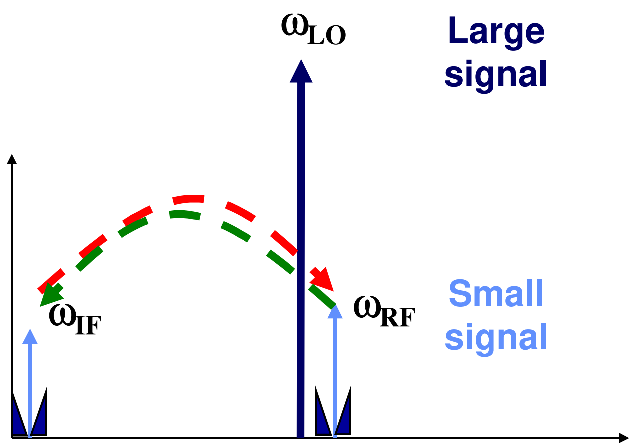
Basics on High-Frequency Mixers

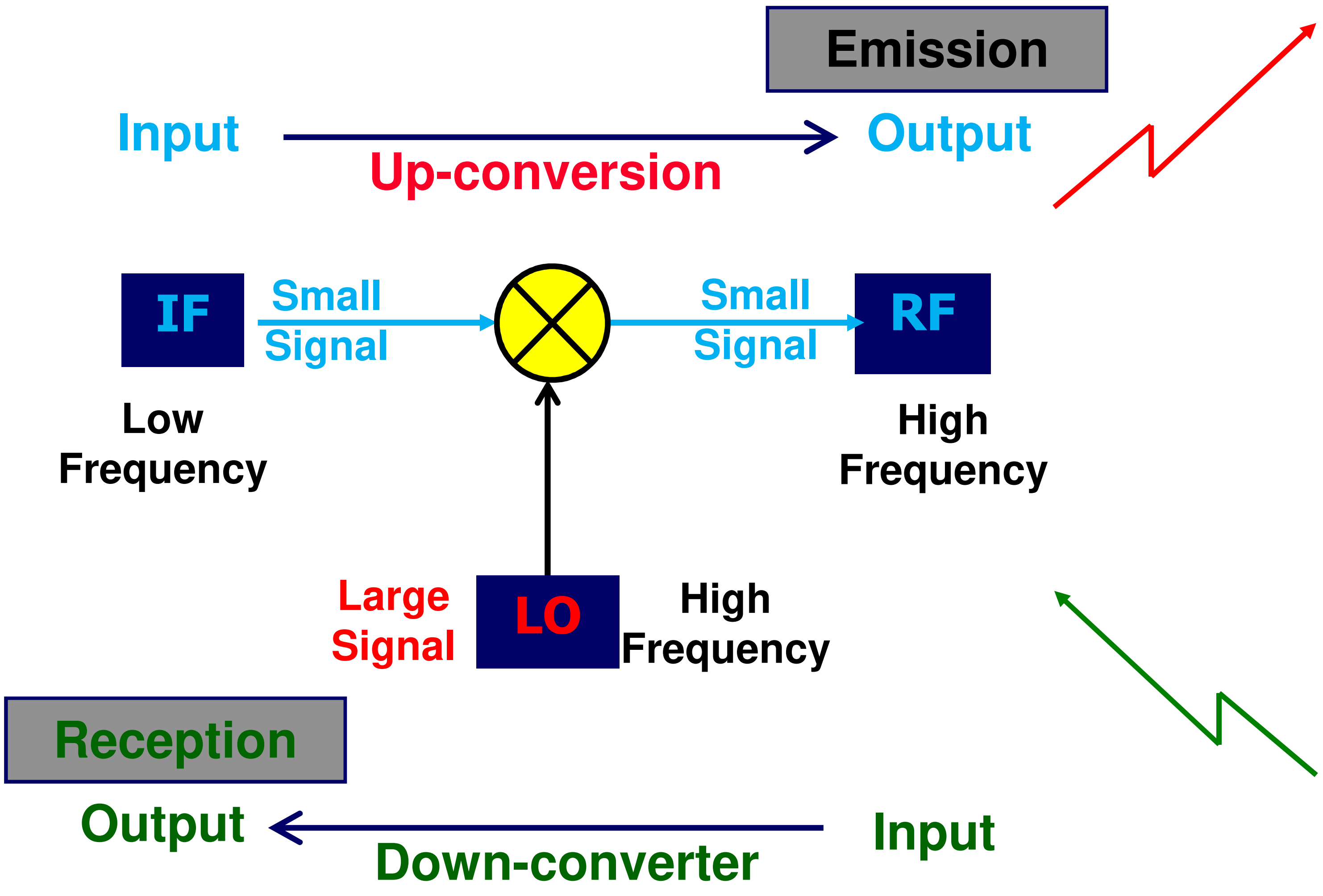
Outline

- **Introduction**
- **Theory of frequency conversion**
- **Characteristic performances of mixers**
- **Active mixers**
  - Single Ended (SEM) → Gate Mixer / Drain Mixer
  - Gilbert Cell→ DBDM Double Balanced Differential Mixer
- **Passive Mixers**
  - Diodes → SEM / SBM / DBM
  - Cold FETs → SEM / SBM
- **IRM: Image Reject Mixers**

Introduction

A mixer is a 3-port nonlinear circuit which performs the frequency translation required by any communication system.

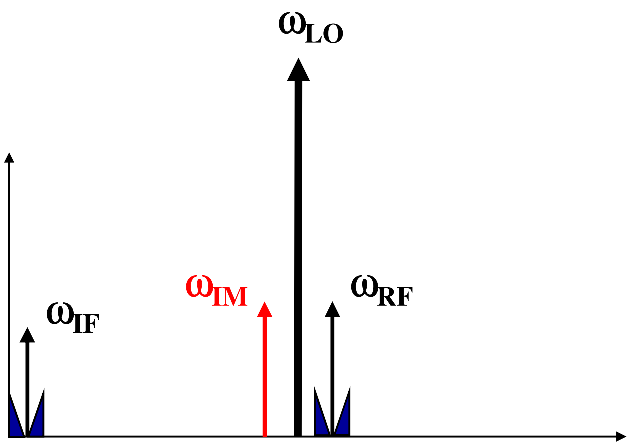




Problem of IMAGE FREQUENCY

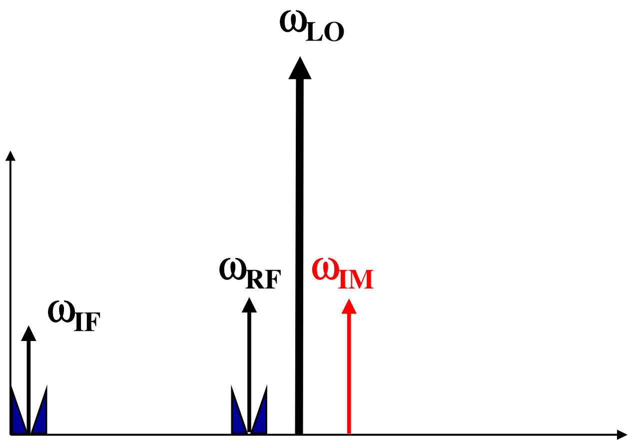
The image frequency is the symmetric of the RF frequency

with respect to the LO frequency



USB Mode

$\omega_{RF} = \omega_{LO} + \omega_{IF}$



LSB Mode

$\omega_{RF} = \omega_{LO} - \omega_{IF}$

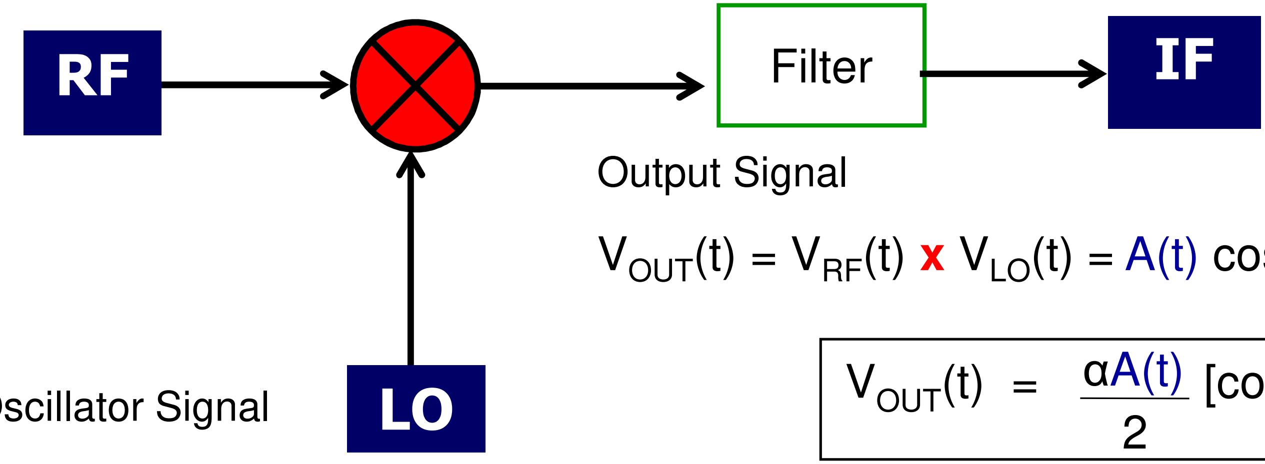
$$\boxed{\omega_{IM} = 2 \cdot \omega_{LO} - \omega_{RF}}$$

Principle of frequency conversion

Mixing Function modelled by an ideal multiplier

Input Signal RF

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



Output Signal

$V_{OUT}(t) = V_{RF}(t) \times V_{LO}(t) = A(t)\cos(\omega_{RF}.t) \times \alpha\cos(\omega_{LO}.t)$

$$V_{OUT}(t) = \frac{\alpha A(t)}{2}[\cos(\omega_{\Delta}t) + \cos(\omega_{\Sigma}t)]$$

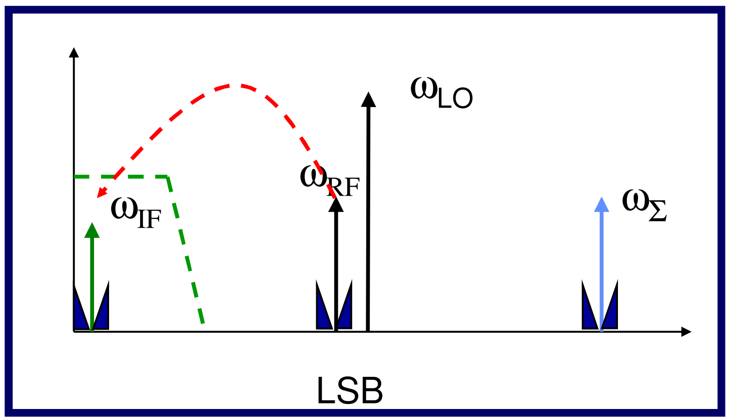
Oscillator Signal

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

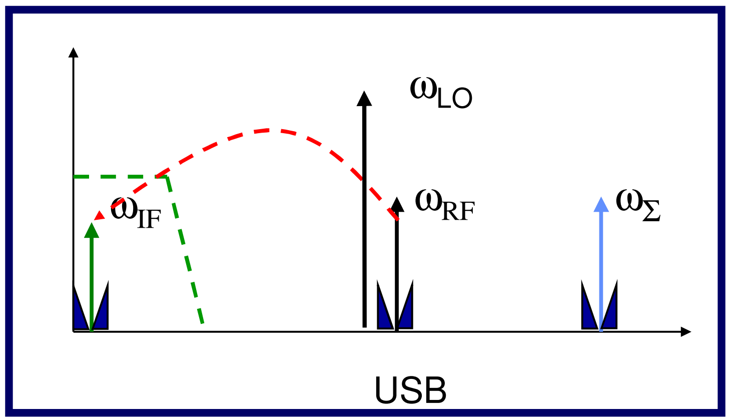
$\omega_{\Sigma} = \omega_{LO} + \omega_{RF}$

