# RADIO COMMUNICATION CIRCUITS

Chapter 5

## RF Mixers


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## Introduction

### Outline





## 1. Introduction

### ❑ What is a Mixer:

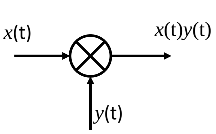
- Frequency translation device
  - Convert RF frequency to a lower IF or base band for easy signal processing in receivers
  - Convert base band signal or IF frequency to a higher IF or RF frequency for efficient transmission in transmitters
- Creative use of nonlinearity or time-variance
  - These are usually harmful and unwanted
  - They generates frequencies not present at input
- Used together with appropriate filtering
  - Remove unwanted frequencies



## 1. Introduction

### ❑ An Ideal Mixer :

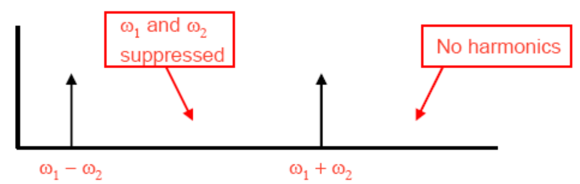
If
$$x(t) = A\cos\omega_1 t$$
$$y(t) = B\cos\omega_2 t$$




Then the output is

$$A\cos\omega_1 t \cdot B\cos\omega_2 t = \frac{AB}{2}\cos(\omega_1-\omega_2)t + \frac{AB}{2}\cos(\omega_1+\omega_2)t$$

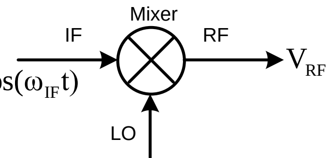
down convert　　　up convert






## 1. Introduction

$$V_{IF} = A_{IF}\cos(\omega_{IF} t)$$




$$V_{RF}$$

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

$$V_{RF} = \frac{A_{IF}A_{LO}}{2}\left(\cos(\omega_{IF}+\omega_{LO}) + \cos(\omega_{IF}-\omega_{LO})\right)$$

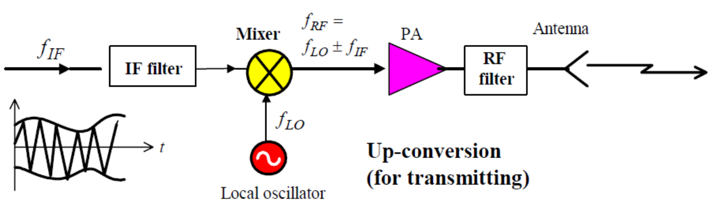
High sideband　　　Low sideband



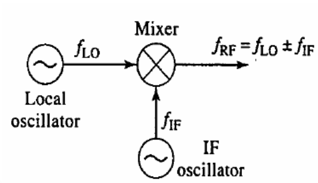
## 1. Introduction - Up-Conversion Mixer

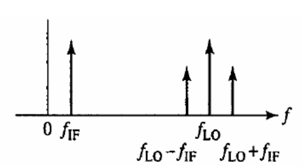
❍ Mixer in a Transmitter (Up-conversion Mixer)

- In a transmitter, a mixer is used to **mix with IF signal** to **up-convert** the signal frequency for **efficient radio-wave transmission from antenna**.



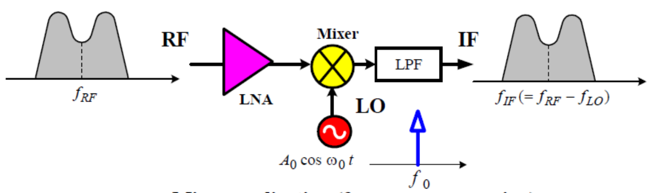

**Up-conversion (for transmitting)**



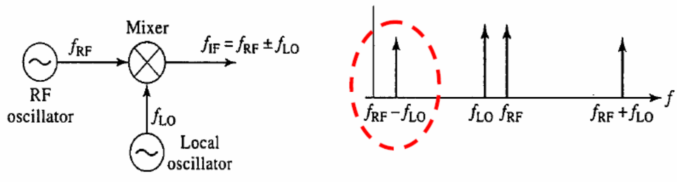



# 1. Introduction - Down-Conversion Mixer

- Mixer in a Receiver (Down-conversion Mixer)




Mixer application (frequency conversion)

