Outline

- **Introduction**
- **Theory of frequency conversion**
- **Characteristic performances of mixers**
- **Active mixers**
  - 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**

Passive “Resistive” Mixers

Multiplication: Resistive Mixers

- **Principle :** Implementing a multiplication by using the Ohm's law

$$V = R.I \quad \text{or} \quad I = G.V$$

$$V_{out}(t)=R(t).I_{in}(t) \quad \text{or} \quad I_{out}(t)=G(t).V_{in}(t)$$

- **Varying nonlinear conductance G(t)** = nonlinear element driven by a large signal @ LO

→ Obtain a time varying conductance and its required frequency spectrum

- **Expansion of G(t) in Fourier transform:**

$$\underbrace{G(t) = G_0 + G_1.\cos(\omega_{LO}.t)}_{\text{Ideal term}} \underbrace{+ G_2.\cos(2\omega_{LO}.t) + G_3.\cos(3\omega_{LO}.t)}_{\text{Spurs for a fundamental mixer}} + \dots$$

Ideal term

Spurs for a fundamental mixer (*However 2nd harmonic can be used for subharmonic mixers*)

- The mixing is obtained by applying a low signal $\mathbf{V_{RF}}$ at the input of the time varying conductance to create the required converted current at IF

$$\mathbf{I_S(t)= G(t)\ .\ V_{RF}(t)}$$

$$\omega_{IF} \qquad \omega_{LO} \qquad \omega_{RF}$$

Principle of Diode Mixers

Minimum of conversion losses for passive mixers

- **Ideal case of a diode mixer :**

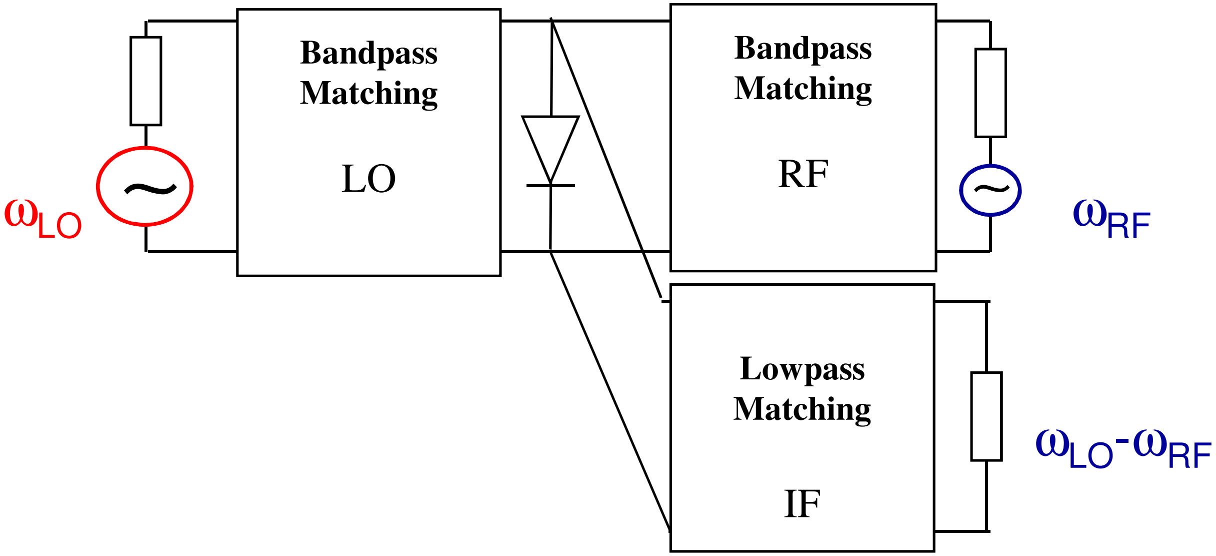
$\rightarrow Lc_{MIN} \cong 4$ dB

- **Actual case :**

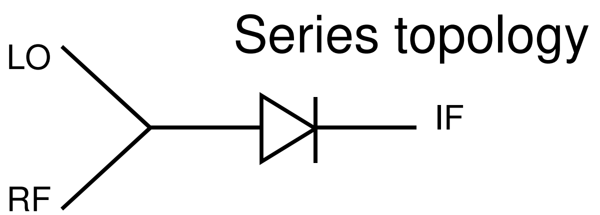
$Lc_{MIN} \approx 5$ à 6 dB

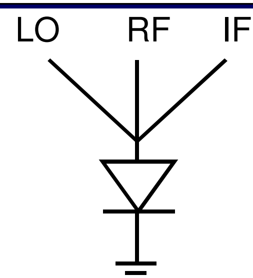
$$Lc = f\ \left[I\text{-}V_{NL}\ ,\ V_{LO}(t)\ ,\ Z_L(\omega_{SPURS}) \right]$$