- <u>USB and LSB Modes</u>

$\omega_{\Delta\_LSB} = \omega_{LO} - \omega_{RF} = \omega_{IF}$



$\omega_{\Delta\_USB} = \omega_{RF} - \omega_{LO} = \omega_{IF}$



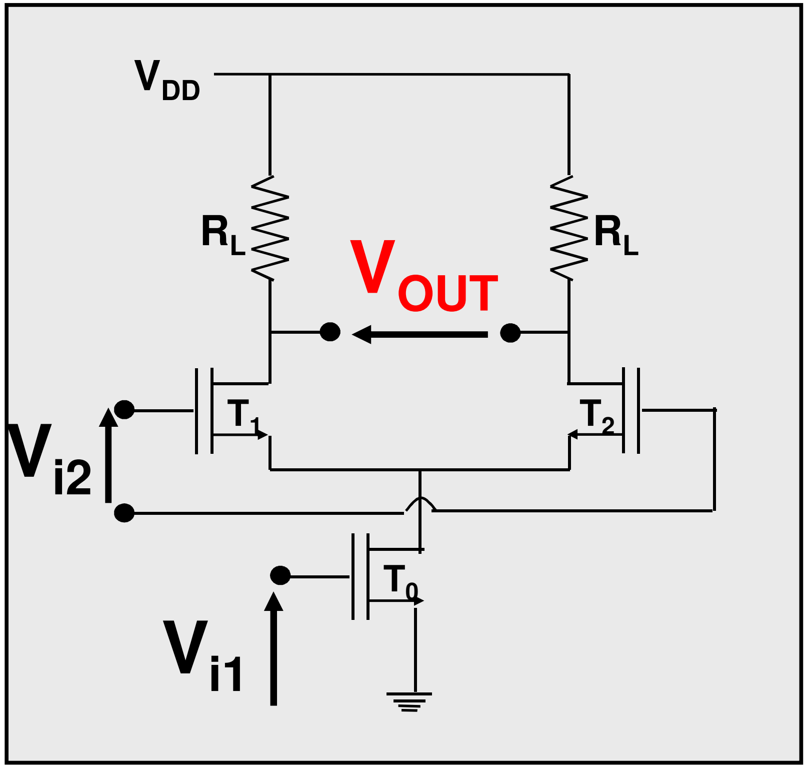
Ideal mixing because the only unwanted frequency is largely outside the useful bandwidth

Example of Active Multiplier

- **Principle :** Voltage Multiplication of Input Voltages

$$V_{out}(t) = V_{i1}(t) \times V_{i2}(t)$$

- **Gilbert Cell**



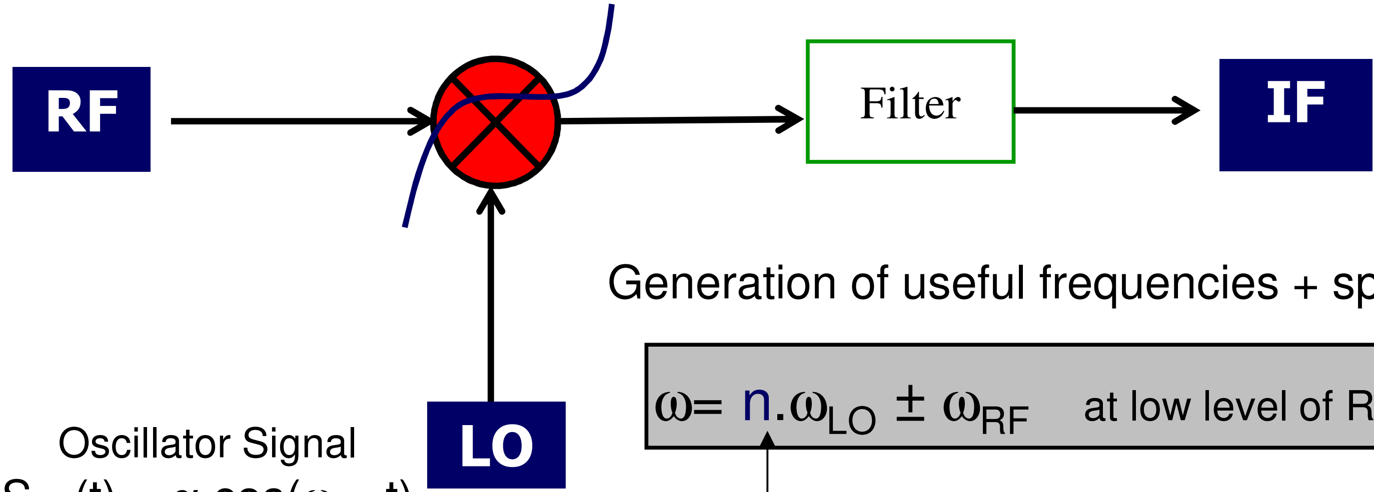
Mixing Function performed by a nonlinear device

$$S_{OUT}(t) = \alpha_1 . S_{IN}(t) + \alpha_2 . S_{IN}(t)^2 + \alpha_3 . S_{IN}(t)^3 + \dots$$

$$S_{IN}(t) = S_{LO}(t) \pm S_{RF}(t)$$

Input RF Signal

$S_{RF}(t) = A(t) \cos(\omega_{RF}.t)$



Oscillator Signal

$S_{LO}(t) = \alpha \cos(\omega_{LO}.t)$

Generation of useful frequencies + spurs:

$\omega = n.\omega_{LO} \pm \omega_{RF}$ at low level of RF

Nonlinearity (Mixing with LO harmonics)

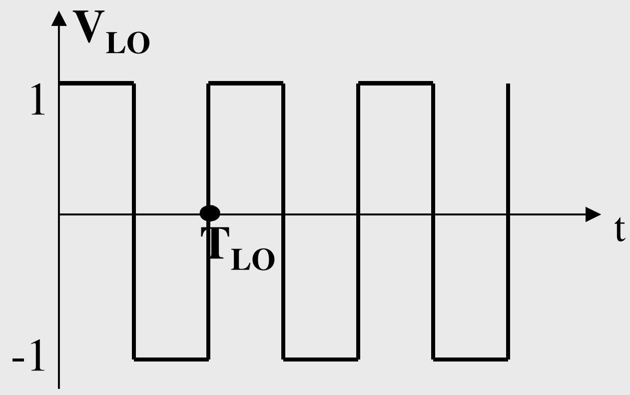
2nd Order Nonlinearity $\rightarrow$ useful signal @ $\pm(\omega_{LO} - \omega_{RF})$

but the nonlinearity gives a lot of parasitic frequencies (spurs)

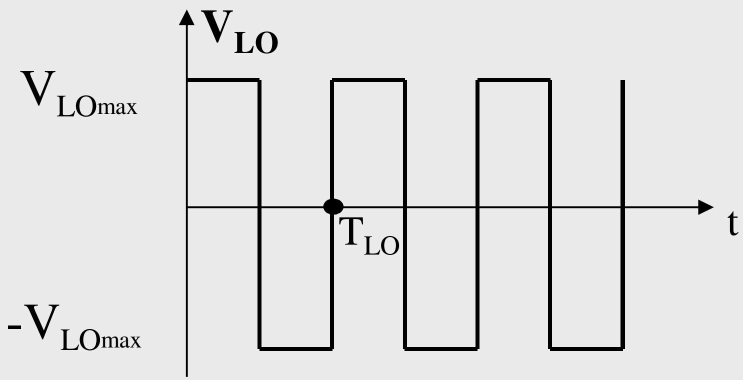
Nonlinear devices used in High-Frequency Mixers : Diodes and Transistors

Mixing by LO switching : Frequency generation of a square signal « Sign Function»

Switches controlled by the LO signal along the signal path RF$\rightarrow$IF *(Gilbert Cell)*



$$V_{LO}(t) = \frac{4}{\pi}\left[\cos(\omega_{LO}.t) - \frac{1}{3}\cos(3\omega_{LO}.t) + \frac{1}{5}\cos(5\omega_{LO}.t) - \ \ldots\right]$$



$$\text{sign}[V_{LO}(t)] = \frac{4}{\pi}\left[\cos(\omega_{LO}.t) - \frac{1}{3}\cos(3\omega_{LO}.t) + \frac{1}{5}\cos(5\omega_{LO}.t) - \ \ldots\right]$$

$V_{OUT}(t) = V_{IN}(t)$. sign $(V_{LO}(t)) \rightarrow$ only odd mixing products $(2k+1)\omega_{LO} \pm \omega_{RF}$

$\rightarrow$ less spurs

Characteristic Performances of Mixers

Conversion Gain (example of Receiver RF → IF)

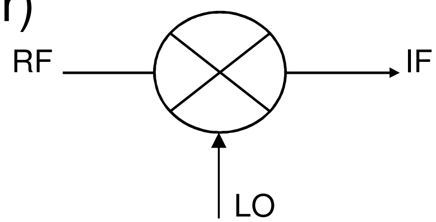
- Voltage Conversion Gain and Power Conversion Gain

$$G_V = 20 \log \left(\frac{Vout_{IF}}{Vin_{RF}} \right)$$

$$G_P = 10 \log \left(\frac{Pout_{IF}}{Pin_{RF}} \right)$$

Down Conversion (Receiver)

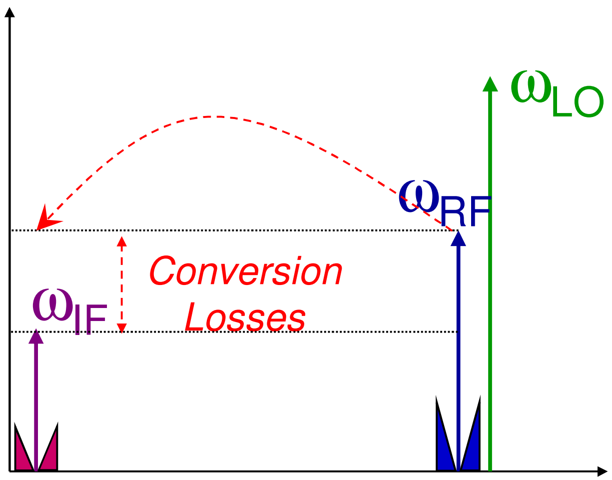
RF → IF



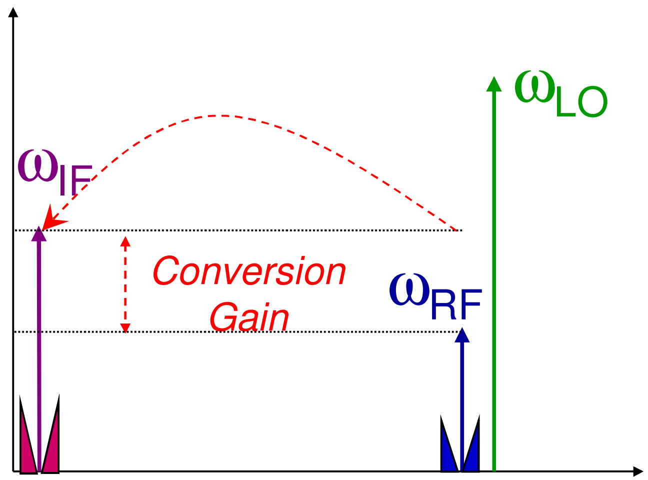
$$G_{dB\_down} = P_{OUTdBm}[\omega_{IF}] - P_{INdBm}[\omega_{RF}]$$