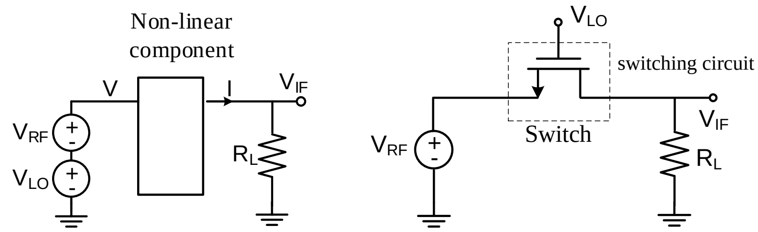





# 1. Introduction

**Mixers can be implemented using:**

- ✓ Nonlinear circuits
- ✓ Switching circuits.




$$I = a_0 + a_1 V + a_2 V^2 + a_3 V^3 + \cdots$$

$$S(t) = \frac{4}{\pi}\text{Cos}(\omega_{LO} t) - \frac{4}{3\pi}\text{Cos}(3\omega_{LO} t) + \frac{4}{5\pi}\text{Cos}(5\omega_{LO} t) \ . \ . \ .$$



# 2. Mixer Performance Parameters

- ❑ **Noise Figure** – impacts receiver sensitivity
- ❑ **Linearity (IIP3)** – impacts receiver blocking performance
- ❑ **Conversion gain** – lowers noise impact of following stages
- ❑ **Power match** – want maximize voltage gain rather than power match for integrated designs
- ❑ **Power** – want low power dissipation
- ❑ **Isolation** – want to minimize interaction between the RF, IF, and LO ports
- ❑ **Sensitivity** to process/temp variations – need to make it manufacturable in high volume



# 2. Mixer Performance Parameters

## Conversion Gain

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

$$Av = \frac{\text{IF voltage}}{\text{RF voltage}}$$

$$A_p = \frac{\text{IF power delivered to the load}}{\text{RF available power from the source}}$$

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.



# 2. Mixer Performance Parameters

## Port-to-Port Isolations

Signals may leak through different paths from one port to the other.

•LO-to-RF leakage

causes self-mixing (problem for zero-IF)

•RF-to-LO feedthrough

allows interferers and spurs present in the RF signal to interact with the LO.

• LO-to-IF feedthrough

may cause desensitization of consequent blocks

• RF-to-IF feedthrough

causes problems in some architectures such as zero-IF because of the leakage of low-frequency even-order intermod. products (even-order distortion).



# 3. Mixer Classification

- ➢ Mixers may be classified according to whether they are based on active or passive devices.
- ➢ Another distinction, that can apply to either passive or active mixers, is whether mixing occurs as a result of a soft nonlinearity such as the current-voltage relationship in a diode or transistor, or whether mixing results from a hard nonlinearity such as from a switch.
- ➢ Most mixers in use today are of the switching type, whereby diodes or transistors are used to switch the connection between the RF input and the IF output at a rate that is controlled by the local oscillator.

- ❑ **Non-linearity/Switching**
- ❑ **Active Mixers / Passive Mixers**
- ❑ **Diode/Transistor Mixers**
- ❑ **Single balance/ Double Balance**

## 2. Mixers Based on Gradual Nonlinearities

### Single-ended BJT/MOSFET Mixer

- The single-ended BJT mixer makes use of the nonlinear relationship between the base-emitter voltage and the collector current.
- If the RF and LO voltages are applied to the base of the BJT so that the base-emitter voltage vi(t) has both RF and LO signal components then the collector current will contain terms that are proportional to all powers of the total input voltage:

$$i_C = i_{DC} + k_1\, v_i(t) + k_2\, v_i^2(t) + k_3\, v_i^3(t) + \dots$$

- In general, this produces all possible mixing products, including:

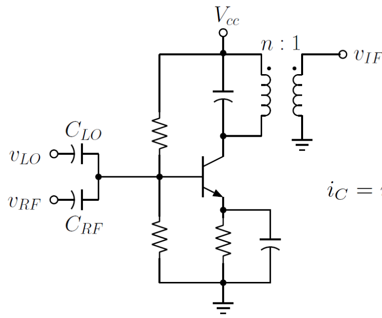
$$f_{RF},\ f_{LO},\ |f_{RF} \pm f_{LO}|,\ |2f_{RF} \pm f_{LO}|,\ |2f_{LO} \pm f_{RF}|, \dots$$

MOSFET Mixer (with impedance matching)