Diode-based SEM



Critical matching constraints for single diode mixers





Advantages:

- Low Lc and P_{LO}

Disadvantages:

- No suppression of spurs
- Bandwidth and isolation are greatly limited by critical filtering issues
- Filter losses increase Lc $\rightarrow$ Very few diode-based SEM

SBM and DBM diode-based mixers

SBM: Single Balanced Mixer= 2 SEM with couplers or baluns

DBM: Double Balanced Mixer = 2 SBM with couplers or baluns

⬇

Advantages

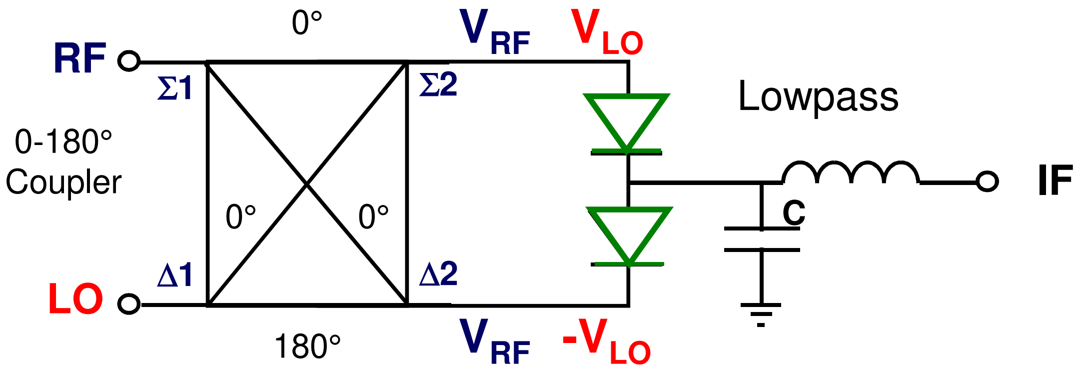
- Suppression of some spurs by out of phase recombination
- Good LO-RF Isolation and sometimes LO-IF isolation without filtering issues

Disadvantages

- Requirement of higher levels of LO power

Example of a diode-based SBM (LO at Δ port)

•Architecture with 180° coupler (LO @ Δ)



180° Coupler

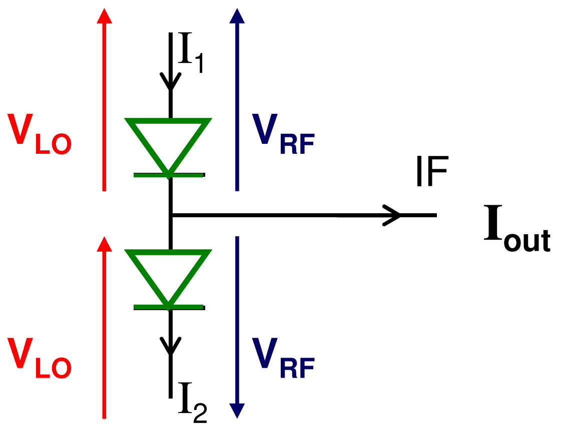
Input Matching $_{@LO/RF} \approx$ Input Matching$_{@LO/RF}$ of coupler

Isolation LO-RF $\approx$ Isolation LO-RF of coupler

LO @ $\Sigma \rightarrow$ mix[EH(LO), *] rejected

LO @ $\Delta \rightarrow$ mix[* , EH(RF)] rejected

• Operation mode (LO @ Δ)



Diode current law

$$I(V) = \mathbf{F}(V) = a.V + b.V^2 + c.V^3 + \ldots$$

$$I_1 = \mathbf{F}\,(\mathbf{V_{LO}} + \mathbf{V_{RF}})$$

$$I_2 = \mathbf{F}\,(\mathbf{V_{LO}} - \mathbf{V_{RF}})$$

$$\mathbf{V_{LO}}^p \;.\; \mathbf{V_{RF}}^q \rightarrow \pm\, p.\boldsymbol{\omega}_{\mathbf{LO}} \pm\, q.\boldsymbol{\omega}_{\mathbf{RF}}$$

$$I_{OUT} = I_1 - I_2 = 0 \;\Leftrightarrow\; \omega = \pm\, m.\boldsymbol{\omega}_{\mathbf{LO}} \pm\, n.\boldsymbol{\omega}_{\mathbf{RF}}$$

