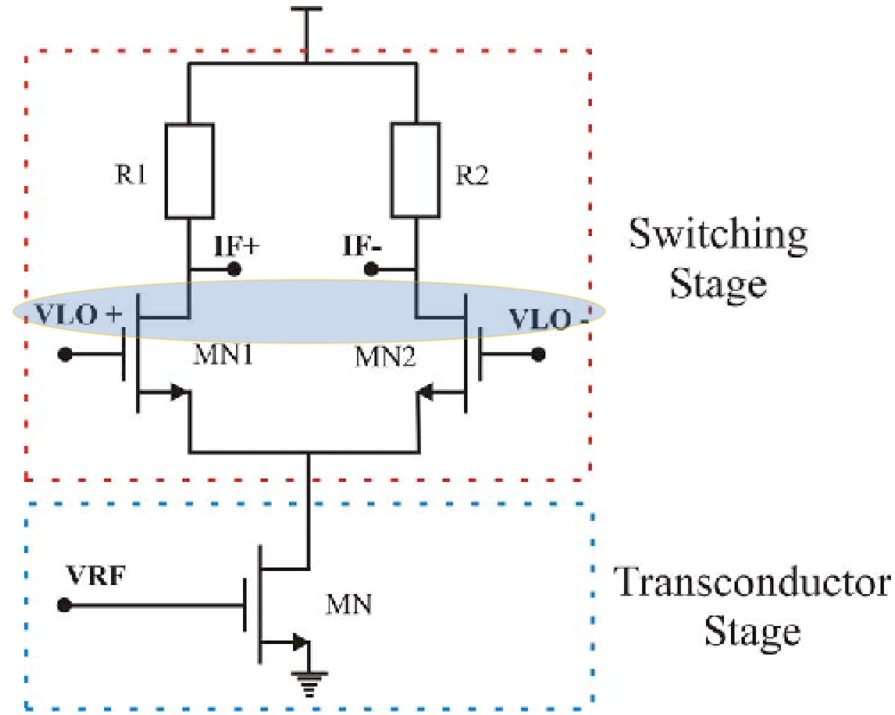
Two configurations
(based on the LO signal)

https://link.springer.com/chapter/10.1007/978-981-10-7965-8_11

Balanced transistor mixer

Balun!



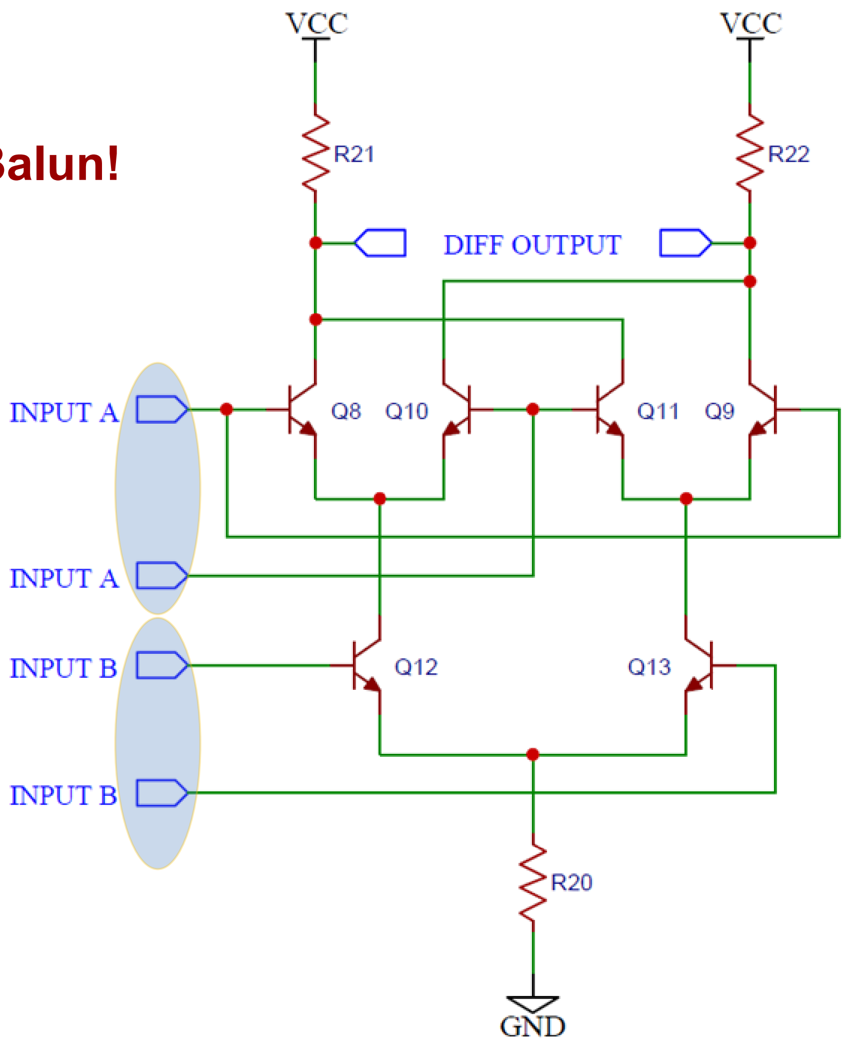


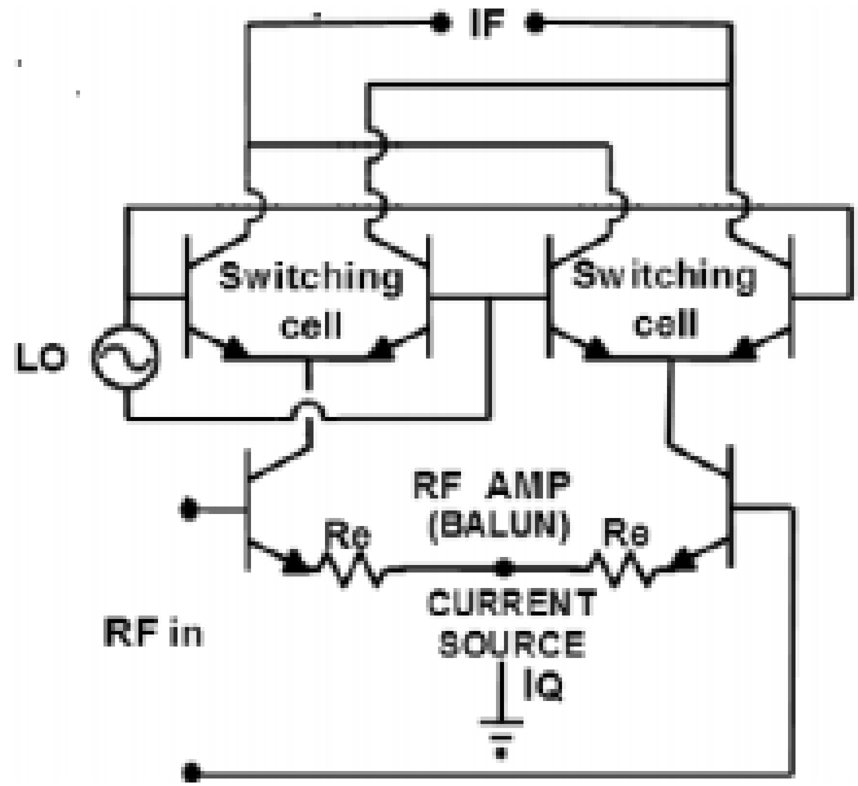
https://circuitdigest.com/electronic-circuits/analog-audio-mixer-additive-and-multiplicative-mixer
http://bwrcs.eecs.berkeley.edu/Classes/icdesign/ee142_f10/Lectures/Lect21_2up.pdf

Double-Balanced transistor mixer

Gilbert-Cell mixer

Balun!