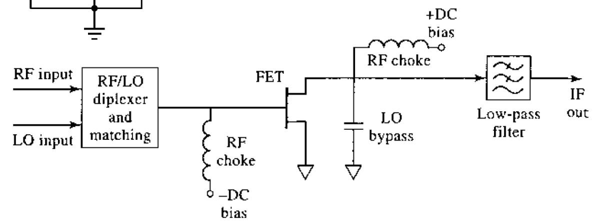


## 2. Mixers Based on Gradual Nonlinearities

### Single-ended BJT/MOSFET Mixer

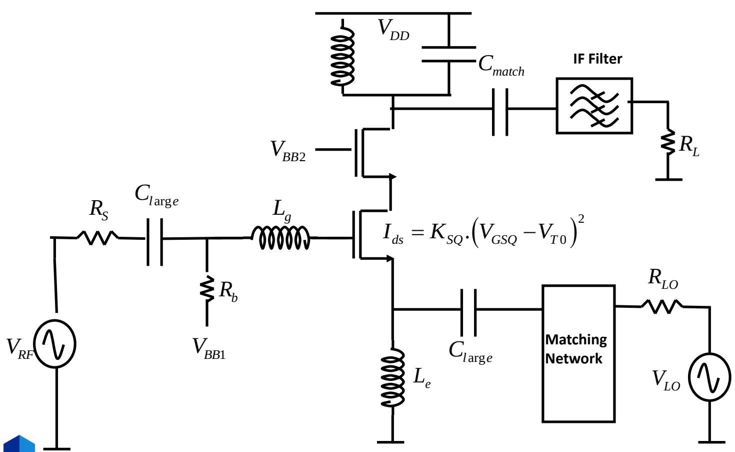



$$i_C = i_{DC} + k_1\, v_i(t) + k_2\, v_i^2(t) + k_3\, v_i^3(t) + \dots$$






## 2. Mixers Based on Gradual Nonlinearities

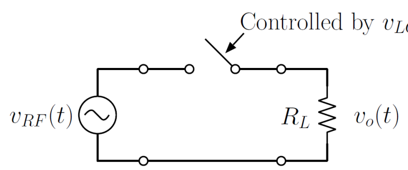



MOSFET Mixer (with impedance matching)



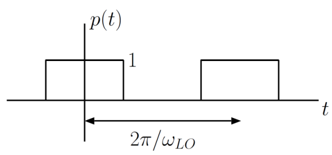
## 3. Mixers Based on Switches

- Most mixers used today are based on switches.
- The basic idea can be illustrated using a very simple circuit as




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

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



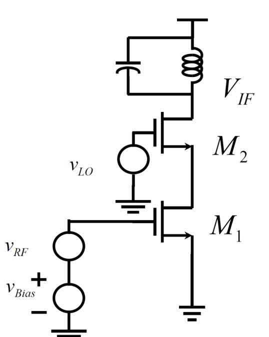

$$p(t) = \frac{1}{2} + \sum_{n=1}^{\infty} \frac{\sin n\pi/2}{n\pi/2} \cos n\omega_{LO}t$$

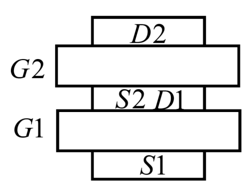
- What is the output IF signal ?



## 3. Mixers Based on Switches

### Implementation of Dual-Gate Mixer

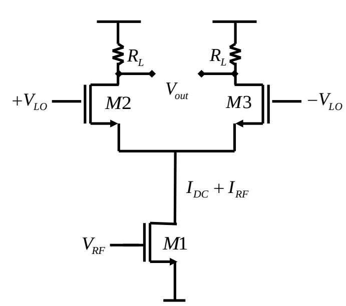


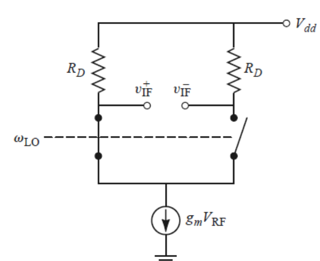






## 3. Mixers Based on Switches

### Single-Balanced Active Mixer



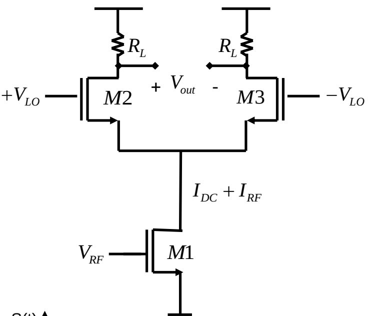

- The transistor M1 converts the RF voltage signal to the current signal.

$$I_1 = I_{DC} + I_{1,RF} = I_{DC} + g_m.V_{RF}$$

- Transistors M2 and M3 commute the current between the two branches.