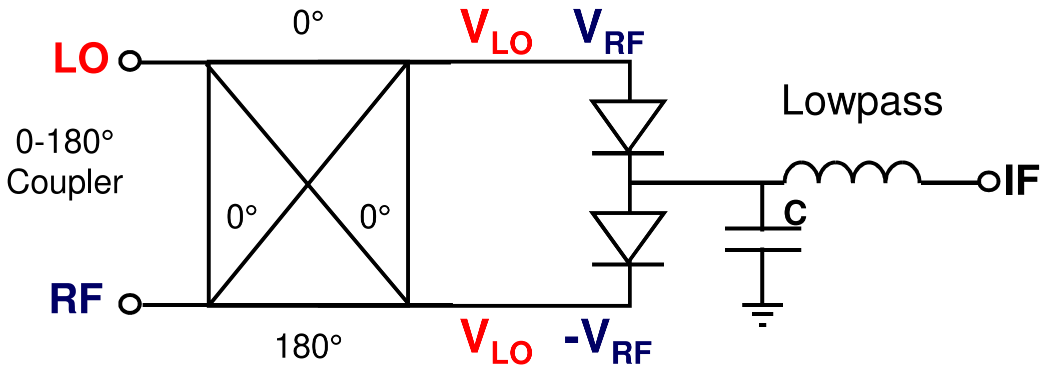
If **n is even** because $(\mathbf{V_{RF}})^n = (-\mathbf{V_{RF}})^n$

ω_{LO} , $2(\omega_{LO} - \omega_{RF})$, … suppressed @ IF port $\rightarrow$(LO-IF Isolation) …

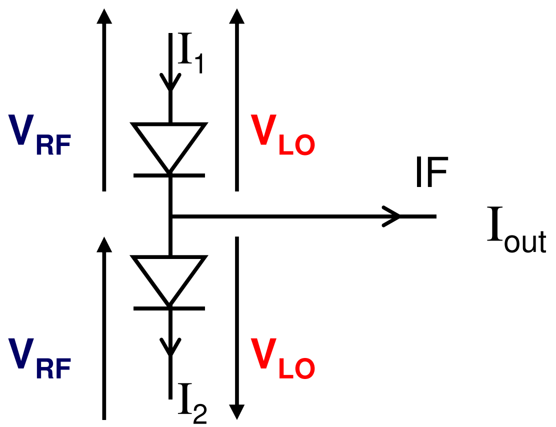
n=0 **n=2**

Diode-based SBM : LO and RF ports are reversed (LO at Σ port)

- Architecture with 180° coupler (LO @ Σ)



- If LO and RF are reversed



$$I(V) = F(V) = a.V + b.V^2 + c.V^3 + \ldots$$

$$I_1 = F\,(V_{RF} + V_{LO})$$

$$I_2 = F\,(V_{RF} - V_{LO})$$

$$V_{LO}^{p}\ .\ V_{RF}^{q} \rightarrow p\omega_{LO} \pm\ q\omega_{RF}$$

$$I_{OUT} = I_1 - I_2 = 0 \ \Leftrightarrow\ \omega = \pm\, m.\boldsymbol{\omega_{LO}} \pm\ n.\boldsymbol{\omega_{RF}}$$

If **m is even** because $(V_{LO})^m = (-V_{LO})^m$

ω_{RF} , $2(\omega_{LO} - \omega_{RF})$, … suppressed @IF port →(RF-IF Isolation) …

m=0 m=2

Less critical

Diode-based SEM

- Properties are linked to the architecture (Baluns, Couplers, …)
- Conversion losses of SBM are higher than conversion losses of SEM

  (Coupler losses, Non ideal phase shift and amplitude balance …)
- SBM enable to suppress critical spurs and enhance isolations