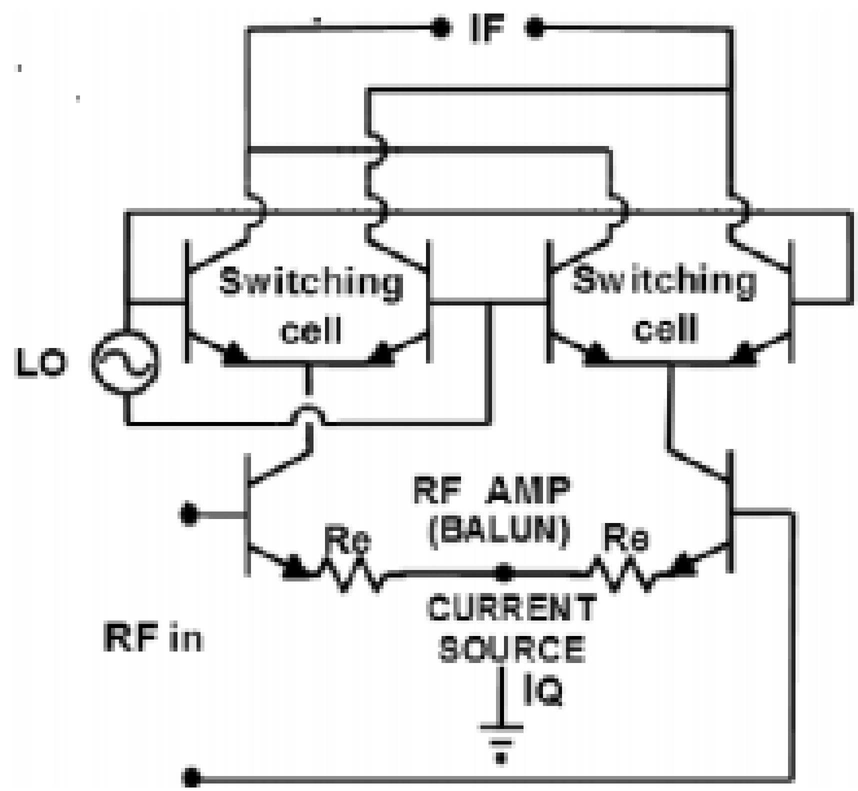


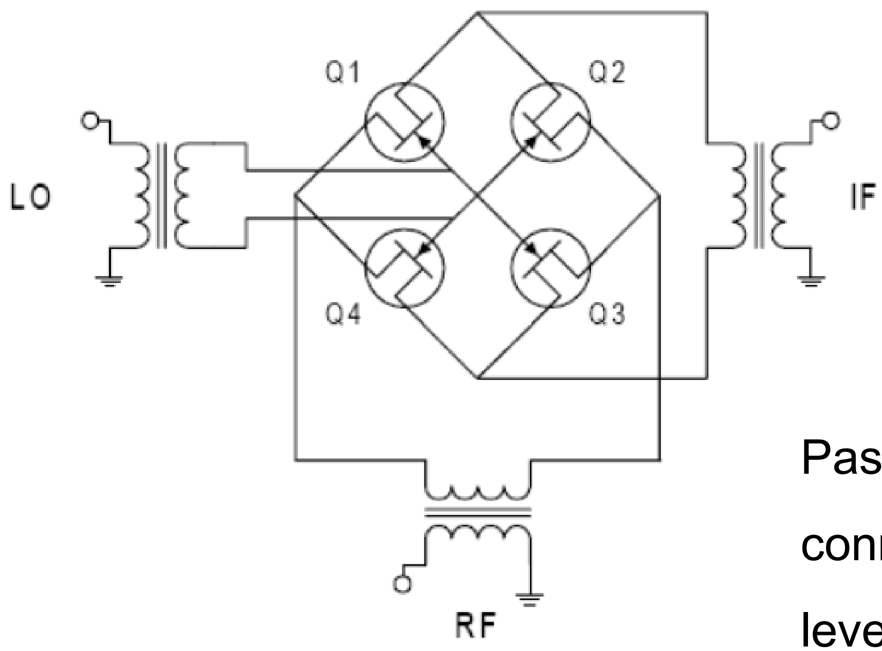
https://www.qsl.net/va3iul/RF%20Mixers/RF_Mixers.pdf
https://circuitdigest.com/electronic-circuits/analog-audio-mixer-additive-and-multiplicative-mixer

Double-Balanced transistor mixer

Gilbert-Cell mixer

Active FET Mixers based on Gilbert Cell architecture with biased semiconductor devices, can work with low LO levels and ofter provide conversion gain, but with decreased linearity compared to passive mixers.



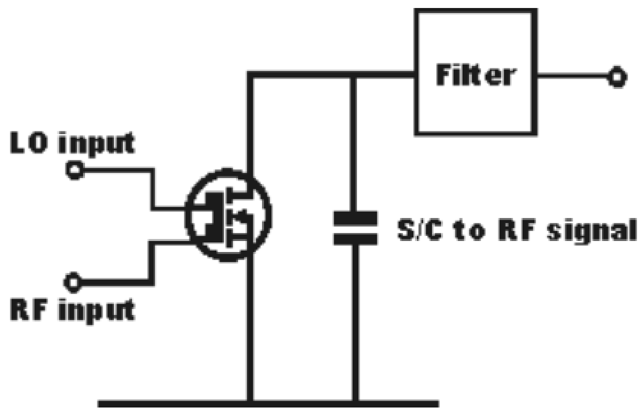


Passive FET Mixers, usually based on FET quads (ring connection), provide good linearity but require high LO levels and exhibit high conversion loss.

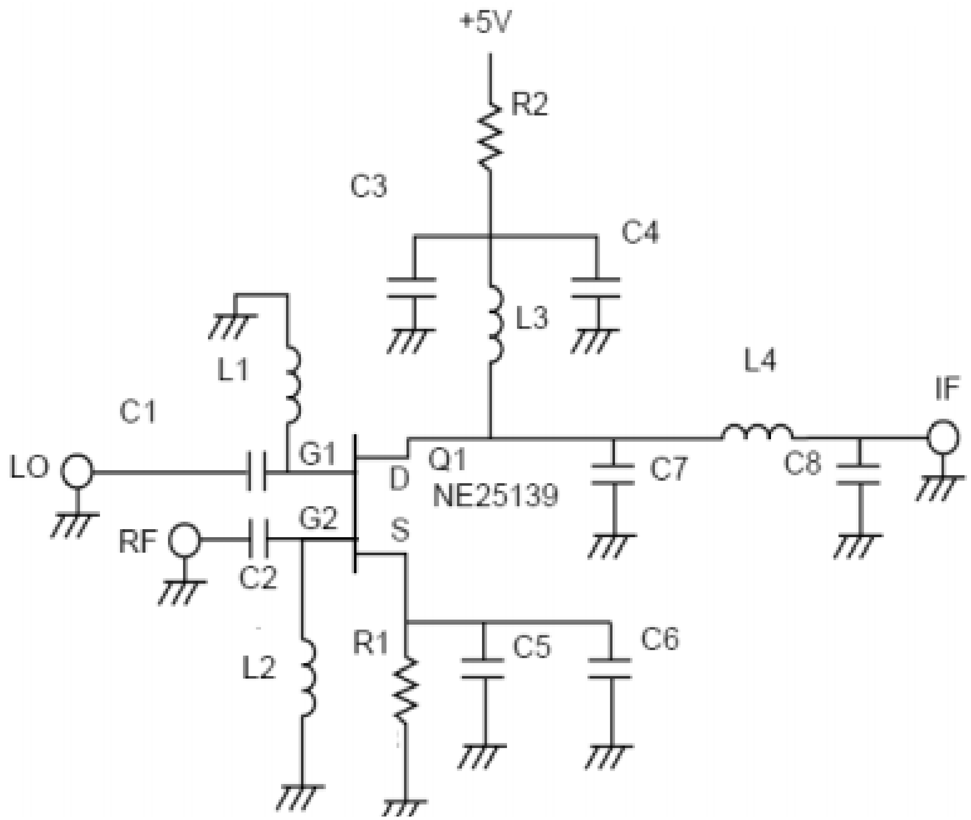
https://www.qsl.net/va3iul/RF%20Mixers/RF_Mixers.pdf

Dual-Gate transistor mixer

- ❖ Stage gain vary with LO amplitude and terminating impedances
- ❖ Simple/inexpensive mixer
- ❖ Good for lower frequency applications
- ❖ Does not require high levels of LO drive
- ❖ Much lower intermodulation distortion



Dual gate FET mixer



No Balun!

Performance comparison of transistor mixers

	Design complexity	Conversion gain	Conversion loss	Noise Figure	LO Rejection	RF Rejection	Spurious rejection	Linearity	LO level	Comments
Single gate FET	+	Yes	No	Lower than passive	No	No	No	Higher than diode	Lower than diode	Need filters
Dual gate FET	+	Yes	No	Lower than passive	No	No	+	Higher than diode	Lower than diode	Good LO to RF isolation without filters Low-cost
Balanced FET mixer	++	Yes	No	Lower than passive	Either LO or RF	Either LO or RF	+	Higher than diode	Lower than diode	Good LO-IF and LO-RF isolation without diplexer
Double balanced FET mixer	4 transistors 2 baluns	Yes	No	Lower than passive	Yes	Yes	++	Higher than diode	Lower than diode	Good
Double double balanced mixer	8 transistors 3 baluns	Yes	No	Lower than passive	Yes	Yes	+++	Higher than diode	Lower than diode	in modulators and signal processing
Image reject	2 mixers 3 hybrids	No	No	Lower than passive				High than diode	High power	

Image-reject mixer

The Image-Reject Mixer is realized as the interconnection of a pair of balanced mixers. It is especially useful for applications where the image and RF bands overlap, or the image is too close to the RF to be rejected by a filter.
The LO ports of the balanced mixers are driven in phase, but the signals applied to the RF ports have 90° phase difference. A 90° IF hybrid is used to separate the RF and image bands.