$$L_{dB\_down} = P_{INdBm}[\omega_{RF}] - P_{OUTdBm}[\omega_{IF}]$$

Example of passive down converter



Example of active down converter

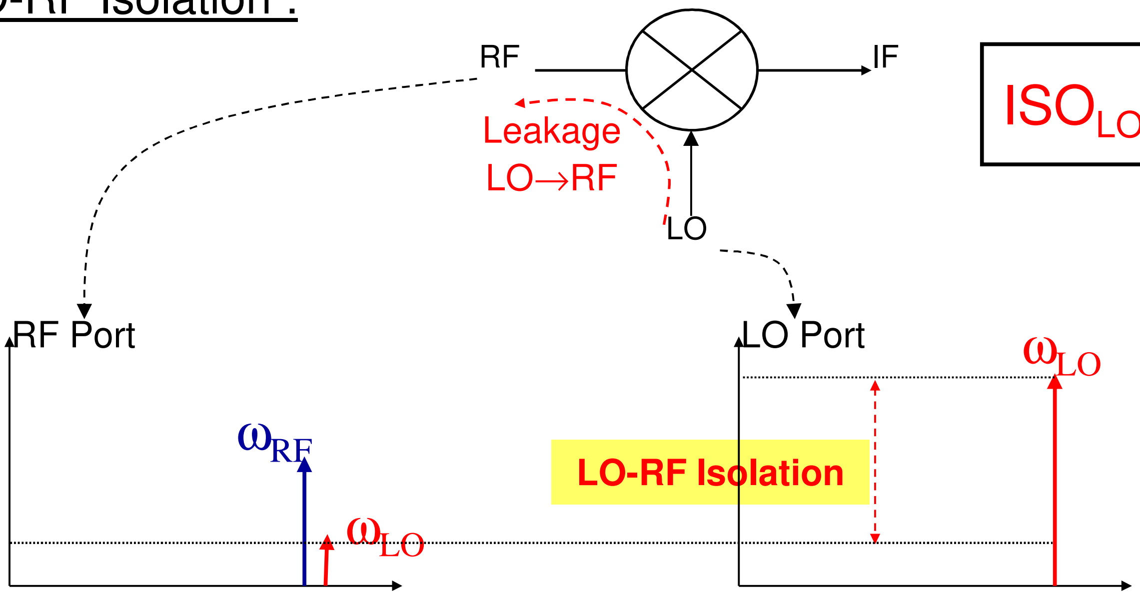


$$\text{Conversion Gain} = F(P_{LO})$$

LO-RF Isolation

ISOLATION = power level coupled from one port to another one within the mixer

• <u>LO-RF Isolation :</u>



$$ISO_{LO\text{-}RF\ (dB)} = P_{dBm}(\omega_{LO})_{LO\ port} - P_{dBm}(\omega_{LO})_{RF\ port}$$

- Cannot be improved by filtering because RF and LO frequencies are too close

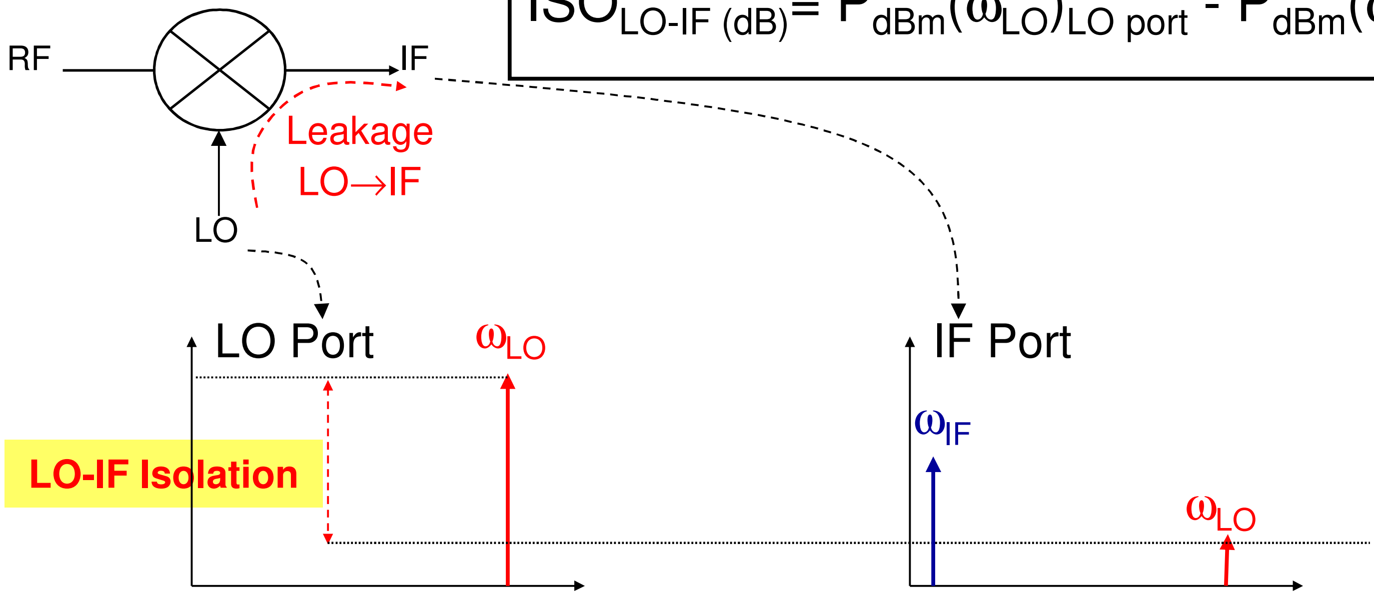
- Can be improved by Balanced Architectures

$ISO_{LO\text{-}RF\ (dB)}$ = LO leakage to the RF port (LNA, antenna)

LO-IF and RF-IF Isolations

• LO-IF Isolation :

$$ISO_{LO\text{-}IF\ (dB)} = P_{dBm}(\omega_{LO})_{LO\ port} - P_{dBm}(\omega_{LO})_{IF\ port}$$



$ISO_{LO\text{-}IF\ (dB)}$ = LO leakage to the IF port (saturation of following stages due to large signal)

• RF-IF and IF-RF Isolations :

$$ISO_{RF\text{-}IF\ (dB)} = P_{dBm}(\omega_{RF})_{RF\ port} - P_{dBm}(\omega_{RF})_{IF\ port}$$

$$ISO_{IF\text{-}RF\ (dB)} = P_{dBm}(\omega_{IF})_{IF\ port} - P_{dBm}(\omega_{IF})_{RF\ port}$$

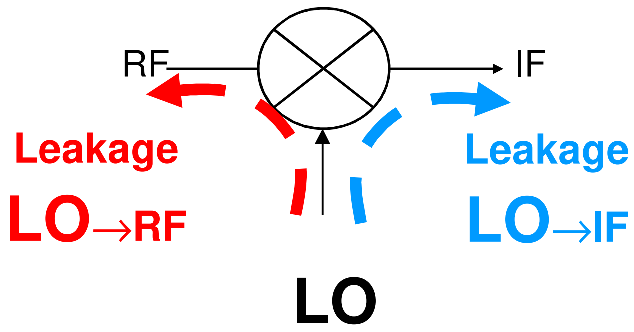
Less critical isolations because they can be improved by filtering

Isolations

•Two critical isolations due to the very large amplitude of the LO signal:

LO- IF Isolation (less critical because filtering is easy $\omega_{LO} >> \omega_{IF}$)

and LO-RF Isolation (the most critical isolation because of impossible filtering $\omega_{LO} \approx \omega_{RF}$)



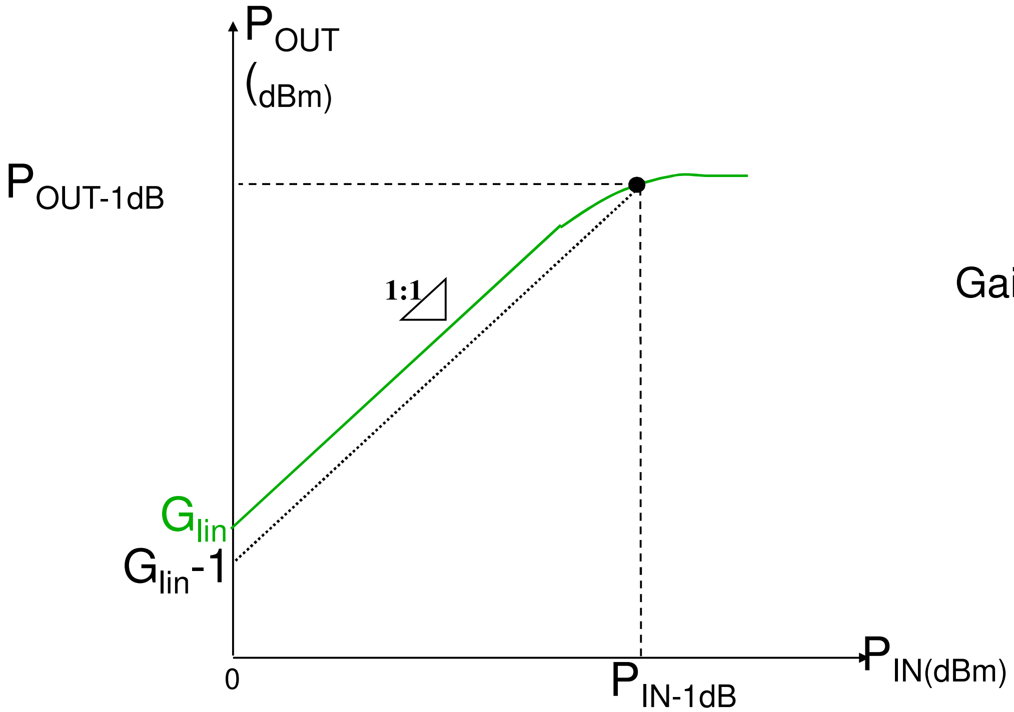
$$\text{Isolations} = F(P_{LO}, P_{IN})$$

Linearity (ex : Single carrier amplifier)

Nonlinearity $y(t) = \alpha_1.x(t) + \alpha_2.\, x(t)^2 - \alpha_3.\, x(t)^3$

$$x(t) = A.\cos(\omega t) \rightarrow y(t) = \left(\frac{\alpha_2 A^2}{2}\right) + \left(\alpha_1 A - \frac{3\alpha_3 A^3}{4}\right)\cos(\omega t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega t) - \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega t)$$

$$\rightarrow G_{lin} = \alpha_1 A$$



Example (amplifier)