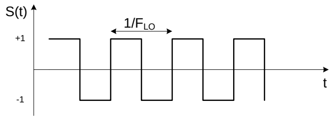
## 3. Mixers Based on Switches

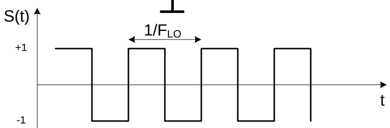
### Single-Balanced Active Mixer




$$V_{IF} = -R_L(I_{DC} + g_m V_{RF}) \quad , V_{LO} > 0$$

$$V_{IF} = R_L(I_{DC} + g_m V_{RF}) \quad , V_{LO} < 0$$



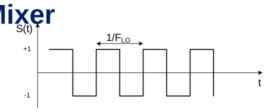

- **The IF output signal is then expressed as**

$$V_{IF}(t) = -R_L(I_{DC} + g_m V_{RF})S(t)$$



## 3. Mixers Based on Switches

### Single-Balanced Active Mixer




In form of Fourier series, S(t) is expressed as

$$S(t) = \frac{4}{\pi}Cos(\omega_{LO}t) - \frac{4}{3\pi}Cos(3\omega_{LO}t) + \frac{4}{5\pi}Cos(5\omega_{LO}t) \ . \ . \ .$$

Then, $V_{IF}(t)$ is expressed as

$$V_{IF}(t) = -R_L(I_{DC} + g_m V_{RF})\left(\frac{4}{\pi}Cos(\omega_{LO}t) - \frac{4}{3\pi}Cos(3\omega_{LO}t) + \frac{4}{5\pi}Cos(5\omega_{LO}t) \ . \ . \ .\right)$$

With the first harmonic LO mixing, the fundamental component of S(t) is considered.

$$V_{IF}(t) = -R_L\frac{4}{\pi}\left(I_{DC} + g_m A_{RF}Cos(\omega_{RF}t)\right)Cos(\omega_{LO}t)$$

$$V_{IF}(t) = -I_{DC}R_L\frac{4}{\pi}Cos(\omega_{LO}t) - \frac{2g_m R_L A_{RF}}{\pi}Cos(\omega_{LO}+\omega_{RF}t) - \frac{2g_m R_L A_{RF}}{\pi}Cos(\omega_{LO}-\omega_{RF}t)$$

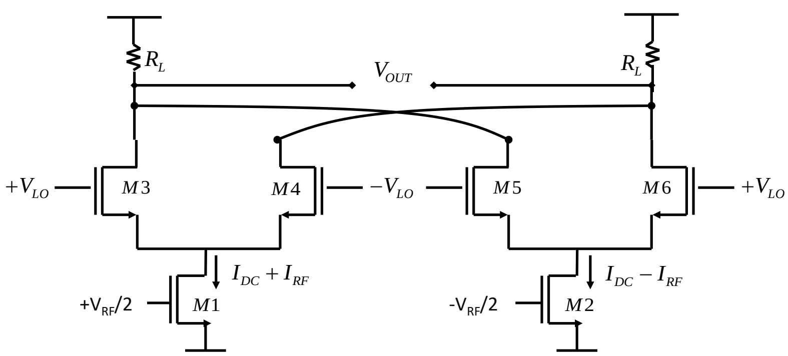
Gain: $A_v = -\frac{2g_m R_L}{\pi}$

Disadvantage: LO feedthrough



## 3. Mixers Based on Switches

### Doulble-Balanced Active Mixer

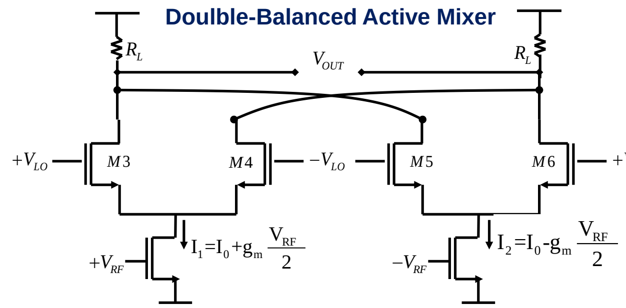



- Strong LO-IF feed suppressed by double balanced mixer.
- All the even harmonics cancelled.
- This is the preferred mixer implementation for most radio systems!