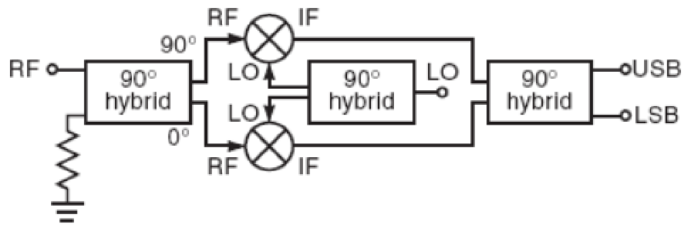


Image-Reject Mixer

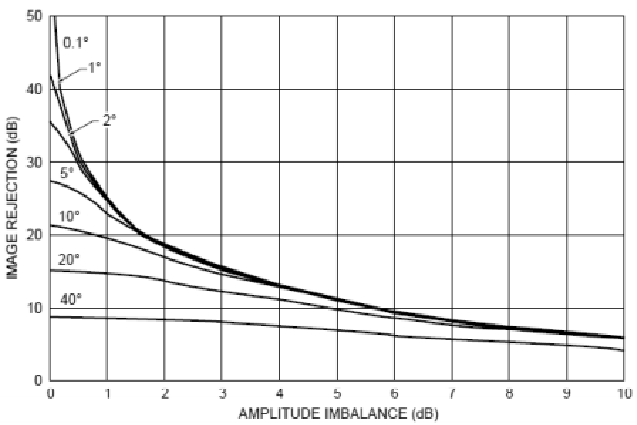


Image-Rejection vs Amplitude Imbalance

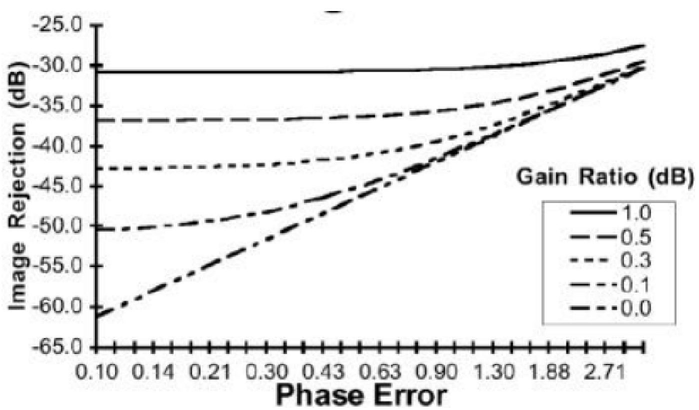
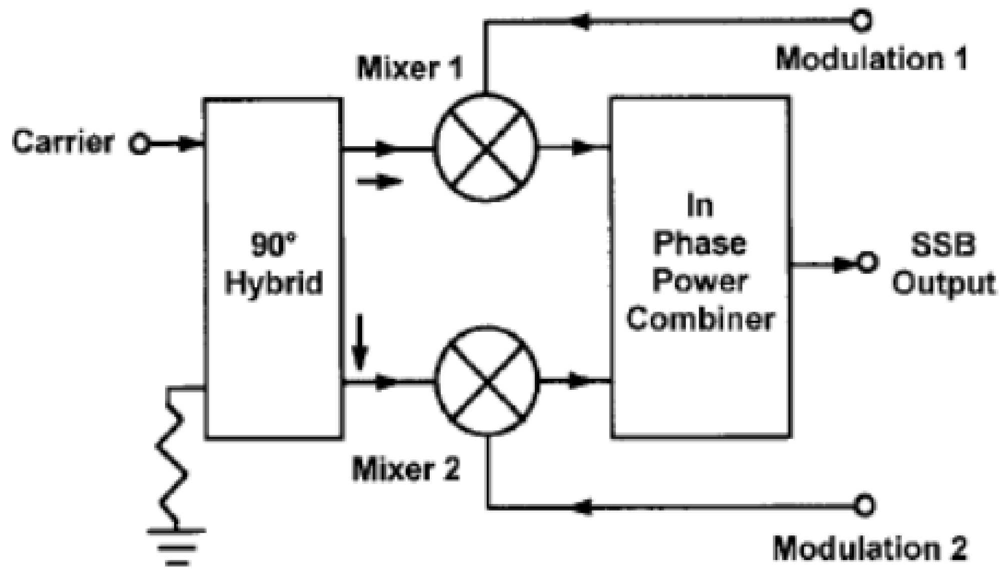


Image-Rejection vs Phase Error

https://www.qsl.net/va3iul/RF%20Mixers/RF_Mixers.pdf

I/Q (In-Phase/Quadrature) Modulators

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



I/Q Modulator

https://www.qsl.net/va3iul/RF%20Mixers/RF_Mixers.pdf

ACTIVE/PASSIVE MIXERS

Active or Passive ?

Passive nonlinear devices or switches

– conversion loss, not gain

– high tolerance to IMD

– external baluns/transformers needed

• Active mixers

– can provide conversion gain

– active baluns/transformers - better for IC implementation

– more difficulty in achieving good IMD performance

Active or Passive ?

Passive mixers are widely used because of their relative simplicity, wide bandwidth, and good IMD performance (baluns generally limit the bandwidth). They introduce some loss into the signal path, which can be of some concern for noise figure.

In this case, an LNA can be introduced ahead of the **passive mixer**, usually with some degradation in IMD performance.

Active mixers are preferred for RFIC implementation. They can be configured to provide conversion gain, and can use differential amplifiers for active baluns.

Because of the need for additional amplifier stages in the RF and IF paths with fully integrated versions, it is often difficult to obtain really high third-order intercepts and 1 dB compression with **active mixers**.

Active or Passive ?

In ***passive mixers***, diodes/transistors are acting as switches and are not active - therefore we have conversion loss, not gain.

Also, if the balancing involves baluns/transformers, then integrating onto an IC is not usually possible.

So, other implementations that provide gain and are more amenable to integration are frequently used in IC front end chips (***active mixers***).

The design objectives are generally the same however:

1. maximize linearity in signal path
2. idealize switching in LO path
3. minimize the noise contribution due to thermal and shot noise

Performance Comparison

Comparison of Various Mixer Types Showing Various Performance Values

Mixer Type	Conversion Loss/Gain (dB)	IP2 (dBm)	IP3 (dBm)	P_{OUT}, −1-dB comp.	NF (dB)
Diode	−7.2	9.5	10.5	0	7.7
Resistive FET	−6.5	23.6	21.5	9.1	6.6
Active FET	+6.0	—	16.0	5.0	5.0

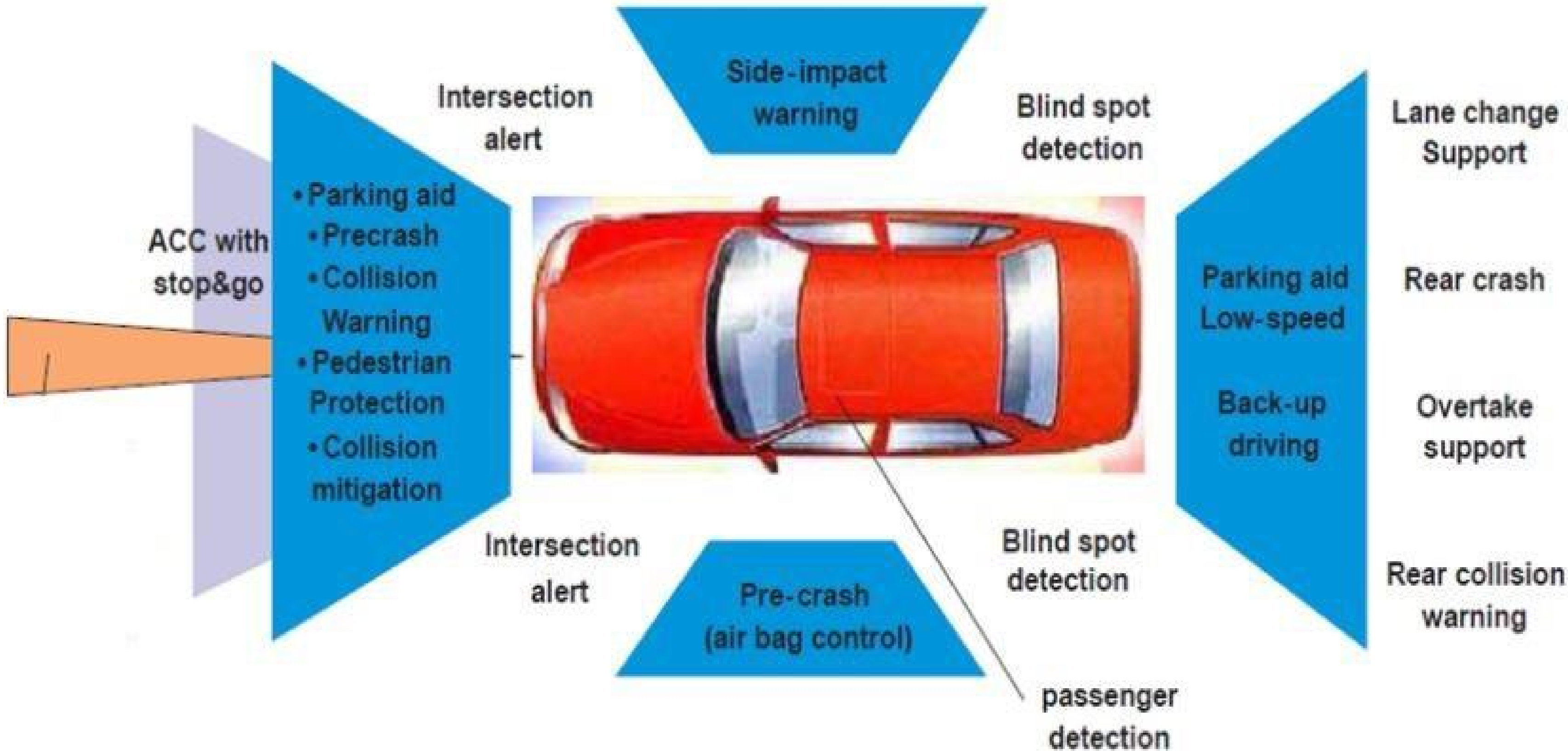
Comparison of the Resistive FET Mixer with a Dual Gate Mixer

Mixer	LO Power (dBm)	Conversion Gain (dB)	IP3 – output (dBm)
Resistive FET	10	< 0	15.3
Dual-gate FET	0	5	13.6

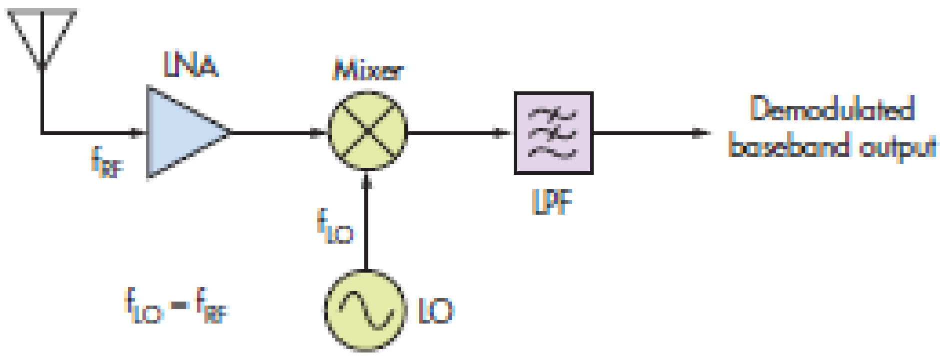
MIXER DESIGN

Mixer for ITS radar sensors operating @ 24 GHz

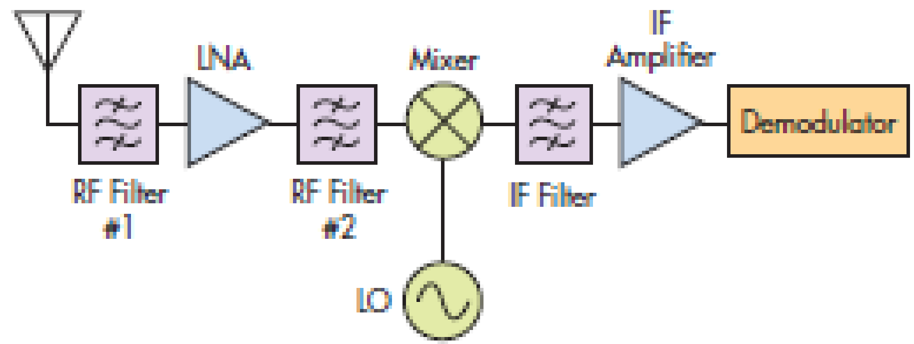
Intelligent Transportation Systems have gained a lot of interest because of their ability to make the transportations systems more safety, greener and more convenient.