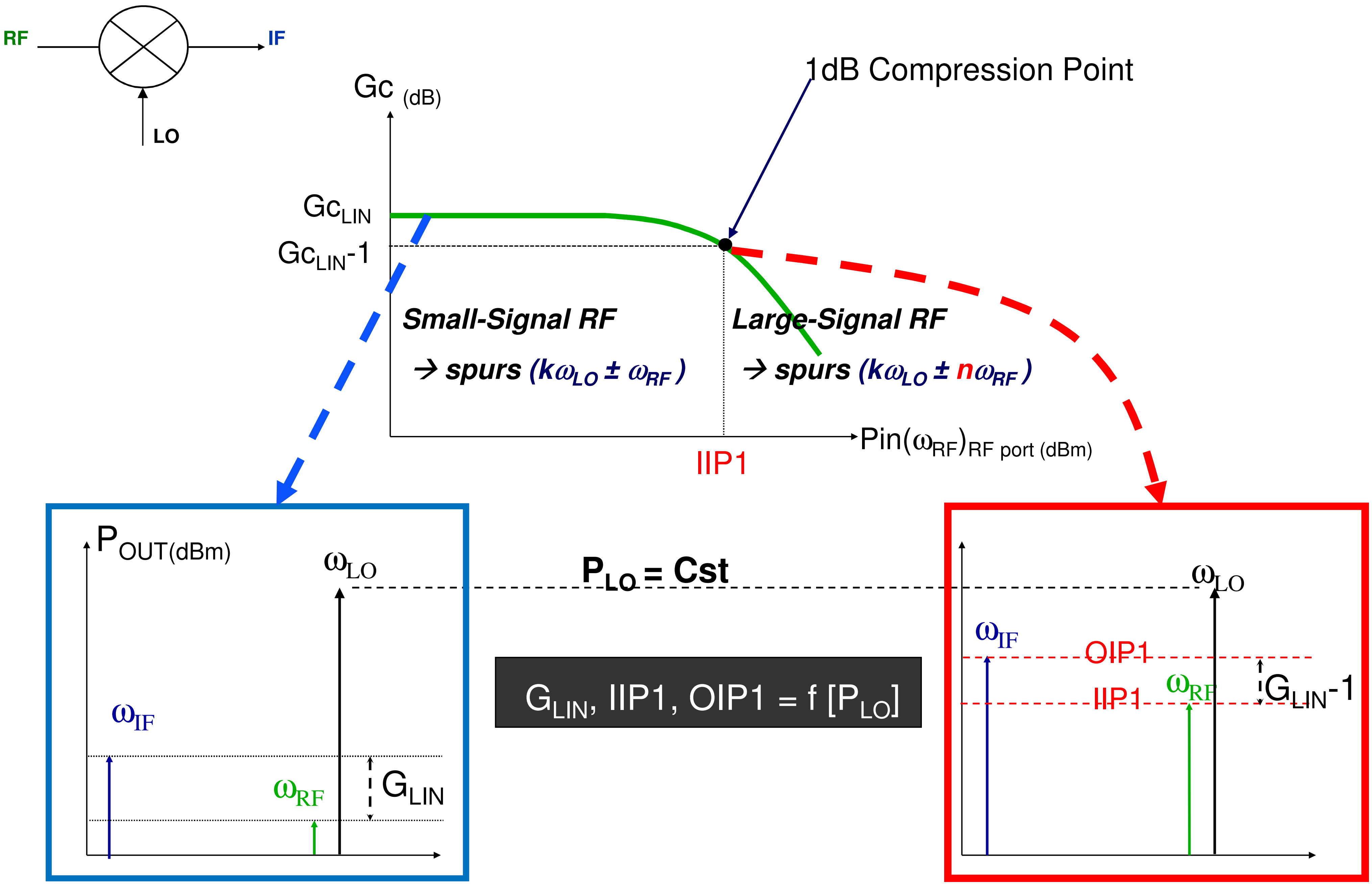
Gain Saturation at the input frequency ω

with

Harmonic Generation ($n.\omega$)

Gain compression of Active Mixers

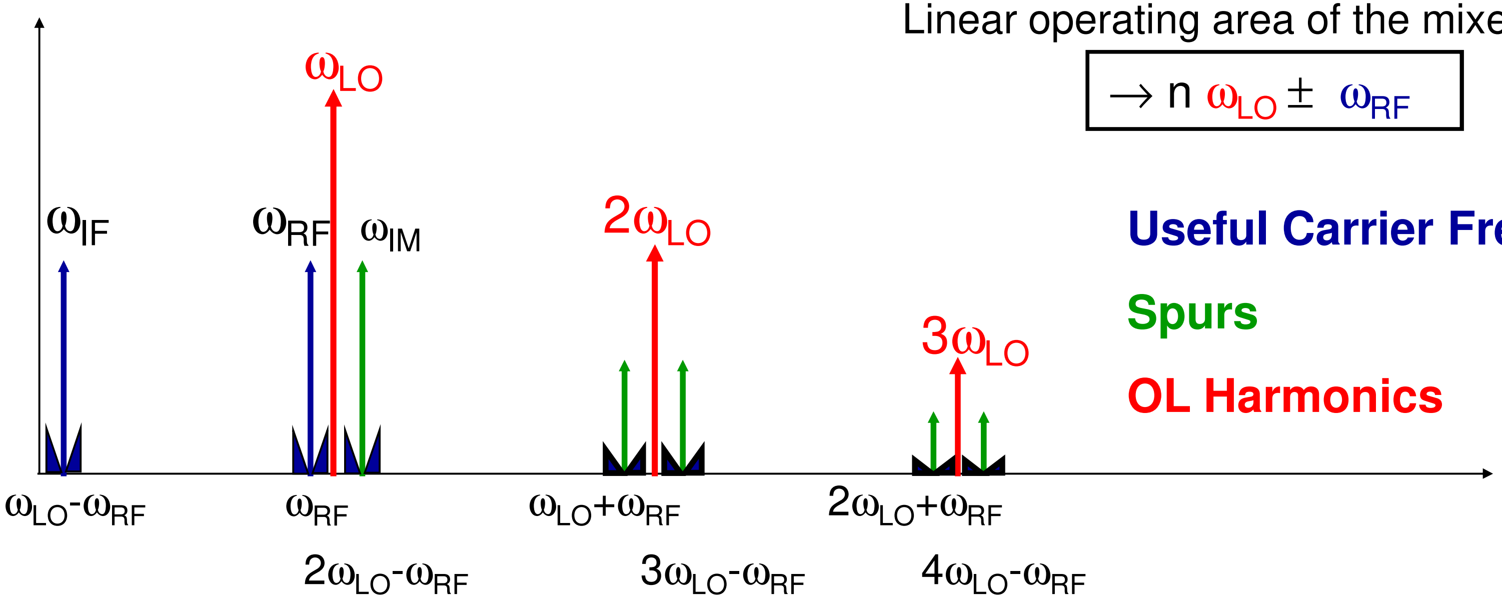
- 1dB compression point at a given LO power



Simplified Output Spectrum

Linear operating area of the mixer

$\rightarrow n\ \omega_{LO} \pm \omega_{RF}$



Useful Carrier Frequencies

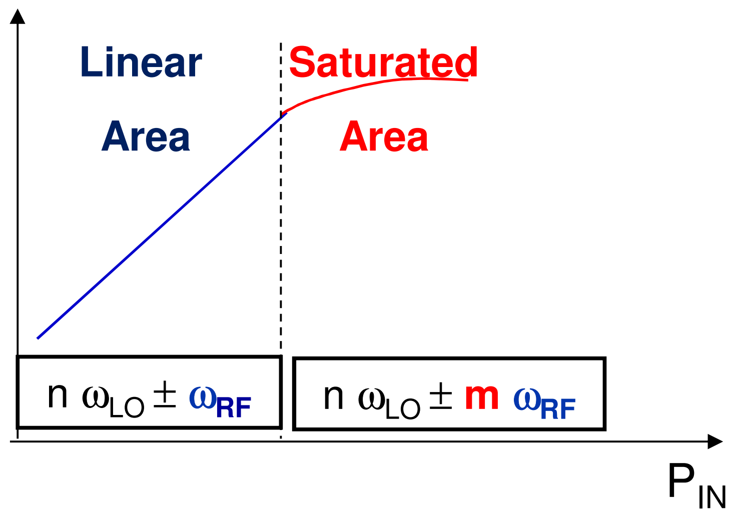
Spurs

OL Harmonics

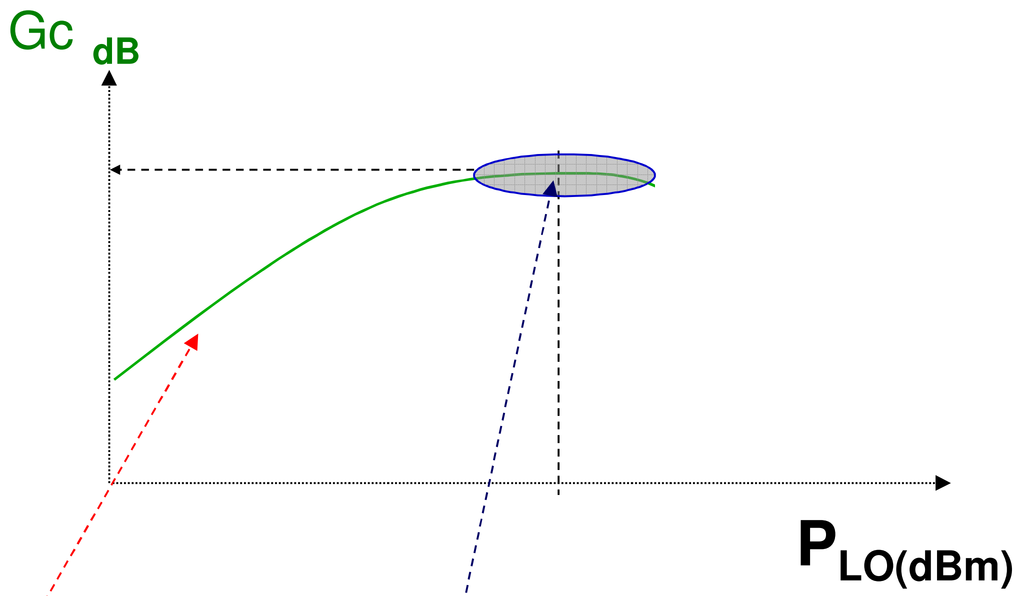
At a given level of P_{LO},

if P_{IN} increases $\rightarrow$ Mixer saturation

$\rightarrow n\ \omega_{LO} \pm m\ \omega_{RF}$



Gain Conversion as a function of P_{LO}



If P_{LO} is too low $\rightarrow$ Gc varies rapidly with P_{LO} ☹

If P_{LO} is high at its optimum value $\rightarrow$ Gc is optimal and remains constant with P_{LO} ☺

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  - Single Ended (SEM) $\rightarrow$ Gate Mixer / Drain Mixer
  - Gilbert Cell$\rightarrow$ DBDM Double Balanced Differential Mixer
- **Passive Mixers**
  - Diodes $\rightarrow$ SEM / SBM / DBM
  - Cold FETs $\rightarrow$ SEM / SBM
- **IRM: Image Reject Mixers**

Active Mixers

Active Mixers = Gain Modulation

The basic architecture of an active mixer is similar to that of an amplifier

except that the biasing conditions of the nonlinear device are chosen to get a 2nd order quadratic response

$$S_{OUT}(t) = \alpha_1 . S_{IN}(t) + \alpha_2 . S_{IN}(t)^2 + \alpha_3 . S_{IN}(t)^3 + \ldots$$

→ Active mixers can give high conversion gains

→ Active mixers require lower levels of LO power compared to passive mixers

However :