⬇

Diode-based SBM are more efficient than diode-based SEM

Diode-based DBM

A diode-based DBM

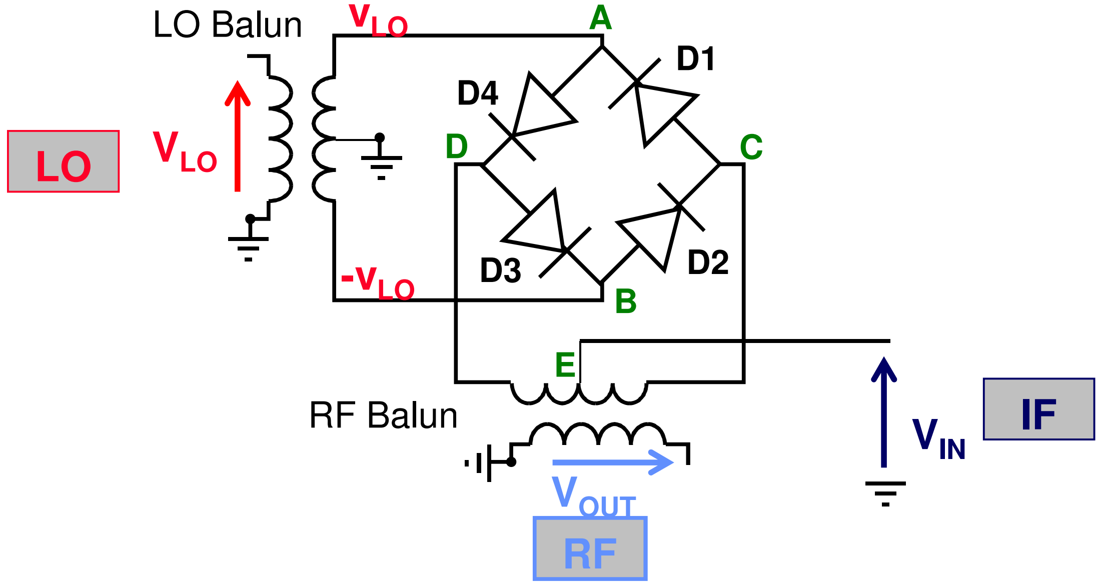
integrates 2 pairs of diodes

Diode-based DBM are preferred to SBM

if the isolation requirements are more critical than the conversion loss specifications

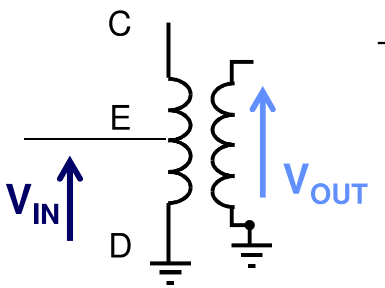
Example of diode-based DBM : Ring oscillator

• Architecture



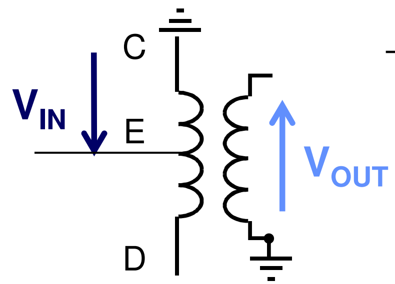
• Operation principle (Diode = switch controlled by LO)

If ($V_{LO}>0$) $\rightarrow$ ($V_A>V_B$) $\rightarrow$ (D_1,D_2)=OFF and (D_3,D_4)=ON
$\rightarrow$ D is a virtual ground
$\rightarrow$ C is an open circuit



$\rightarrow$ $\boxed{V_{OUT} = + V_{IN}}$

Si ($V_{LO}<0$) $\rightarrow$ ($V_A<V_B$) $\rightarrow$ (D_1,D_2)=ON and (D_3,D_4)=OFF
$\rightarrow$ C is a virtual ground
$\rightarrow$ D is an open circuit