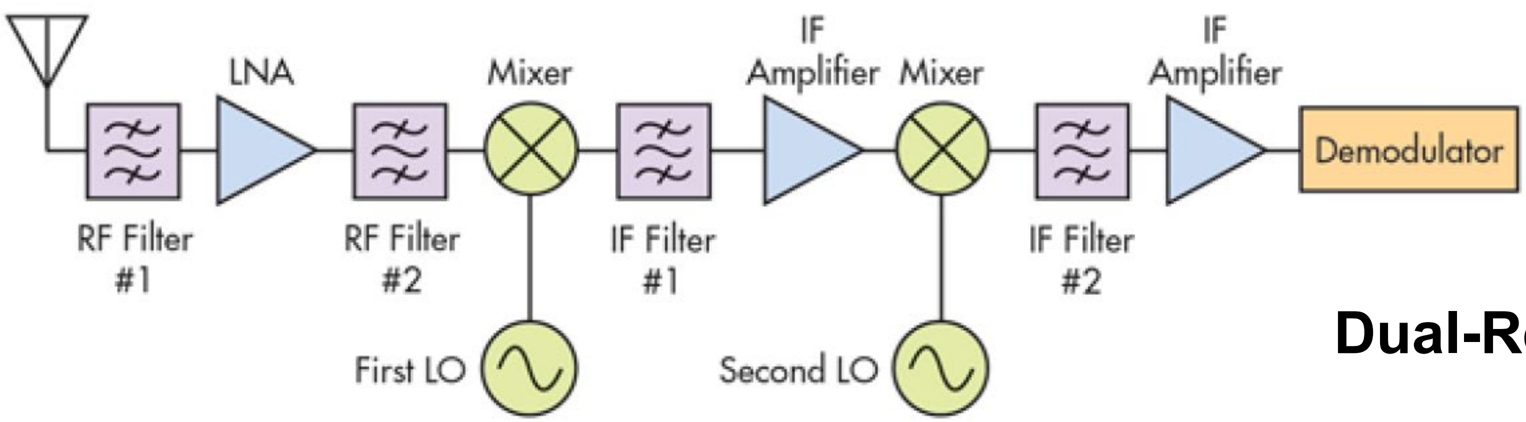
MIXER IN RECEIVERS



1. Direct-conversion receivers translate an RF input signal to a baseband output in one stage.



2. The traditional superheterodyne receiver has been used for many years.



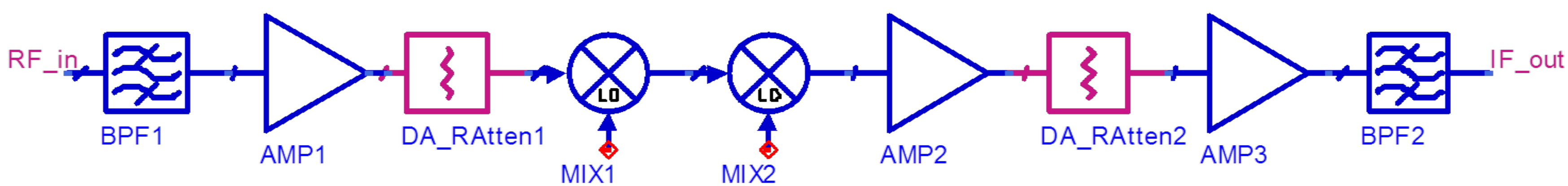
Dual-Receiver

Mixer for ITS radar sensors operating @ 24 GHz

- Radar sensor is one of the most common ITS that integrate between communications and information technology.

- Multi-function radar receiver specs:

  * Input = 24 GHz, compatible with radar sensors
  * First conversion stage = 5.2 GHz compatible with WLAN standards.
  * Second conversion stage = 2.9 GHz for NEXRAD meteorological purposes.



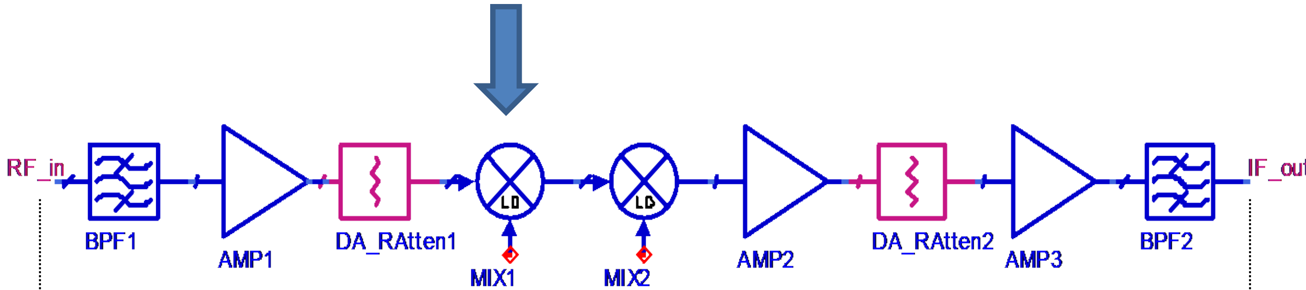
Mixer for ITS radar sensors operating @ 24 GHz

Designing a 24 GHz Gilbert Cell Mixer for ITS System Radar.

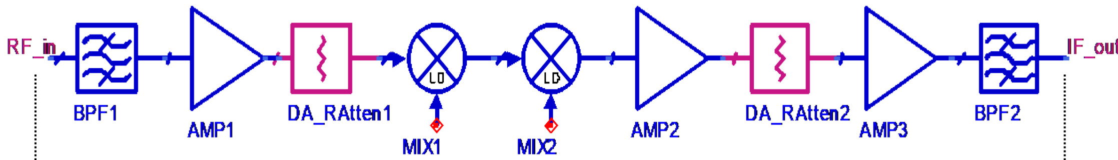
Parameters	Radar Mode
Function Range	100 m
Total Cycle	37.5 ms
Receiver Band width	100 KHz
Transmitting Power	10 dBm
Transmitting Antenna Gain	22 dBi
Path Loss	200.2 dB
Radar Cross Section Gain of Car	49.1 dB
Receiving antenna Gain	22 dBi
Signal power at the receiver input	-97.1 dBm
Noise power at the receiver input	-131.0 dBm
SNR at the receiver input	33.9 dB
Receiver Noise Figure	8 dB
SNR at the receiver output	25.9 dB
Required SNR (E_b/N_o for radio mode)	15 dB
Link Margin	10.9 dB

Mixer for ITS radar sensors operating @ 24 GHz

Link budget !



Gain (dB)	-2.5	25	-3	8.3	-0.4	19	-3	19	-2.5
S_{11} (dB)	-55	-15	-100	-10	-10	-9	-100	-9	-34.5
S_{22} (dB)	-55	-15	-100	-10	-10	-9	-100	-9	-34.5
Out_P1dB (dBm)	100	13.1	100	-18.7	-19.1	14.7	100	14.7	100
Out_TOI (dBm)	100	25	100	-1.8	-2.2	36	100	36	100
NF(dB)	2.5	2.1	3	10.5	0.4	3.9	3	3.9	2.5



Gain (dB)	-2.5	25	-3	8.3	-0.4	19	-3	19	-2.5
S_{11} (dB)	-55	-15	-100	-10	-10	-9	-100	-9	-34.5
S_{22} (dB)	-55	-15	-100	-10	-10	-9	-100	-9	-34.5
Out_P1dB (dBm)	100(1)	13.1	100	-18.7	-19.1	14.7	100	14.7	100
Out_TOI (dBm)	100	25	100	-1.8	-2.2	36	100	36	100
NF(dB)	2.5	2.1	3	10.5	0.4	3.9	3	3.9	2.5

Mixer MIX1

Parameters	Values
RF Frequency	24 GHz
LO Frequency	18.8 GHz
IF frequency	5.2 GHz
Minimum Conversion Gain	8.3 dB
Maximum NF (dB)	10.5 dB
Minimum P1dB (dBm)	-18 dBm
Minimum IIP3	-8 dBm
Minimum leakage	> 20 dB
Maximum Current (mA)	As low as possible
Maximum Power consumption (mW)	As low as possible
Minimum S_{11}/S_{22}	< -10 dB

Mixer selection

i) passive Mixers ii) active mixers ?

Passive mixers:

i) shows loss instead of gain
ii) higher LO power consumption
iii) less Isolation.

but at the same time

i) higher B.W.
ii) No dc power consumption.

Mixer selection

Active Mixer :

i) shows gain instead of loss
ii) less LO power consumption.

Could be divided to

i) single balanced
ii) double balanced.

Double balanced mixers have

i) higher gain,
ii) higher isolation,
iii) higher linearity,
iv) better noise performance.

So double balanced mixer (Gilbert Cell) is the suitable choice.

Parameters	Values
RF Frequency	24 GHz
LO Frequency	18.8 GHz
IF Frequency	5.2 GHz
Minimum Gain	8.3 dB
Maximum NF	10.5 dB
Minimum P1dB	-18 dBm
Minimum IIP3	-8 dBm
Minim. Leakage	20 dB
Minim.S_{11} , S_{22}	10 dB

Used Technology

Technology	RF noise	1/f noise	Power	Linearity	Cost
IP	Very good	Poor	Fair	Good	High
GaAs PHEMT	Very good	Poor	High	Good	High
GaAs HBT	Good	Good	Fair	Very good	High
SiGe	Good	Good	Low	Good	Medium
BiCMOS	Fair	Good	Low	Fair	Low
CMOS	Fair	Poor	High	Good	Low
SOI/SOS	Fair	Poor	Fair	Good	Low

0.15 µm GaAs PHEMT Technology

Low noise Technology

High f_t in the switching stage, to keep high mixing efficiency that leads to higher gain and lower noise.