→ Active mixers saturate at very low powers

→ Active mixers require DC consumption

→ Active mixers are not well suited to IRM architectures

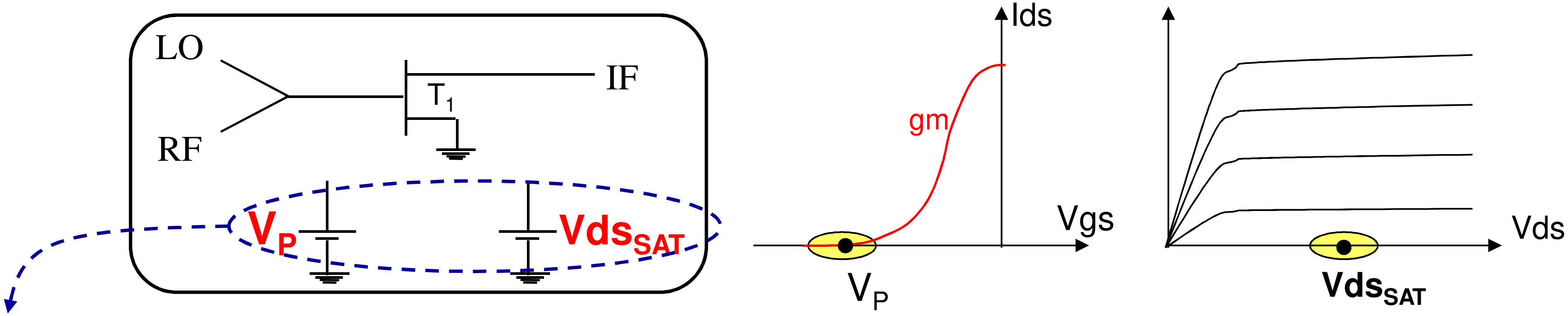
At high frequencies:

→ Performances of active mixers do not reach the required level → Passive mixers are preferred @ HF

♦ Active Mixers : Single Ended Mixers

FET-based SEMs

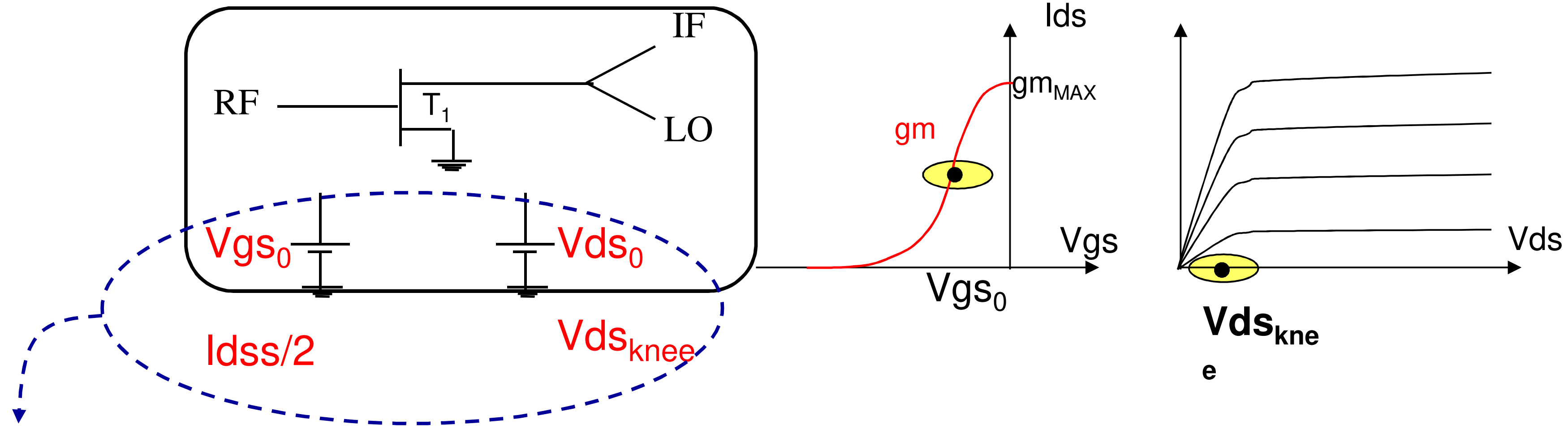
FET-based SEM (Gate Mixer)



<u>Biasing conditions → High nonlinearity of the transconductance gm</u>

$$gm(t) = gm_0 + gm_1.\cos(\omega_{LO}t) + gm_2.\cos(2\omega_{LO}t) + \ldots$$

FET-based SEM (Drain Mixer)



<u>Biasing conditions → Nonlinearities of gm and gd)</u>

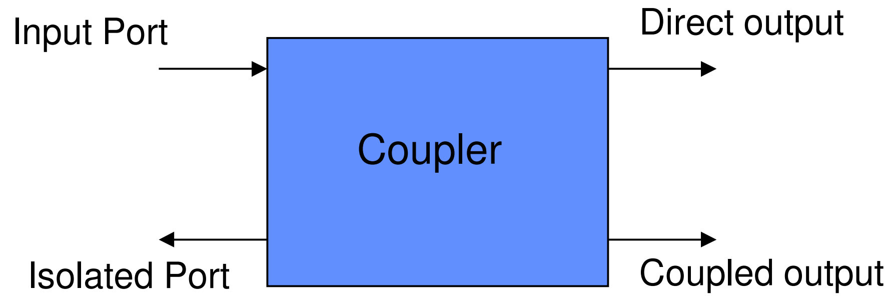
$$gm(t) = gm_0 + gm_1.\cos(\omega_{LO}.t) + gm_2.\cos(2\omega_{LO}.t) + \ldots$$
$$Gd(t) = Gd_0 + Gd_1.\cos(\omega_{LO}.t) + Gd_2.\cos(2\omega_{LO}.t) + \ldots$$

Lower Conversion Gain compared to the Gate Mixer

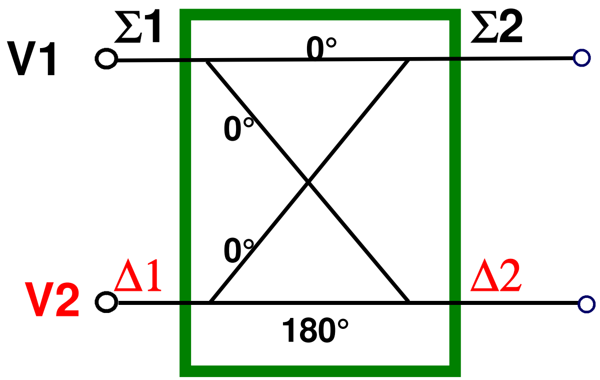
♦ Active Balanced Mixers

Reminder : Coupler

Coupler



ΣΔ Coupler



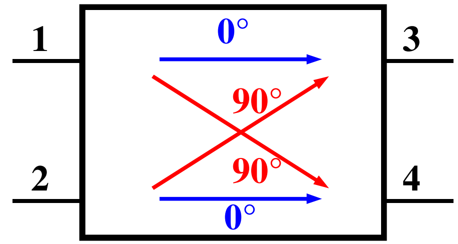
$+\alpha V1 \ + \alpha V2$

$0 < \alpha < 1$

$+\alpha V1 \ - \alpha V2$

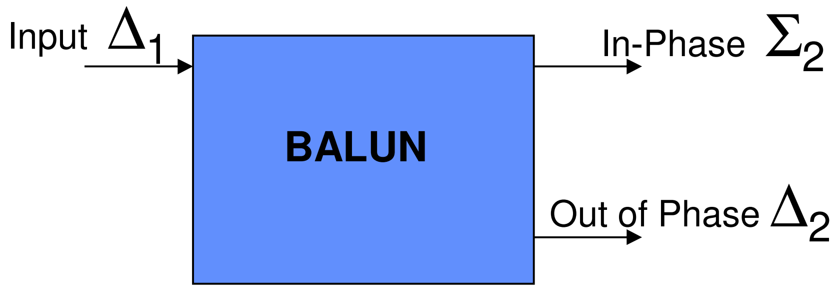
Coupler
0-180°

90° Coupler



BALUN

BALanced to UNbalanced



Phase relationships of frequency products

$$2 \times \mathbf{cos}\Big(\underbrace{\omega_{LO}t + \varnothing_{LO}}_{\text{LO}}\Big) \times \mathbf{cos}\Big(\underbrace{\omega_{RF}t + \varnothing_{RF}}_{\text{RF}}\Big) = \mathbf{cos}\Big[\underbrace{(\omega_{LO} + \omega_{RF})t + (\varnothing_{LO} + \varnothing_{RF})}_{\text{LO+RF}}\Big] + \mathbf{cos}\Big[\underbrace{(\omega_{LO} - \omega_{RF})t + (\varnothing_{LO} - \varnothing_{RF})}_{\text{LO-RF}}\Big]$$

$$(\omega_{LO} + \omega_{RF}) \rightarrow (\varnothing_{LO} + \varnothing_{RF})$$

$$(\omega_{LO} - \omega_{RF}) \rightarrow (\varnothing_{LO} - \varnothing_{RF})$$

If $\omega_{IF} = \omega_{LO} - \omega_{RF} \rightarrow \varnothing_{IF} = (\varnothing_{LO} - \varnothing_{RF})$

SBM Active Mixers

$\omega_{IF} = \omega_{LO} - \omega_{RF}$ → Phase(IF) = Phase(OL) - Phase(RF)

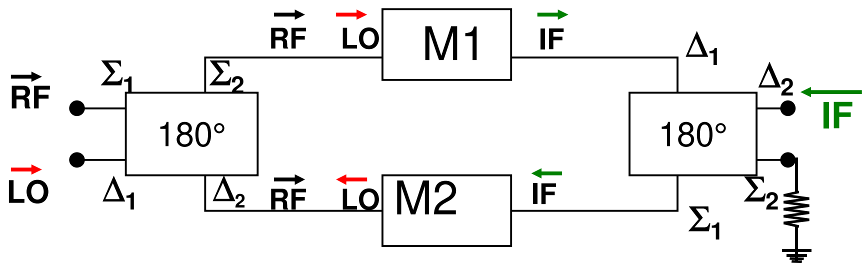
Notations

EH = Even Harmonic

OH = Odd Harmonic

Mix [EH(LO) , OH(RF)]= $\pm 2m\,\omega_{LO} \pm 2(n+1)\,\omega_{RF}$ with (m,n) integers

- SBM with 180° Couplers

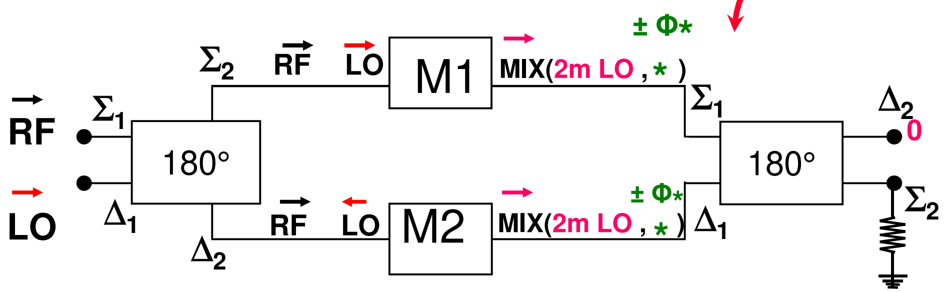


- Good LO-RF isolation ⇔ Good Input Coupler isolation
- In all cases, **mix [EH(LO) , OH(RF)] are rejected at the output**
- LO at Δ port (the illustrated case in this slide)