$\rightarrow$ $\boxed{V_{OUT} = - V_{IN}}$

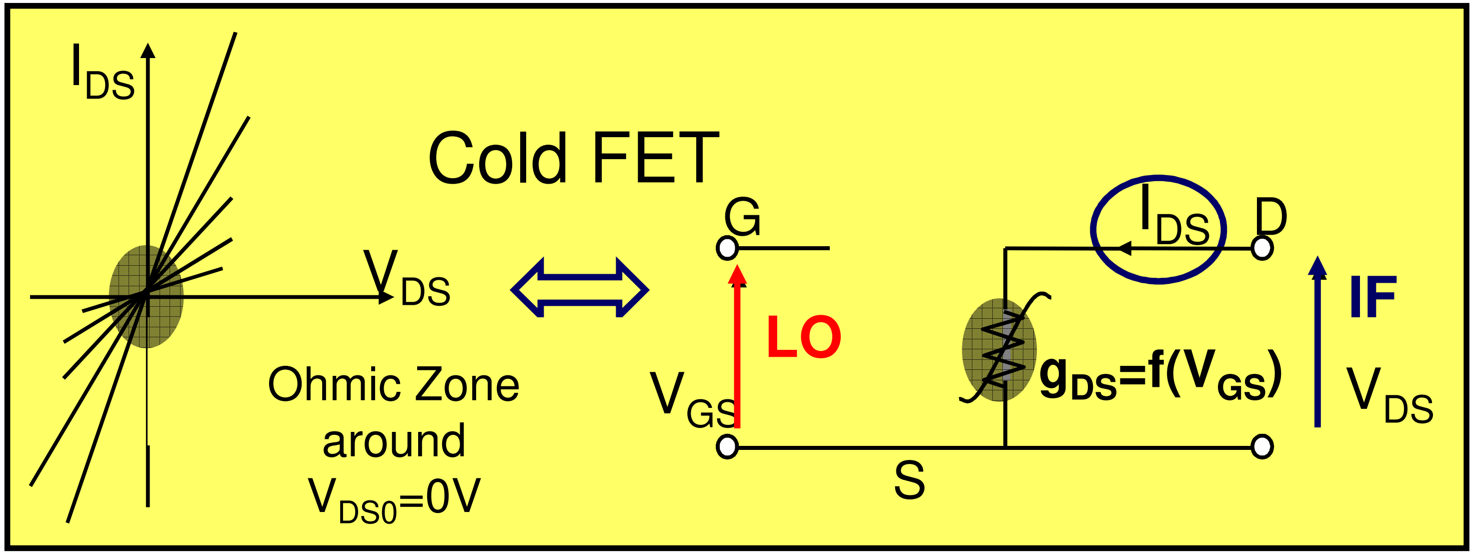
$\rightarrow$ $\boxed{V_{OUT}(t) = \mathbf{sign}[V_{LO}(t)] \times V_{IN}(t)}$ avec $\mathbf{sign}[V_{LO}(t)] = \frac{4}{\pi}\left[\cos(\omega_{LO}t) - \frac{1}{3}\cos(3\omega_{LO}t) + \frac{1}{5}\cos(5\omega_{LO}t) - \ ...\right]$

$\boxed{V_{OUT} = 0 \Leftrightarrow \omega = m.\omega_{LO} \pm n.\omega_{IF}}$ / (m or n) even $\rightarrow$ ω_{LO} , ω_{IF} … suppressed @ RF port