High g_m

24 GHz Gilbert Design

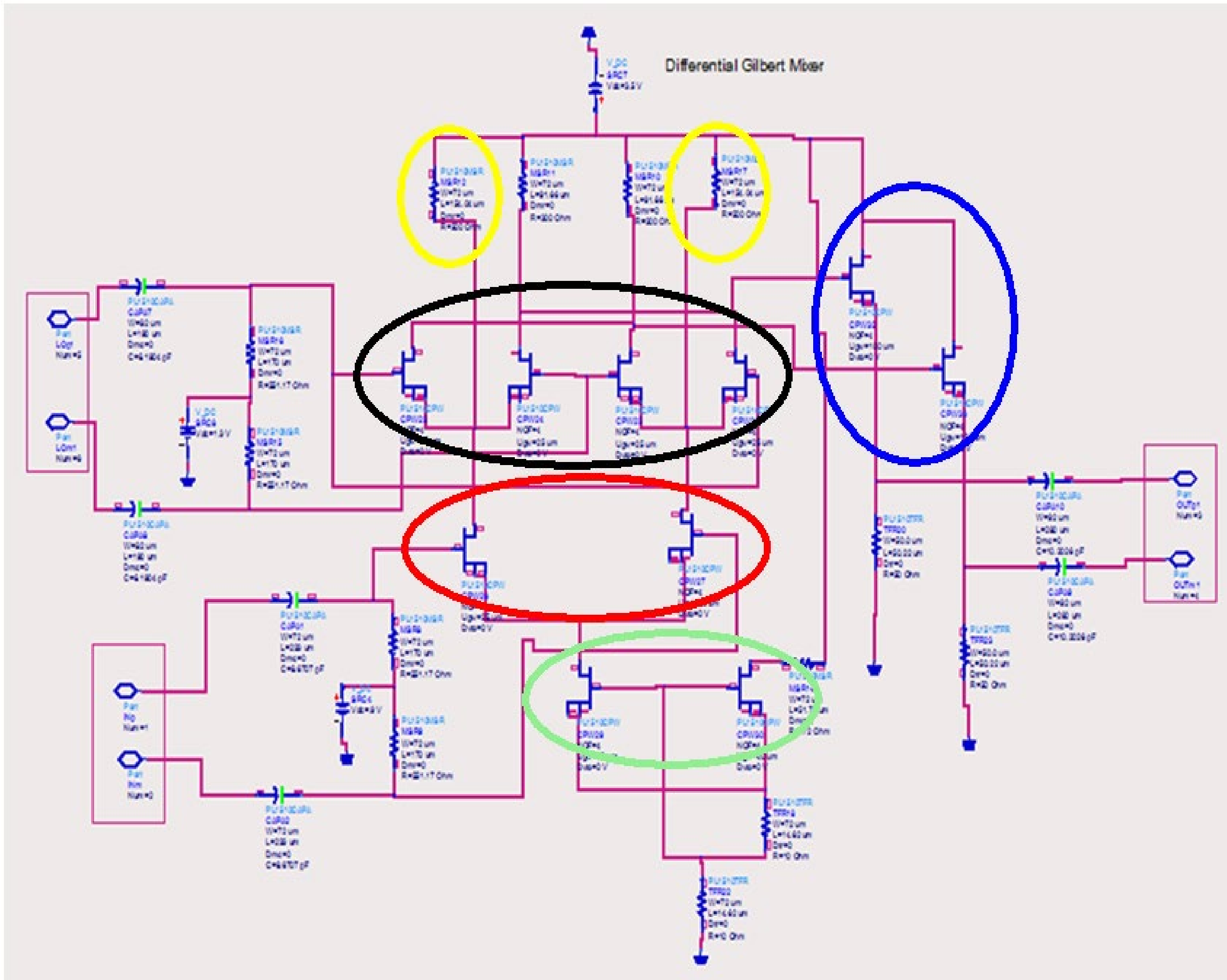
Current bleeding technique

Switching stage

Buffer stage

Transconductance stage

Current mirror



Mixer design

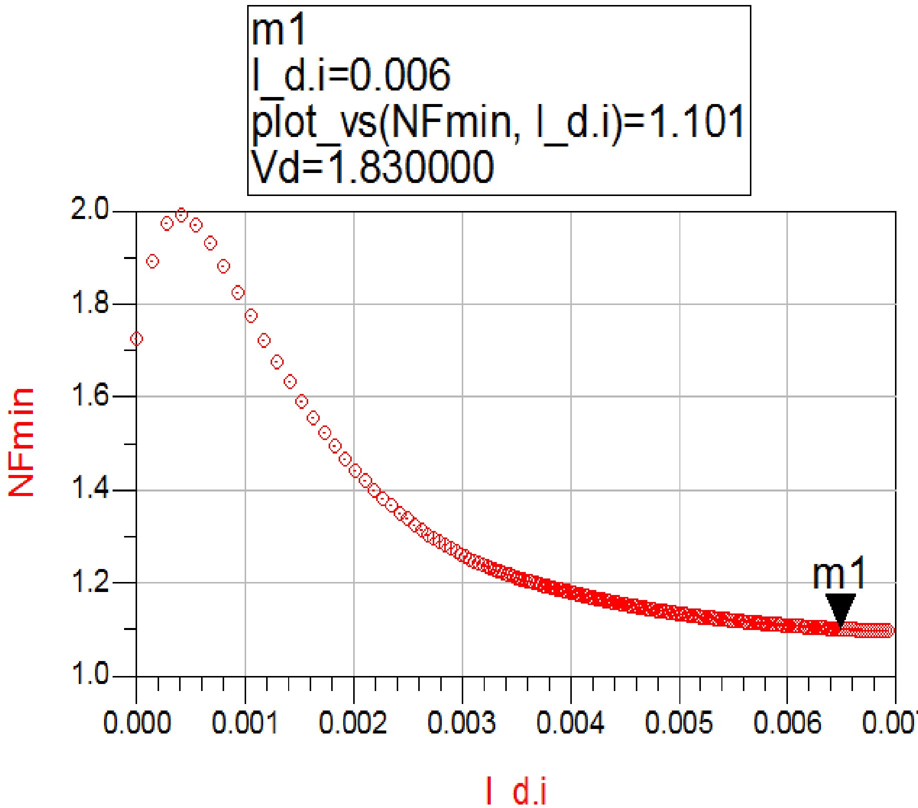
Transconductance stage should be biased in saturation region,

Switching stage should be biased beside the pinch off region,

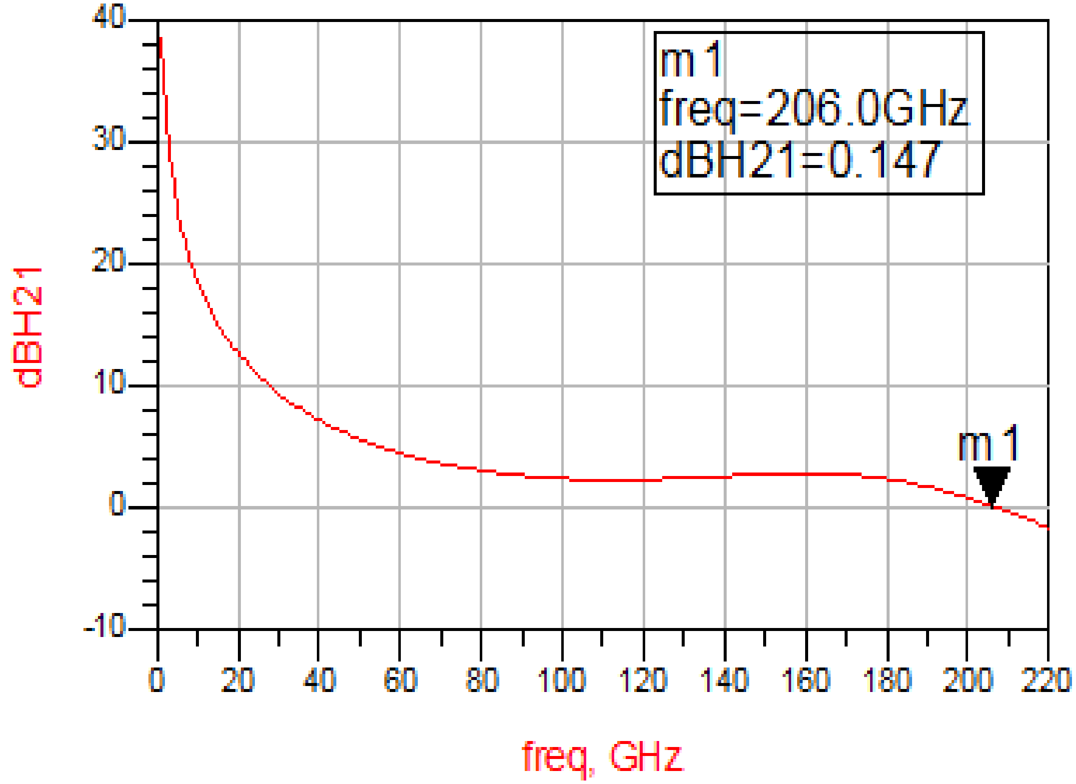
Sizing the transconductance stage so that the current passing through ensure minimum noise figure,

Sizing the switching stage so that the current ensure high ft.