  → **mix [EH(LO) , *] are rejected**

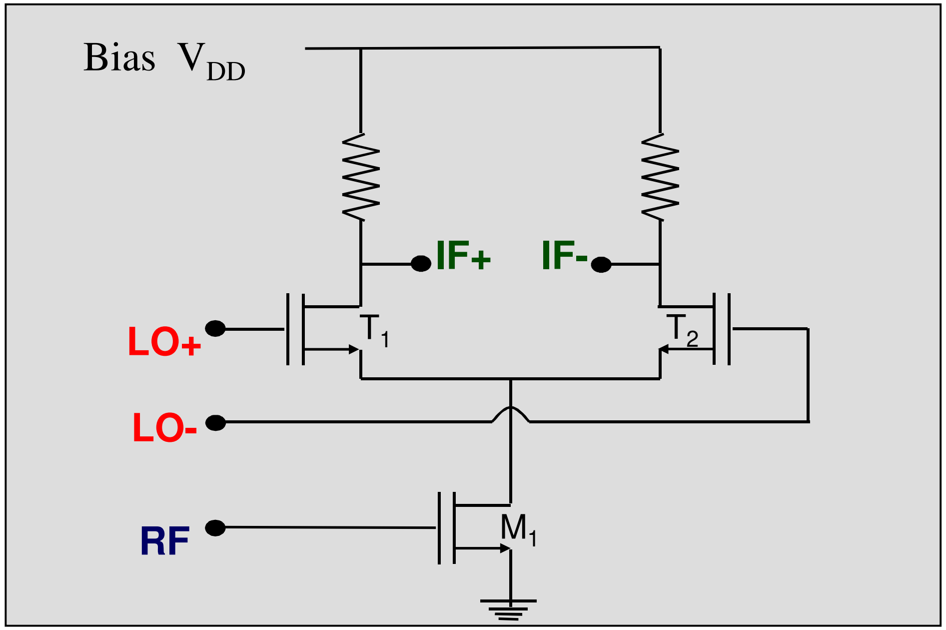
- LO at Σ port

  → **mix [* , OH (RF)] are rejected**



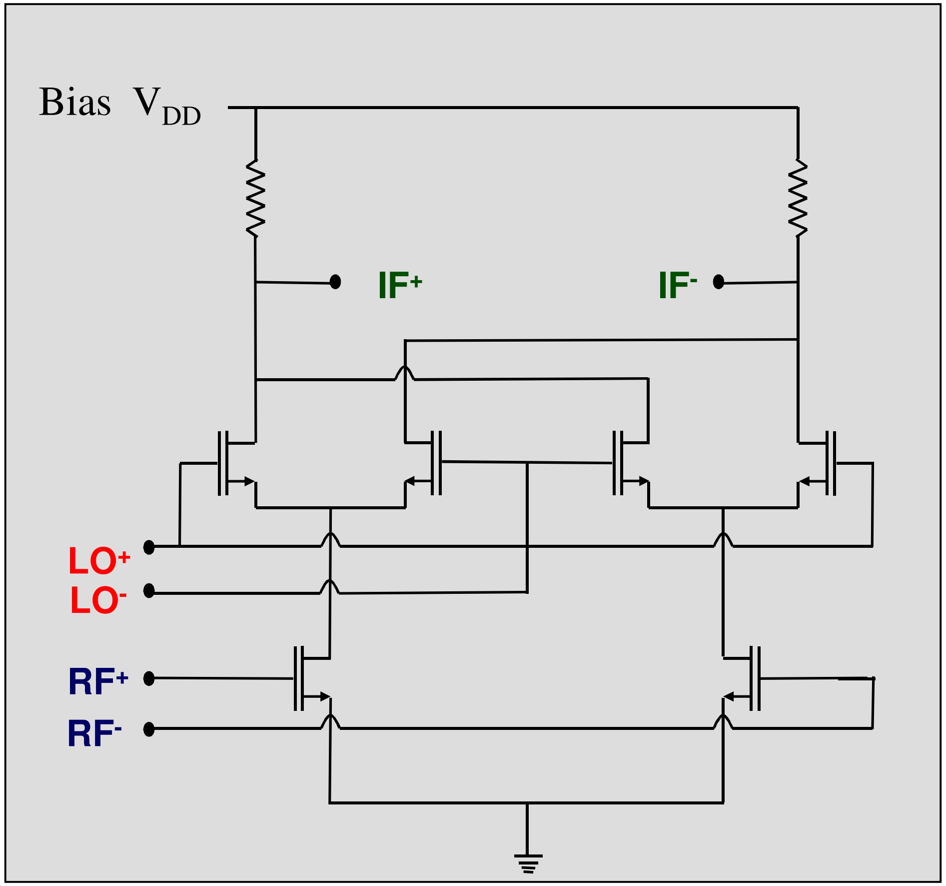
Example of Gilbert Cell Mixers

Single Balanced Gilbert Cell Mixer

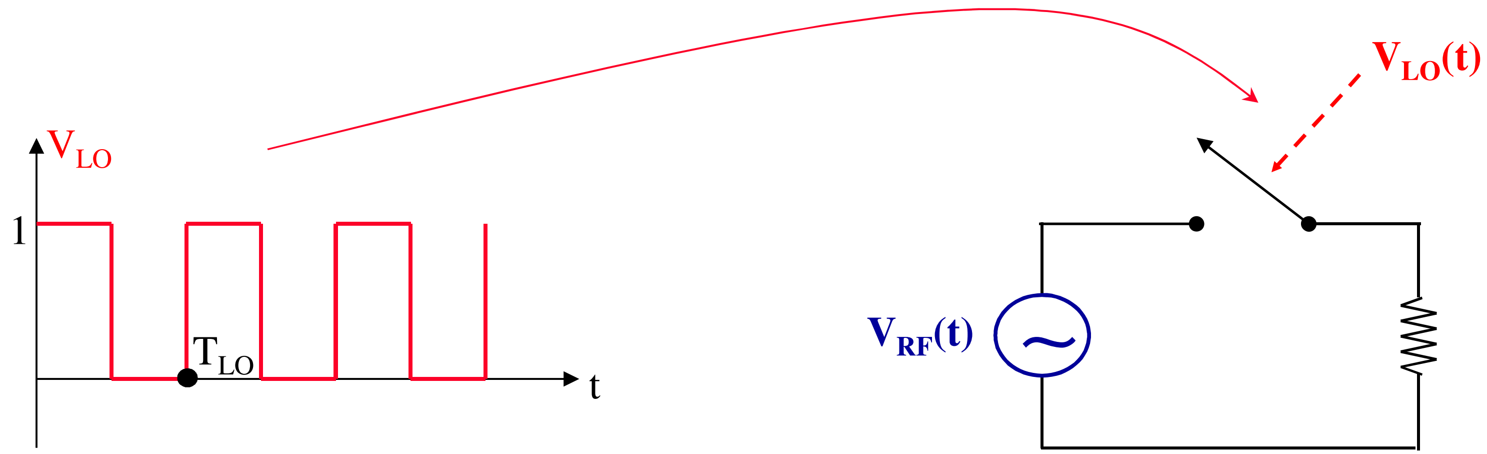


♦ Double Balanced Gilbert Cell Mixer

Double Balanced Gilbert Cell Mixer



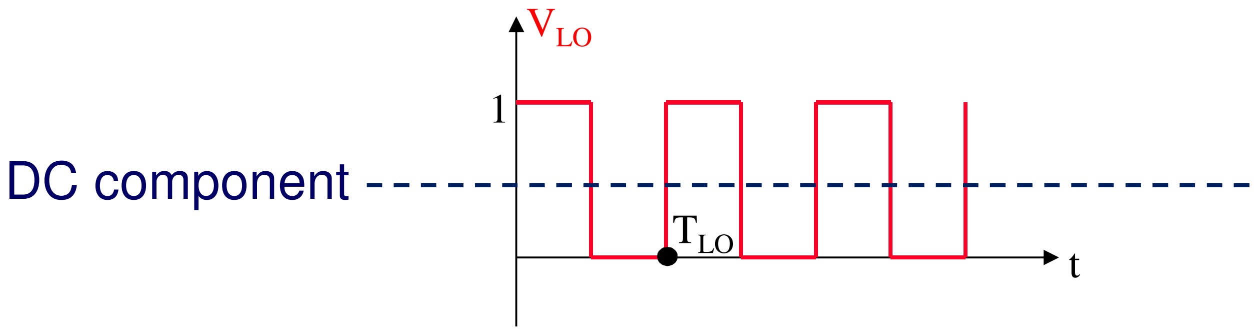
Switch controlled by the LO signal
Square Signal (50% duty cycle)



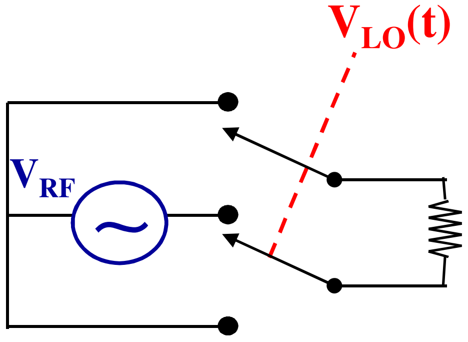
The linear signal path RF→IF is open and closed by a switch controlled at the LO rate

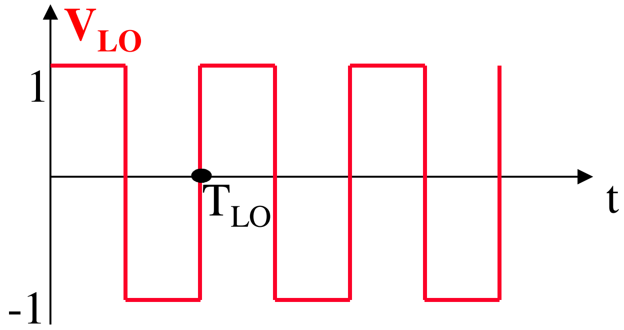
→ The output signal results from the multiplication of the RF signal by the square LO signal

→ Unfortunately, the output signal includes a parasitic RF component
due to the DC component of the LO signal