Cold-FET mixers : Principle

Main advantages : High linearity and No Consumption

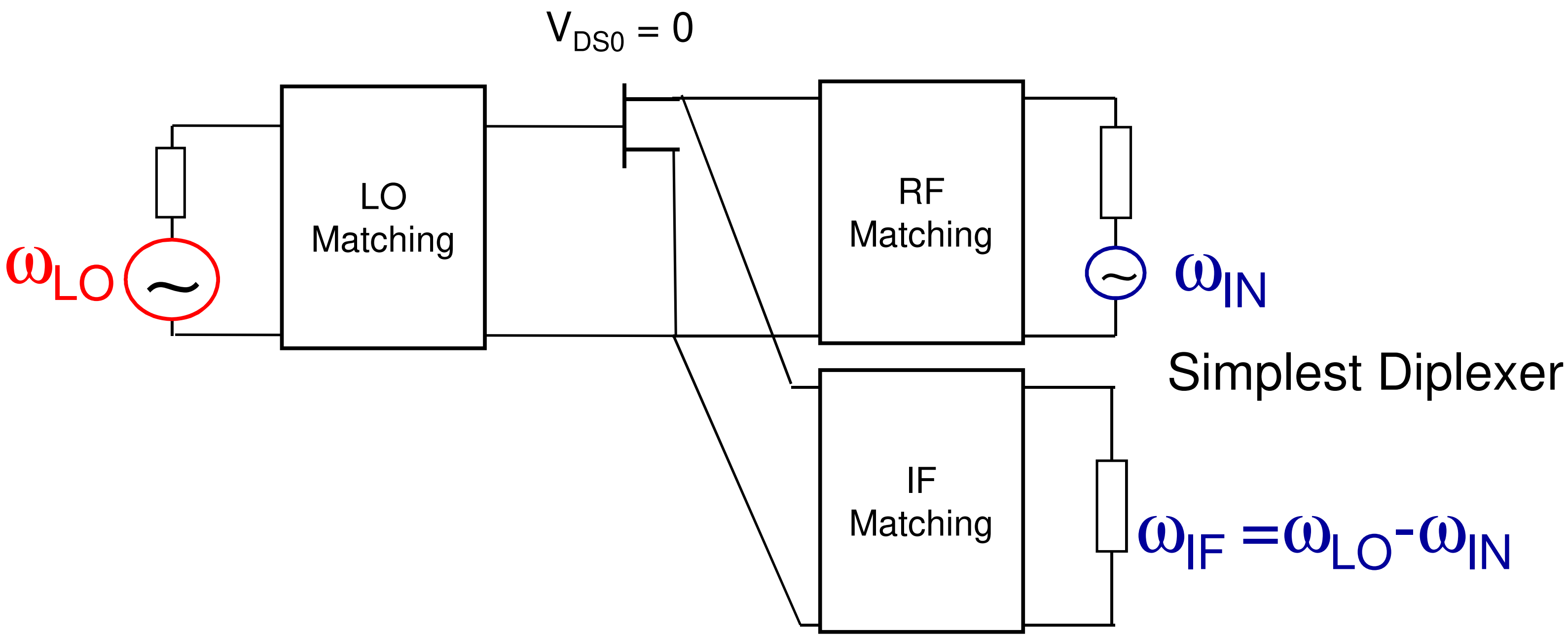
Principle of cold-FET resistive mixers



<u>Not biased Drain</u> → Transconductance gm is zero @ $V_{DS0}=0$

→ Resistive Nonlinearity R_{DS} (V_{GS}) between drain and source

Cold-FET advantages



$\rightarrow$ <u>Simplified design constraints</u>

- better LO-RF isolation due to the intrinsic G-D isolation of FETs (depends on Cgd and ω)
- limited interactions between matching circuits (LO @ gate port and $\omega_{RF} >> \omega_{IF}$ @ drain port)
- higher linear voltage swing of RF signal from 0 to knee voltage $\rightarrow$ higher linearity
- Only mixer that can be efficiently used in SEM configuiration

$\rightarrow$ <u>Other solutions</u>: SBM and DBM cold-FET mixers

Comparison (Diode / Cold FET)

- Conversion losses

  $\rightarrow L_C$(Diode Mixers) < L_C(Cold-FET mixers) because R_{MIN}(Diode)<R_{MIN} (Cold-FET)

- Linearity/Saturation

  - Linearity of diode-based mixer is limited to very low level of RF signal (exponential current)

  - Linearity of cold-FET mixer is limited to moderate level of RF signal (ohmic zone)

    $\rightarrow$ Higher linearity of cold-FET and higher output power

- Isolations

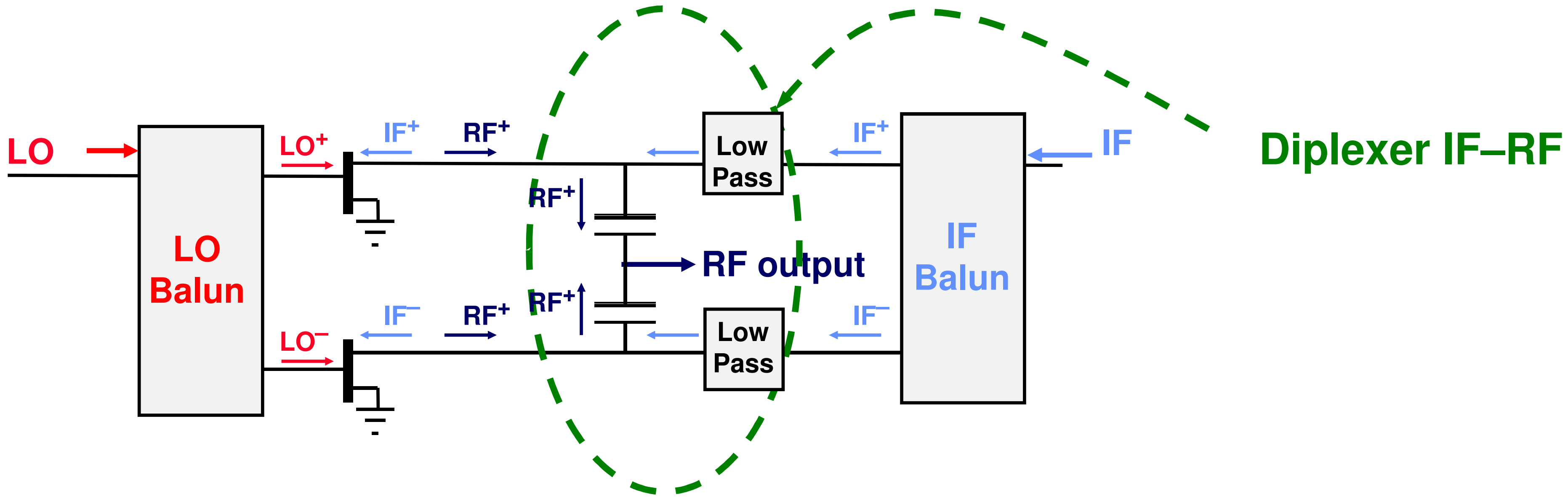
  - Diodes do not have intrinsic isolation → can only used in complex balanced architectures
  - Cold-FETs have the intrinsic G-D isolation → can be used as SEM or balanced topologies