## 3. Mixers Based on Switches

### Doulble-Balanced Active Mixer




$$I_1 = I_0 + g_m\frac{V_{RF}}{2}$$

$$I_2 = I_0 - g_m\frac{V_{RF}}{2}$$

$$V_{IF} = R_L(I_2 - I_1) = -g_m R_L V_{RF} \quad , V_{LO} > 0$$

$$V_{IF} = R_L(I_1 - I_2) = g_m R_L V_{RF} \quad , V_{LO} < 0$$

$$\Rightarrow V_{IF}(t) = -g_m R_L V_{RF}(t)S(t)$$

Gain:

$$V_{IF}(t) = -\frac{4}{\pi}g_m R_L A_{RF}Cos(\omega_{RF}t)Cos(\omega_{LO}t)$$

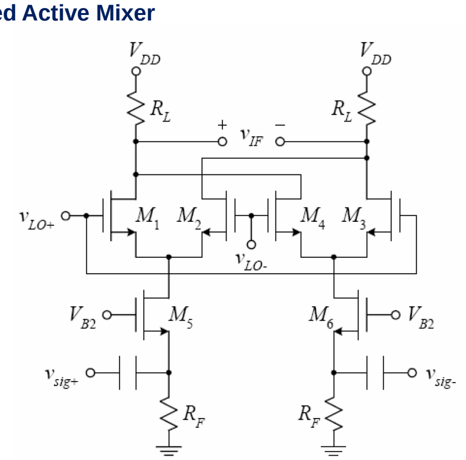
$$A_v = -\frac{2g_m R_L}{\pi} \qquad V_{IF}(t) = -\frac{2g_m R_L A_{RF}}{\pi}Cos(\omega_{RF}+\omega_{LO})t - \frac{2g_m R_L A_{RF}}{\pi}Cos(\omega_{RF}-\omega_{LO})t$$



## 3. Mixers Based on Switches

### Doulble-Balanced Active Mixer

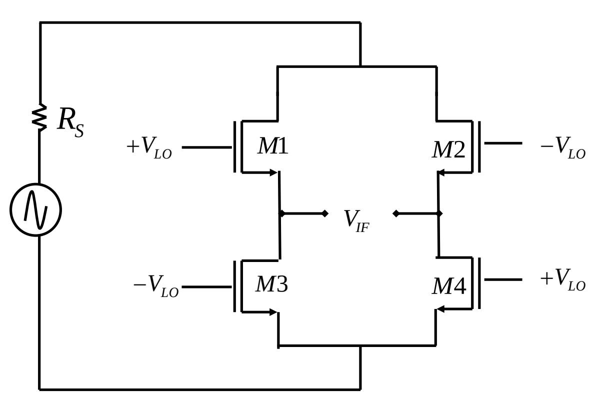
- Common-gate input stage
  - ✓ Best linearity






## 3. Mixers Based on Switches

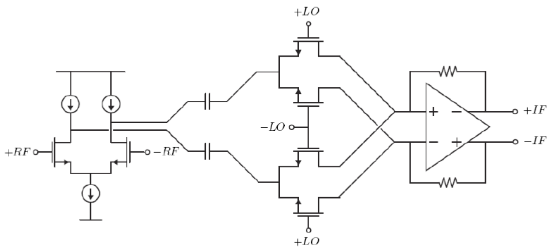
### Doulble-Balanced Active Mixer




Voltage Gain: $A_v = \frac{2}{\pi}$

# 3. Mixers Based on Switches

## Passive Current Mixer




•The input stage is a Gm stage similar to a Gilbert cell mixer. The Gilbert Quad, though, has no DC current and switches on/off similar to a passive mixer.
•The output signal drives the virtual ground of a differential op-amp. The current signal is converted into a voltage output by the op-amp.



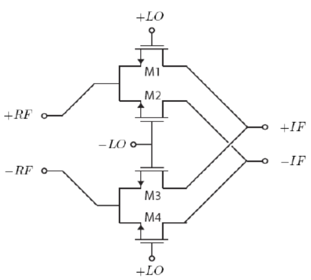
# 3. Mixers Based on Switches

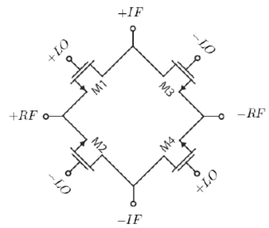
No DC current in quad implies that there is no flicker noise generated by the switching quad. This is the key advantage.
•The linearity is very good since the output signal is a current. The voltage swing does not limit the linearity of the mixer. This is to be contrasted to a Gilbert cell mixer where the voltage swing is limited due to the headroom of the switching mixer and the transconductance stage.
•The op-amp output stage can be converted into an IF filter (discussed later)
•Need large LO drive compared to the active Gilbert cell mixer.
•Need an op-amp. This requires extra power consumption and introduces additional noise.
•Need a common mode feedback circuit at the input of the op-amp.



# 3. Mixers Based on Switches

## Passive Current Mixer




Note that the Gilbert quad is really a folded ring. Thus the passive and active mixers are very similar. The main difference is how the quad devices are biased. In the Gilbert cell they are biased nominally in saturation and have DC current. In the passive mixers, they are biased near the threshold.