Switch controlled by the LO signal with the suppression of its DC component





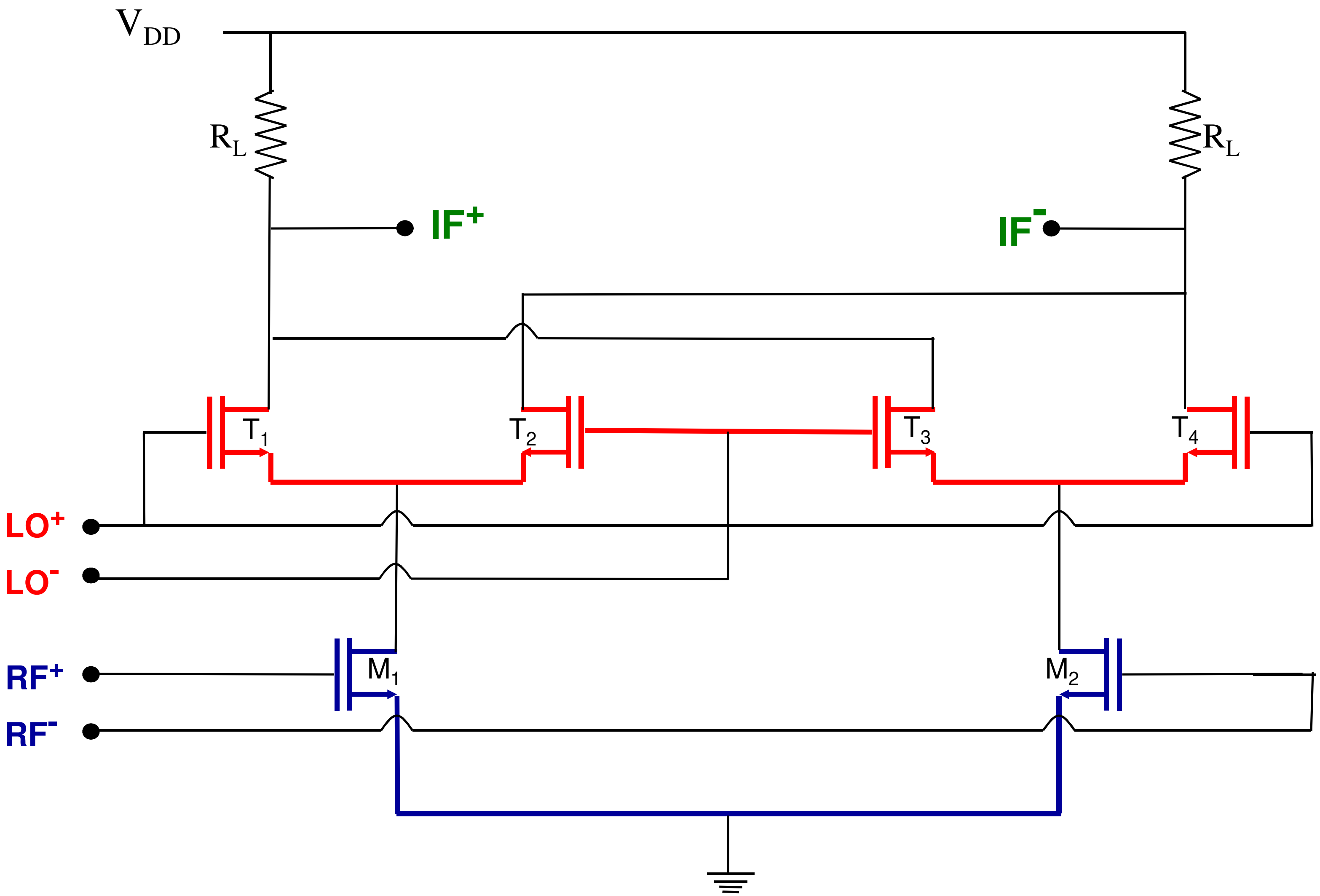
$$\text{sign}[V_{LO}(t)] = \frac{4}{\pi}\left[\cos(\omega_{LO}.t) - \frac{1}{3}\cos(3\omega_{LO}.t) + \frac{1}{5}\cos(5\omega_{LO}.t) - \ ...\right]$$

The sign of the RF signal is periodically changed at the LO rate instead of being cut

→ There is no DC component and the RF signal is fully rejected at the output

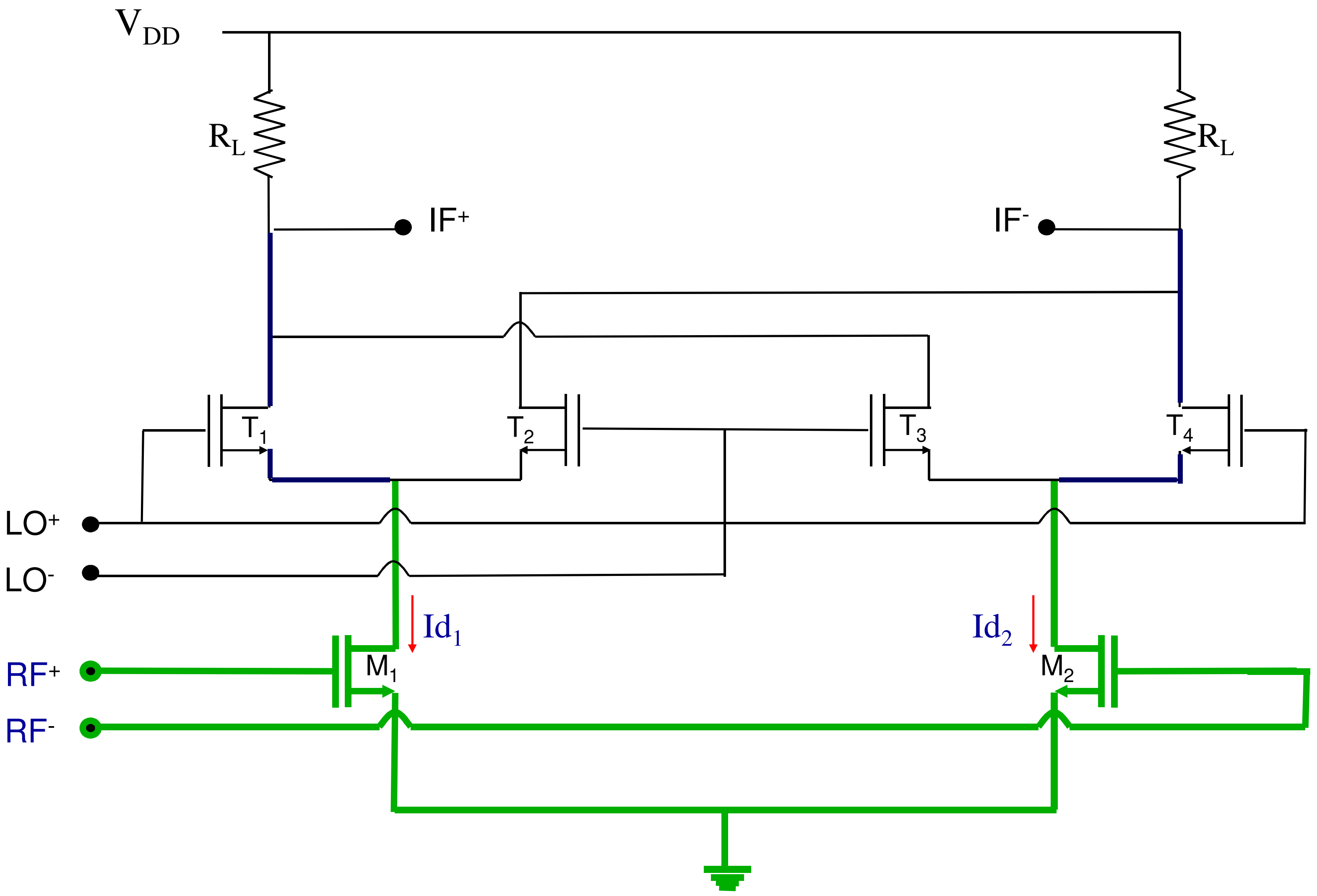
→ The RF signal is fully transposed at the IF frequency

Double Balanced Active Gilbert Cell Mixer



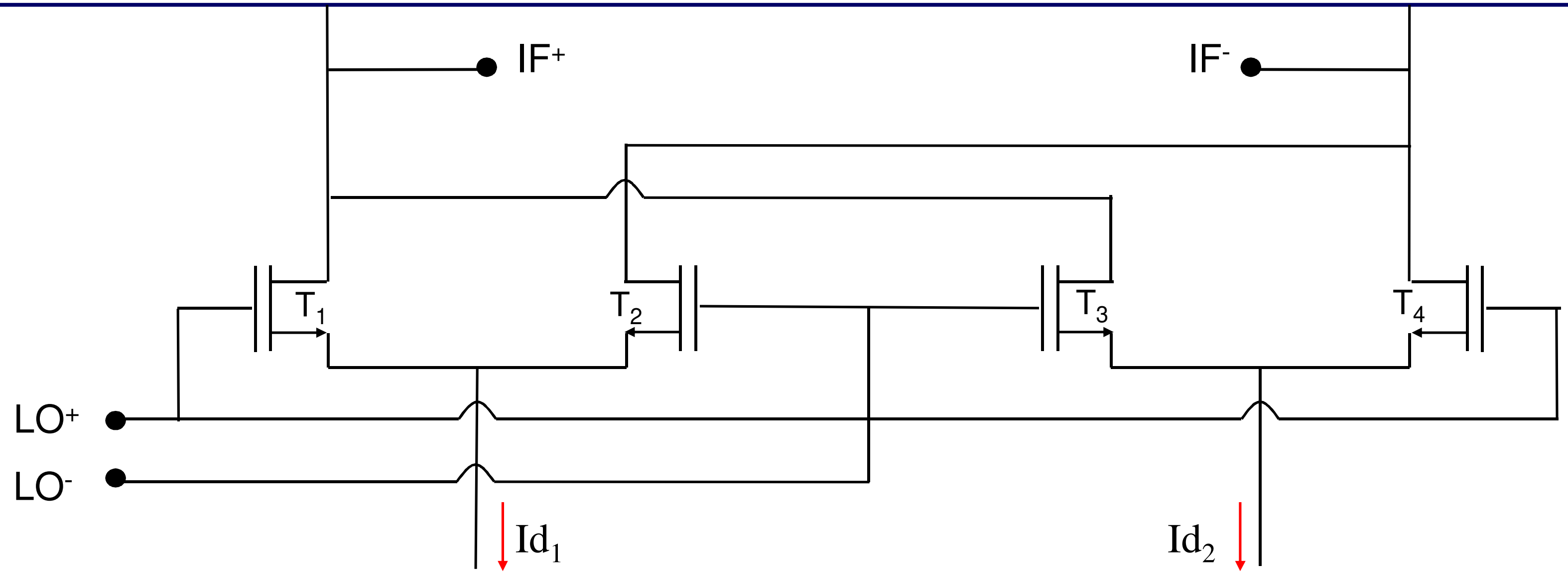
- **The differential RF pair** gives gain and the RF-IF path must be as linear as possible
- **The 2 LO pairs** work as switches to perform the frequency conversion

Differential RF pair : Voltage-Current conversion



The differential RF pair gives the conversion gain through the drain current Id (Vgs)

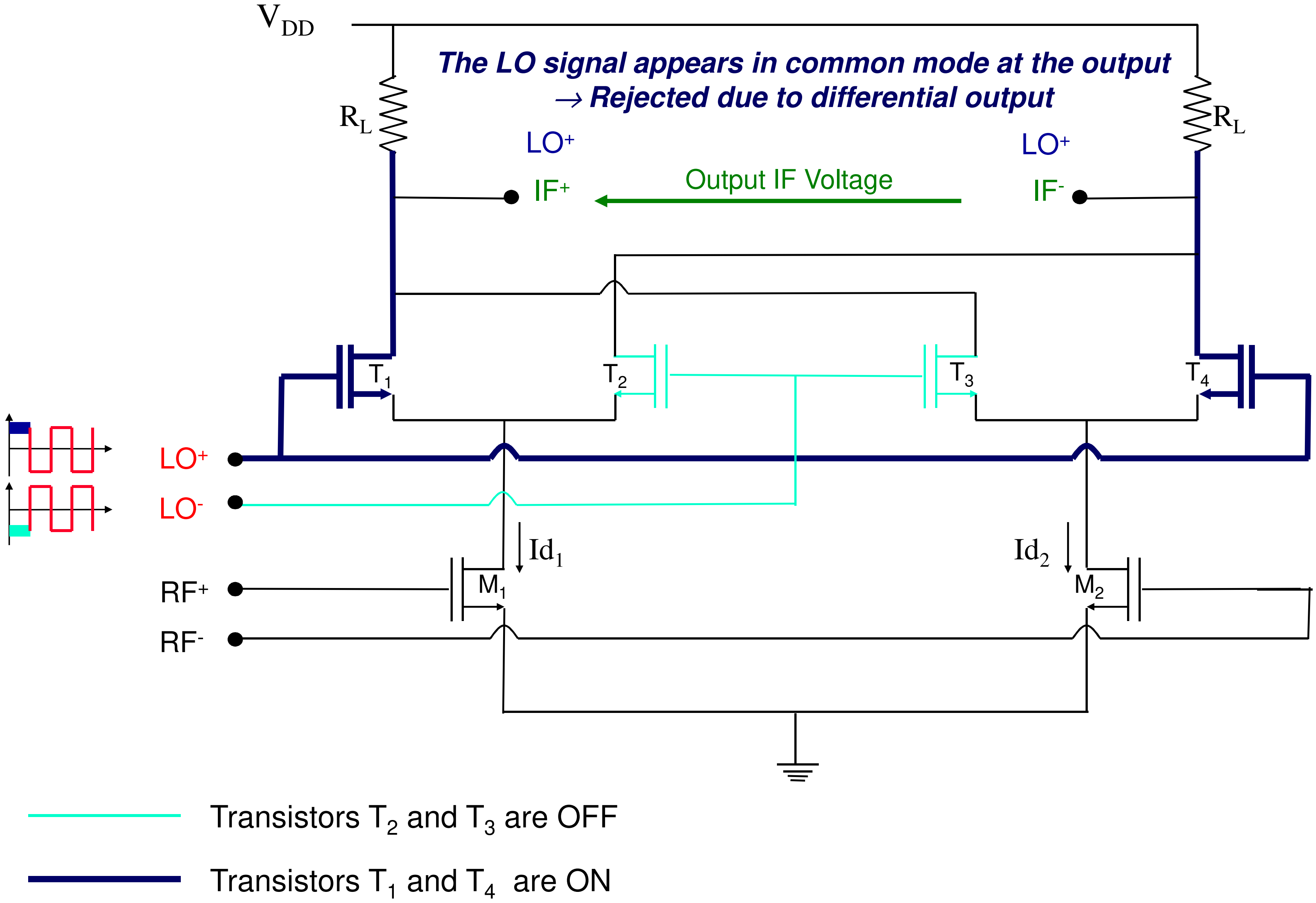
Differential LO pairs operate as switches : Mixing Core