Mixer design: biasing and sizing

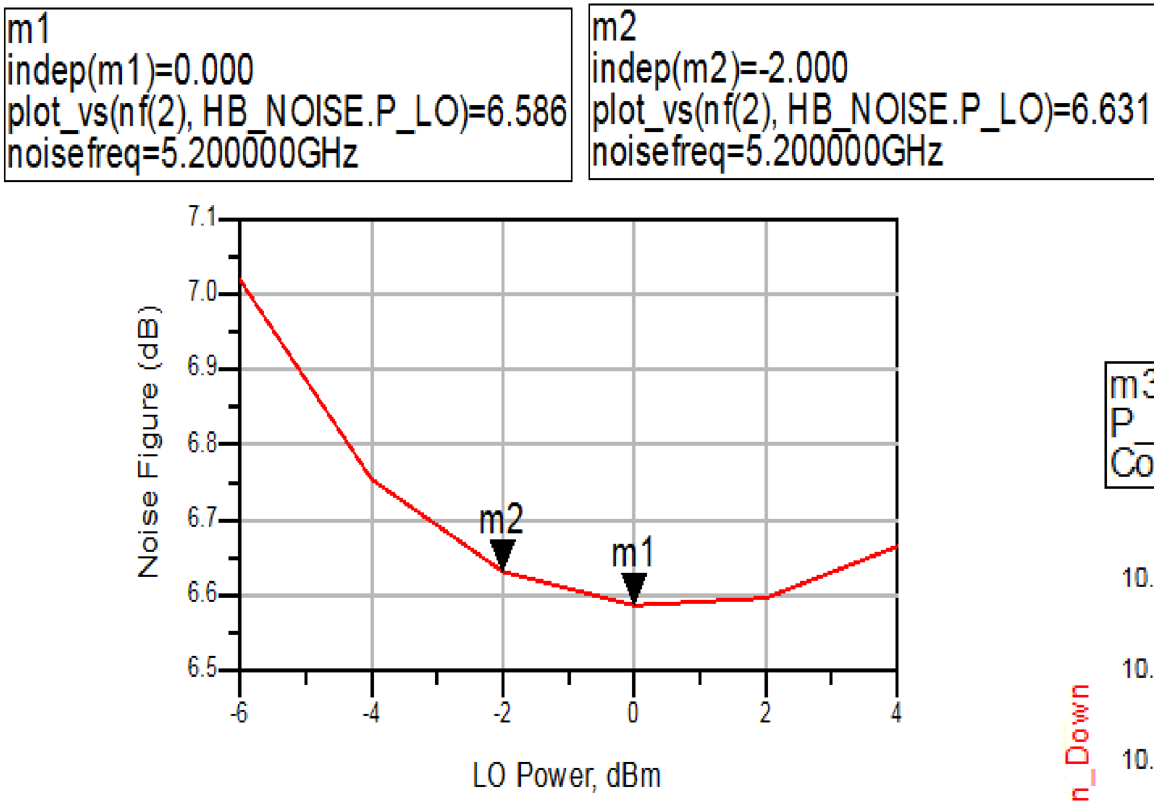


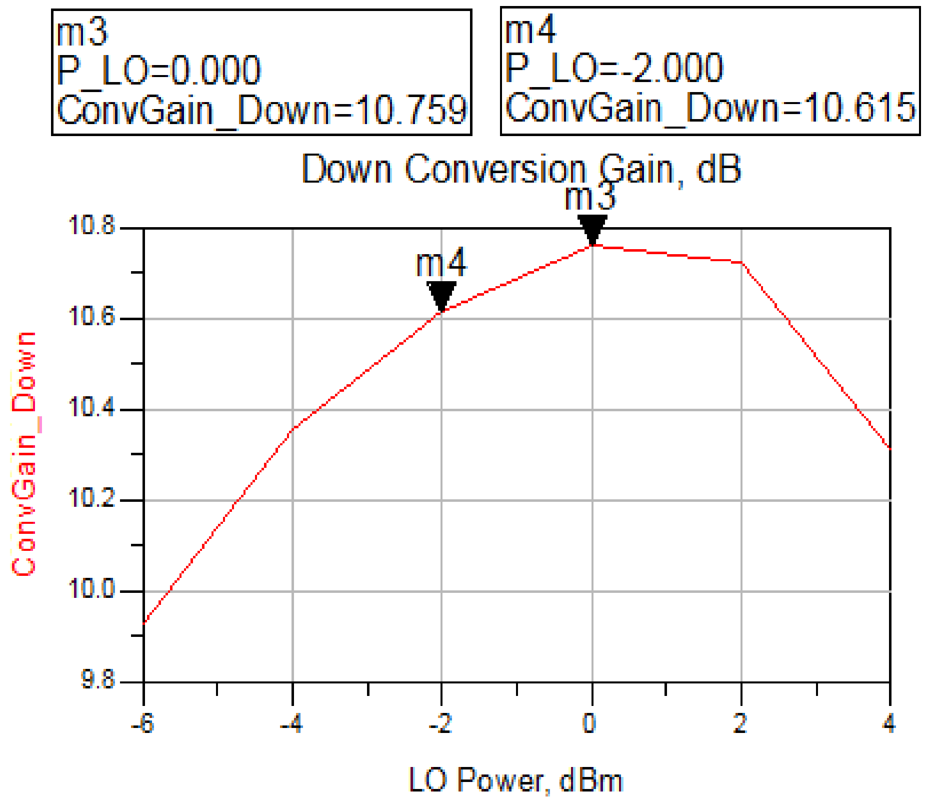
Sizing for switching stage: ft



Schematic Results

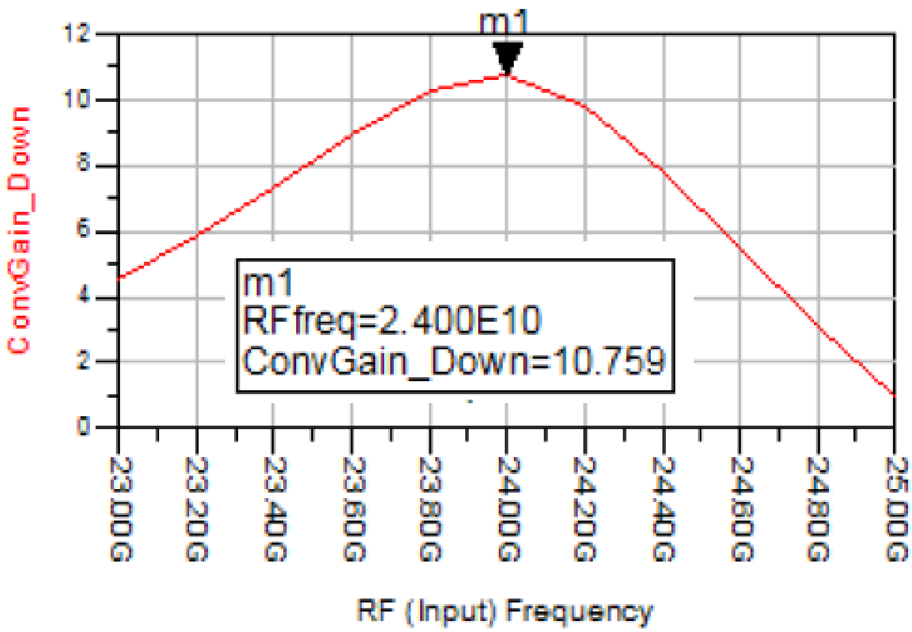
LO Power Sweeping (optimum value for both Noise and Conversion Gain).