Cold-FET SBM

Cold-FET SBM

- Example of SBM with LO and IF baluns (emission)

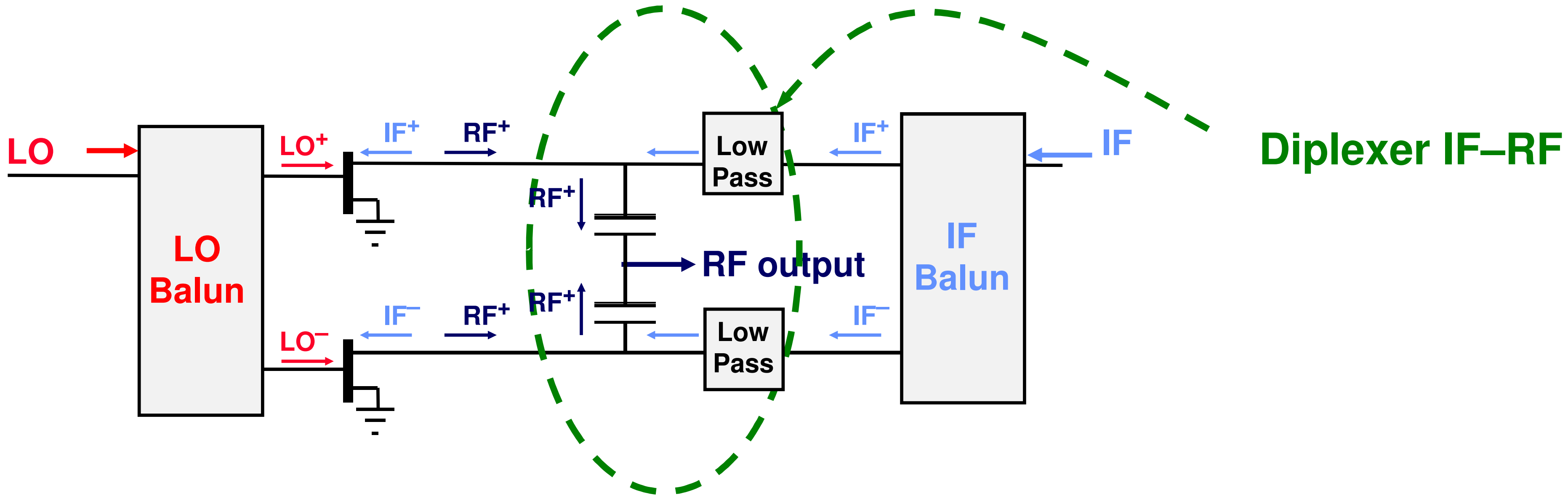
  - Pair of cold-FETs



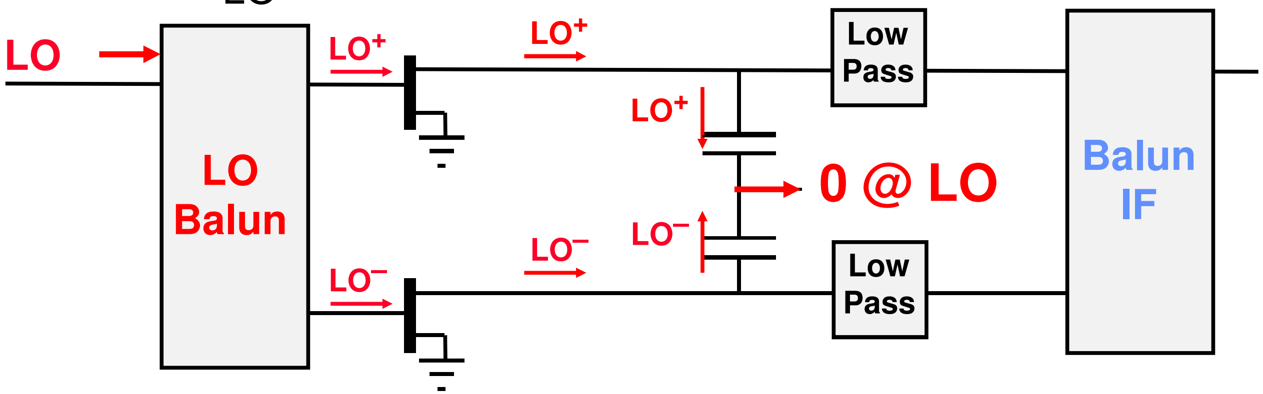
Cold-FET SBM

- Example of SBM with LO and IF baluns (emission)