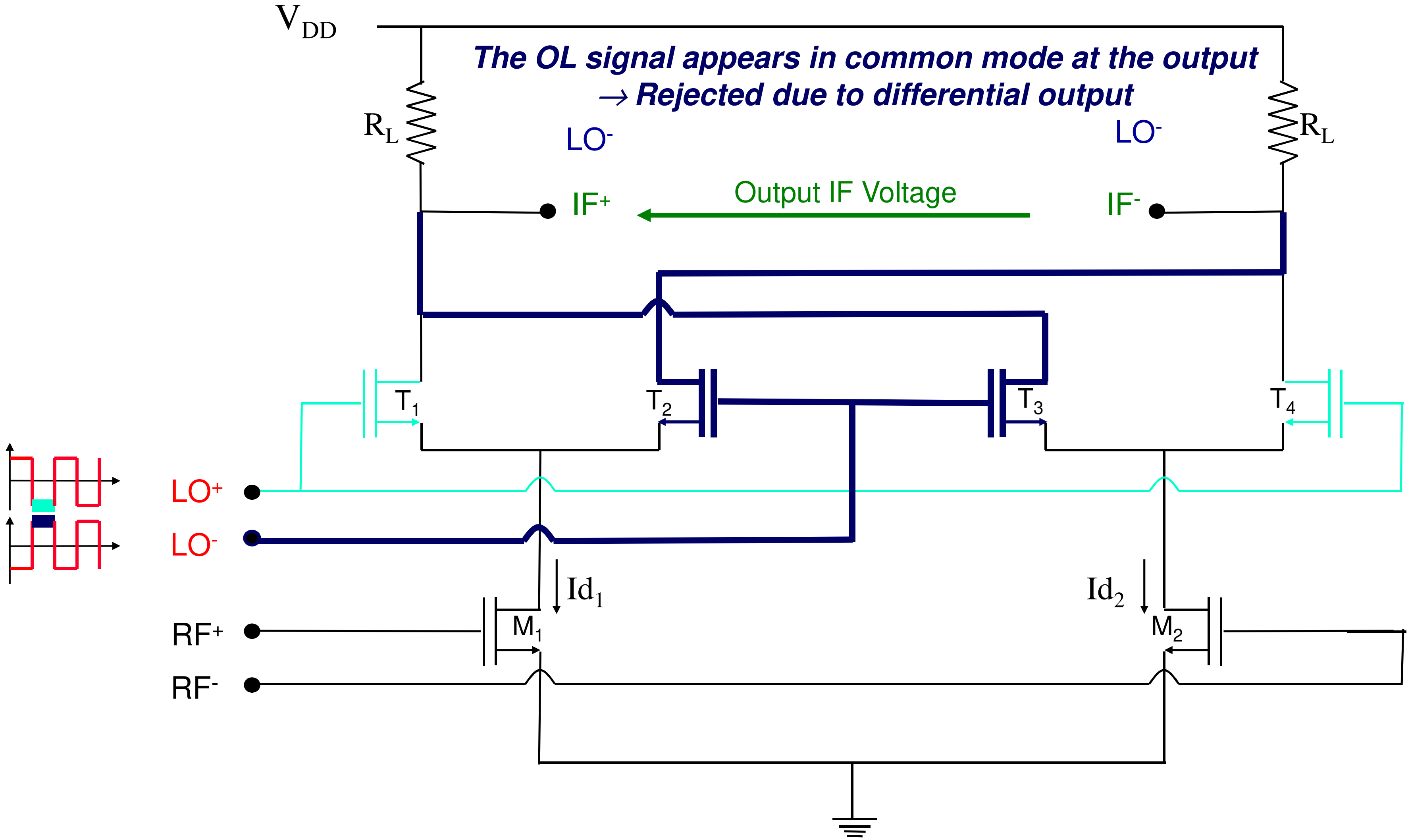
• Id_1 and Id_2 currents of the RF pair are flowing towards the two LO pairs controlled by the outphased LO signals

• The 2 LO pairs operate as switches ⇔ Requirement of a large LO power to allow an efficient ON/OFF operation

LO pair : Switching
1st Positive Alternation [0 - $T_{LO}/2$]



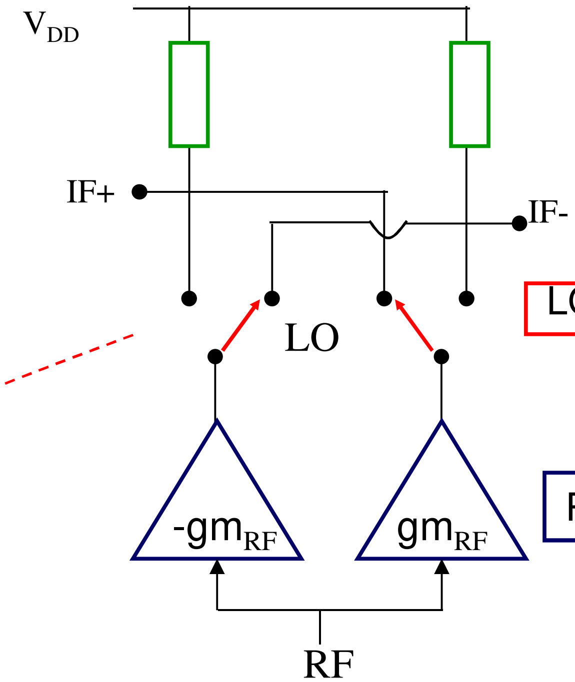
LO pair : Switching
2nd Negative Alternation [$T_{LO}/2 - T_{LO}$]



Transistors T_1 and T_4 are OFF

Transistors T_2 and T_3 are ON

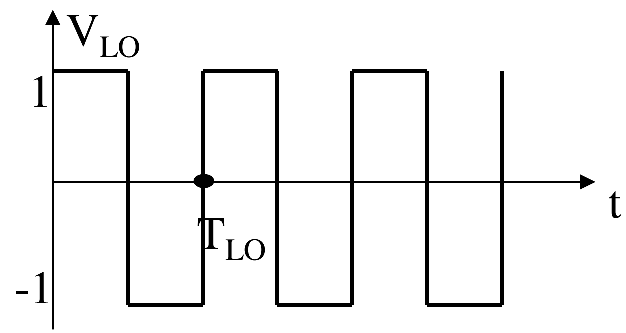
Operating mode of the Gilbert DBM



LO stage « switching - mixing »

RF stage « Linear Conversion V→I »

LO switching

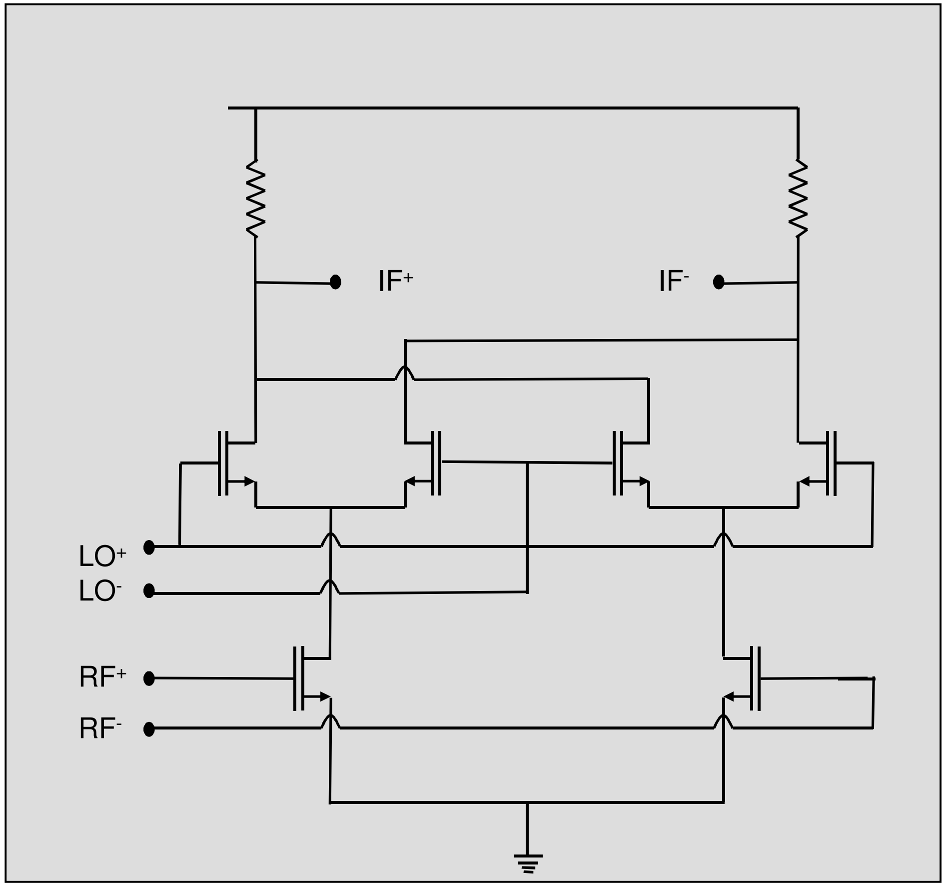


- *No generation of even LO Harmonics*

$$\text{sign}[V_{LO}(t)] = \frac{4}{\pi}\left[\cos(\omega_{LO}.t) - \frac{1}{3}\cos(3\omega_{LO}.t) + \frac{1}{5}\cos(5\omega_{LO}.t) - \ \dots\right]$$

Example of two DBM (Active and Passive):
Active DBM mixer (Gilbert Cell) / Passive DBM mixer (Ring mixer of cold FETs)

Double Balanced Mixer « Gilbert Cell»



« Passive ring mixer »