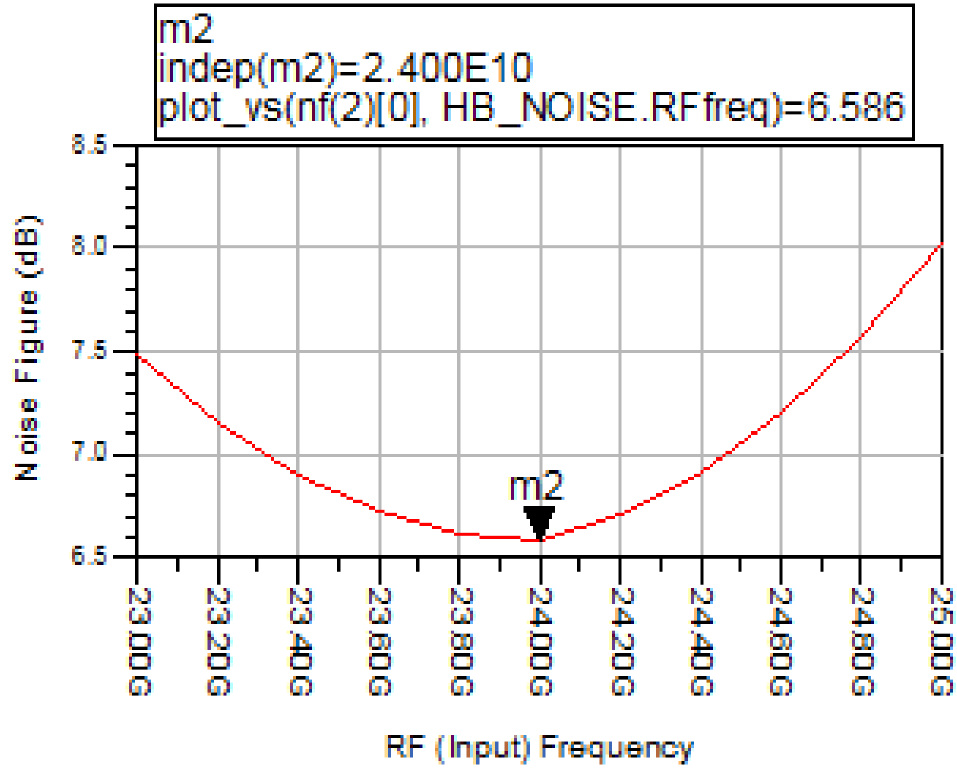




Schematic Results

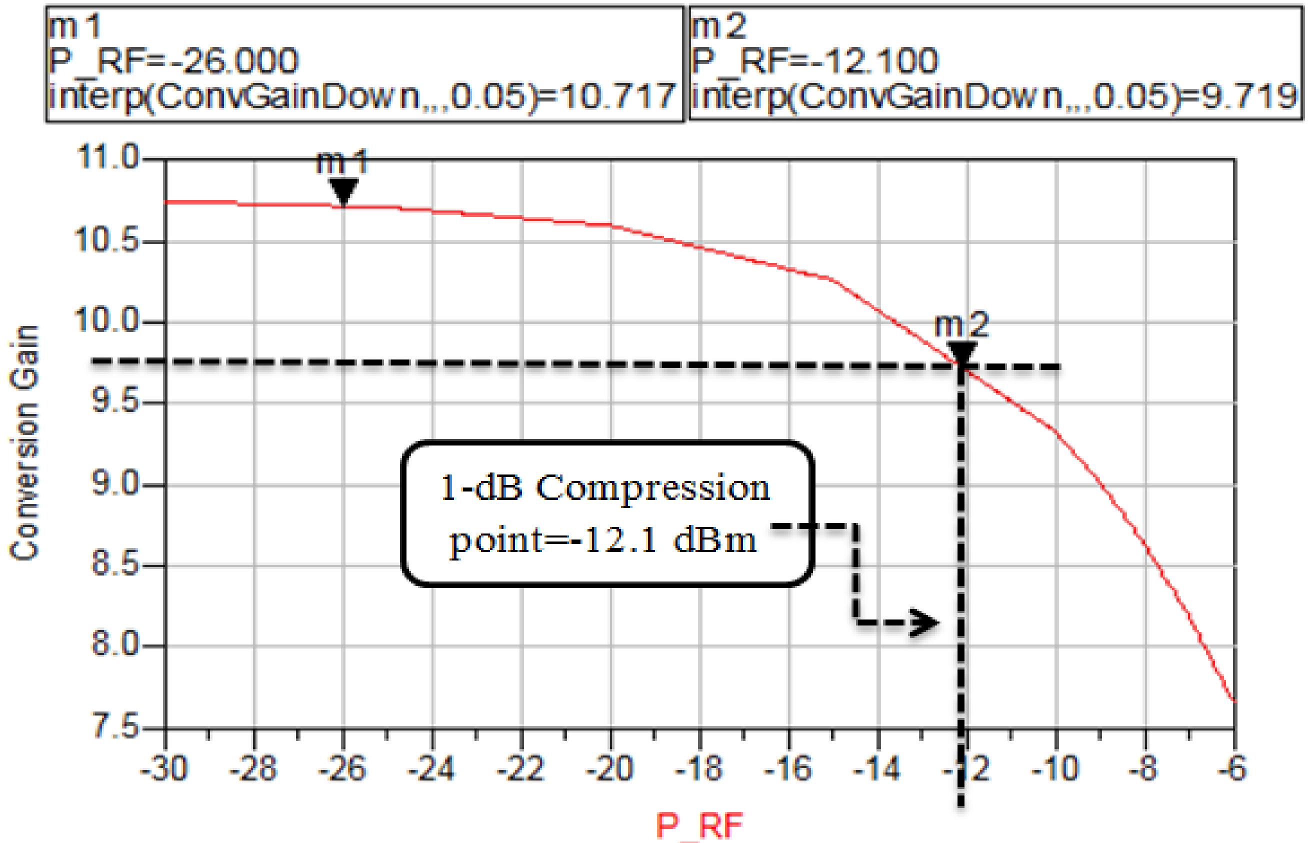
Frequency Sweeping (optimum value for both Noise and Conversion Gain).





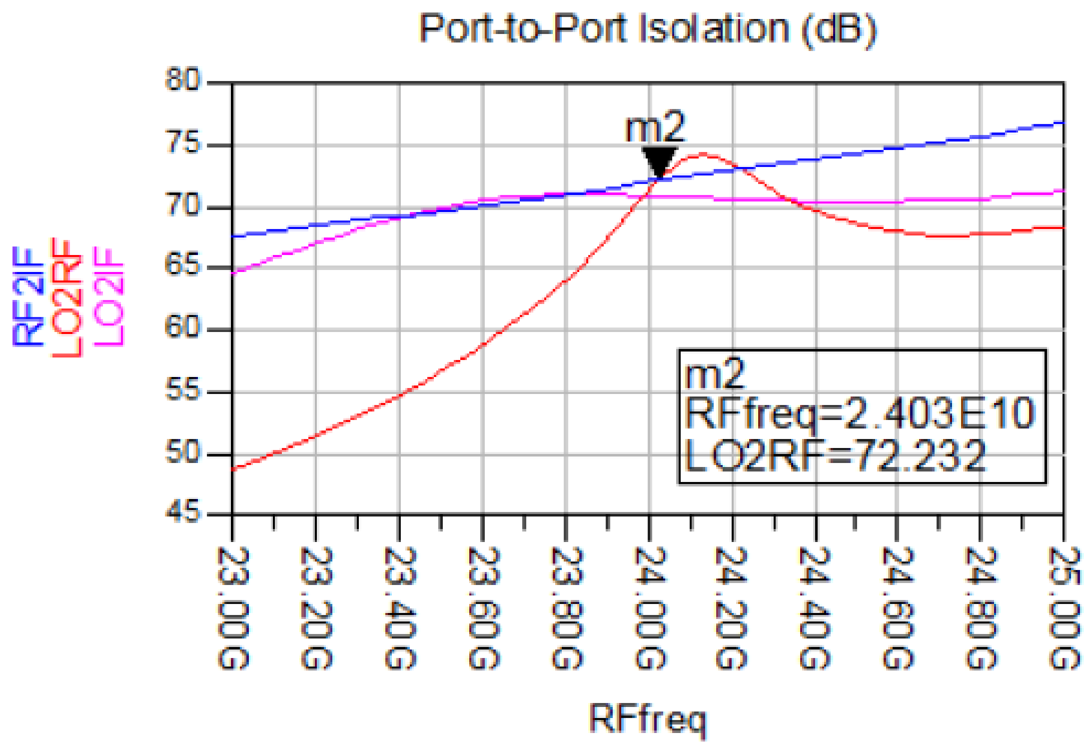
Schematic Results

Linearity (1-dB Compression point).

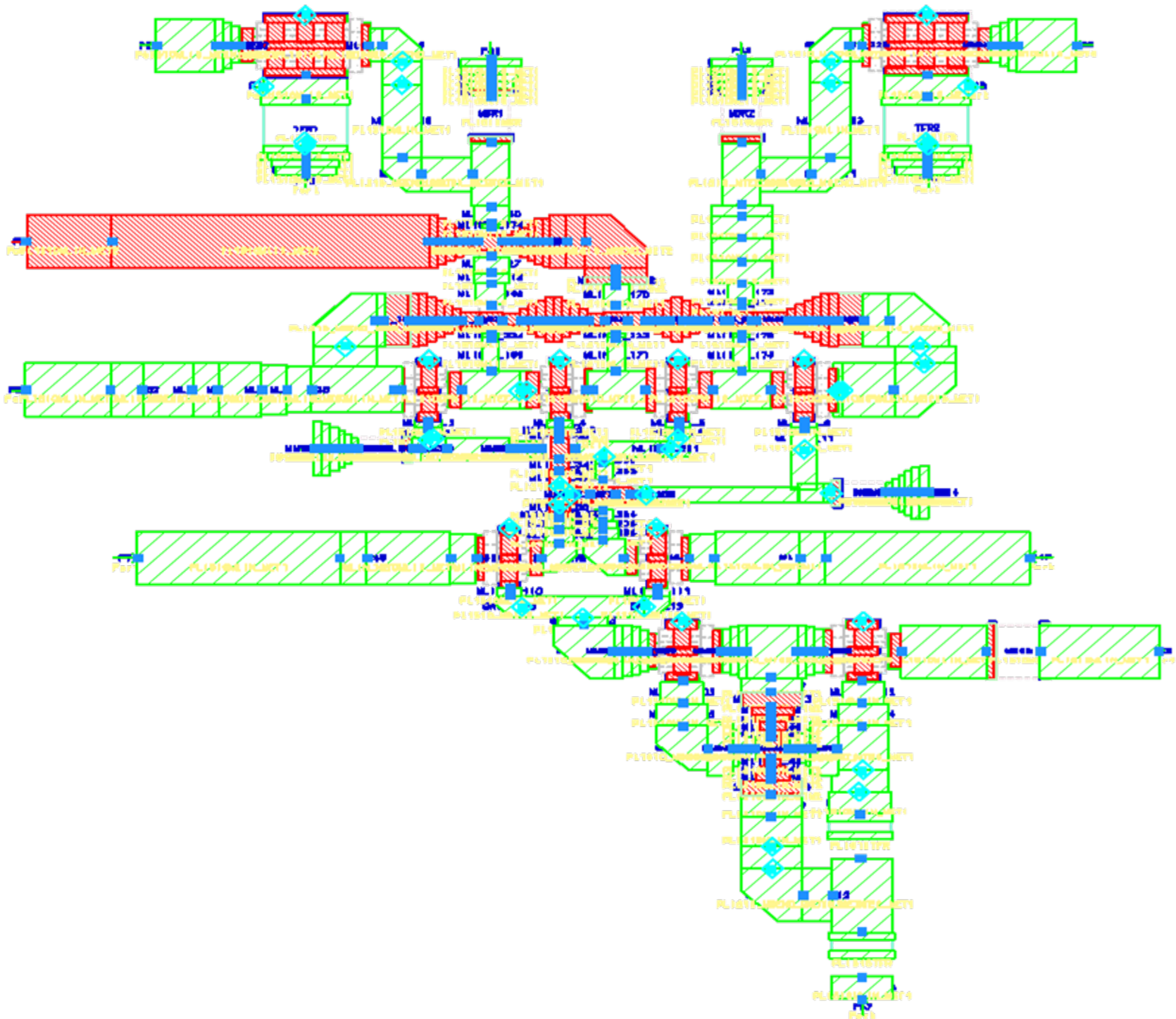


Schematic Results

Isolation (over RF frequency)

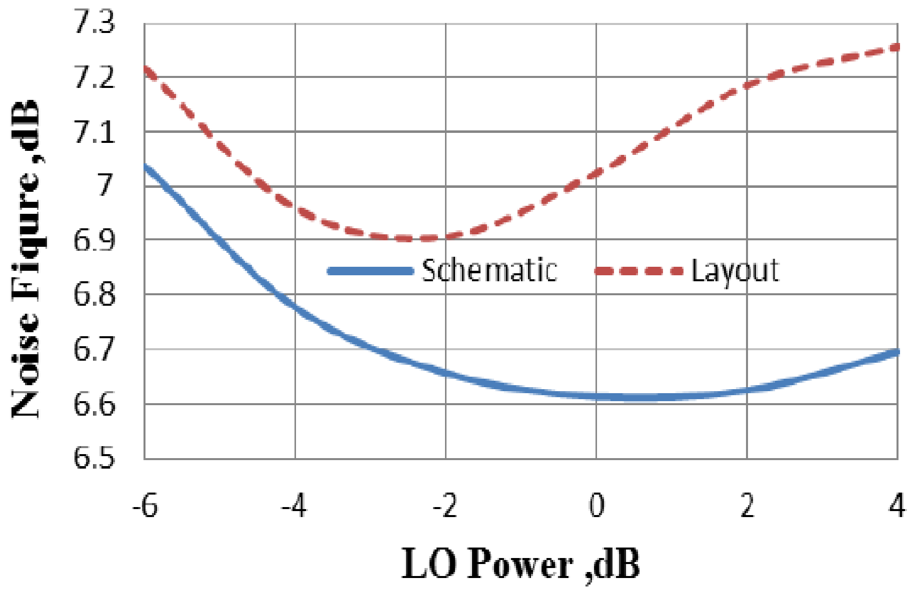


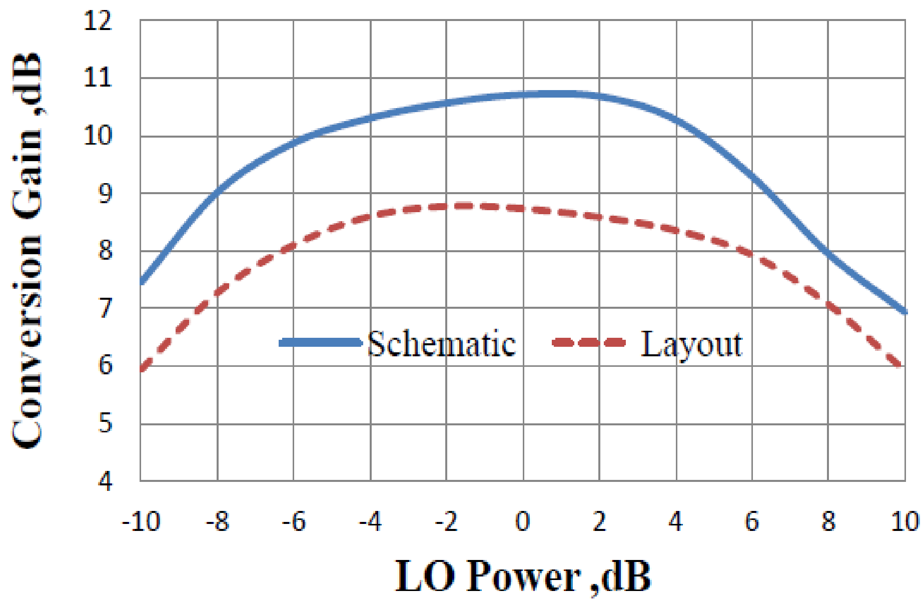
Layout



Comparison between Layout/Schematic Results

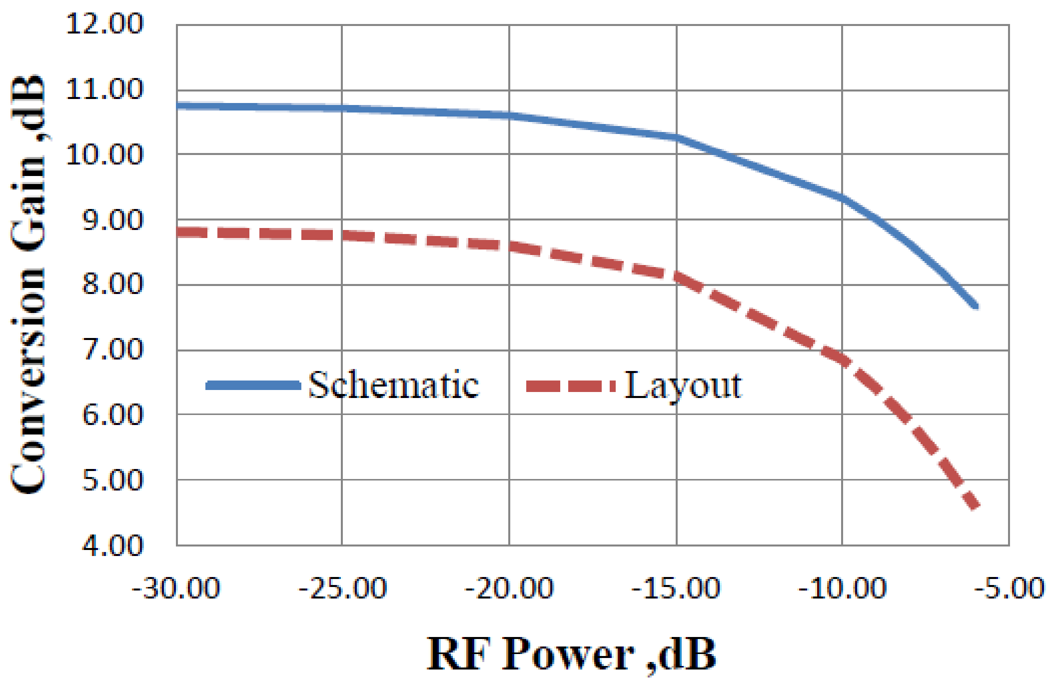
LO Power Sweeping (Noise and conversion gain).





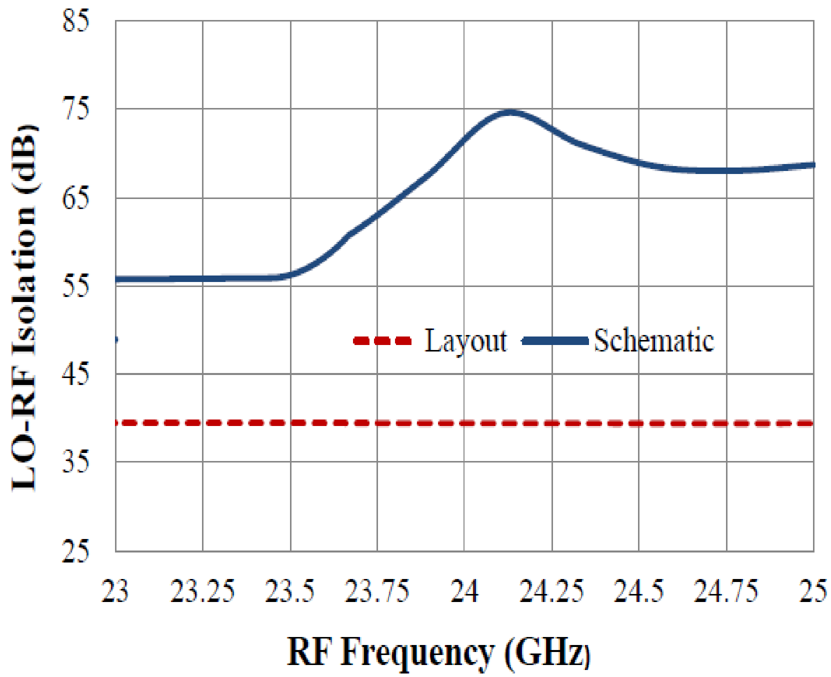
Comparison between Layout/Schematic Results

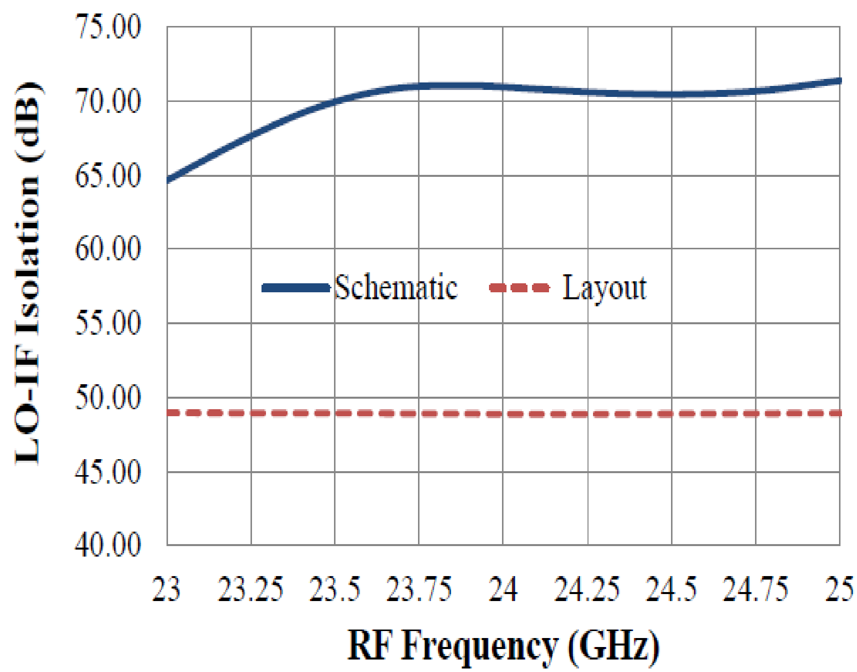
Linearity (1dB compression point)



Comparison between Layout/Schematic Results

Isolation





Comparison between Layout/Schematic Results

Summary

Parameter	Specs	Schematic	Co-simulation
Conversion Gain (dB)	> 8.3	10.71	8.77
SSB Noise Figure (dB)	< 10.5	6.58	6.9
P1-dB (dBm)	> -18	-12.1	-13.55
RF-IF Isolation (dB)	> 20	72	36
LO-RF Isolation (dB)	> 20	72	39
LO-IF Isolation (dB)	> 20	72	48
LO power (dB)	N/A	0	-2
S_{11} (dB)	< -10	-24.6	-28.2
S_{22} (dB)	< -10	-35.4	-44.2
Pdc (mW)	Low	46.9	46.9

Thank you !

End of Chapter 7