  - Pair of cold-FETs



  - Balanced architecture ⇒ ω_{LO} suppressed @ drain port

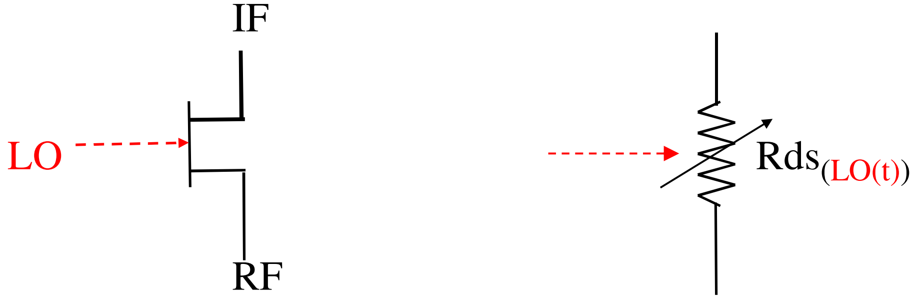


Cold-FET DBM

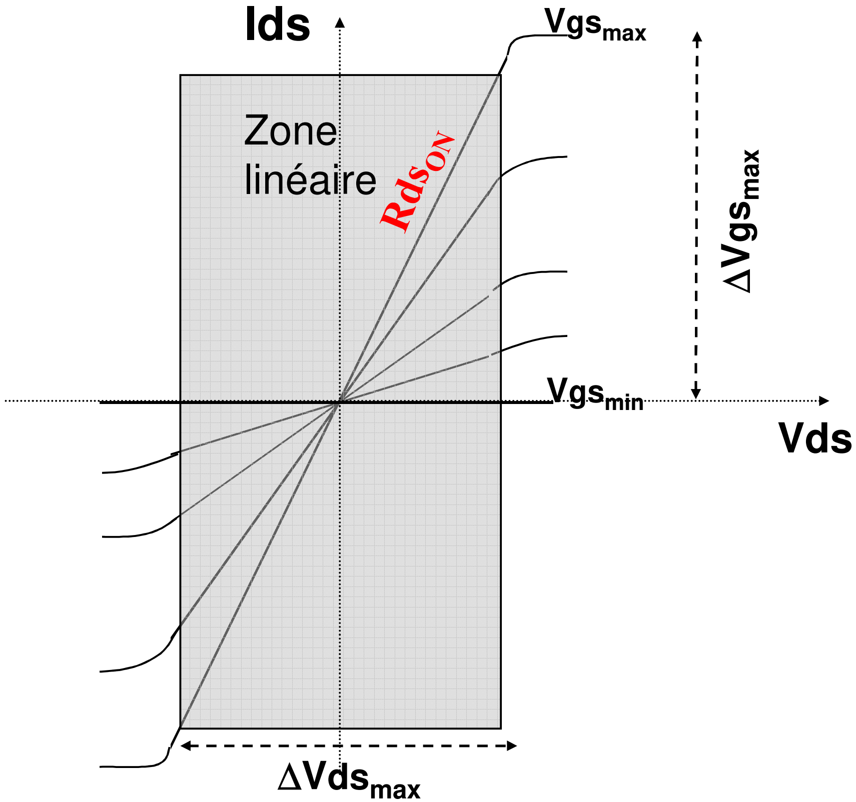
Ring mixer

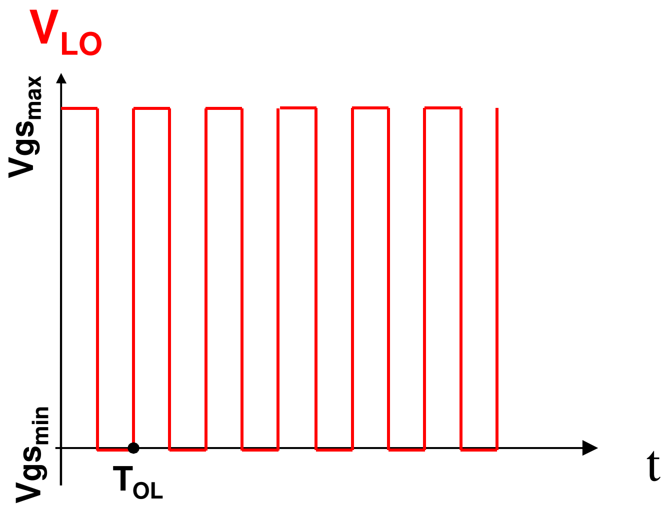
4 Cold-FETs + 3 Baluns (RF, IF, LO)

Switch mode of Cold-FET



The Cold-FET is switched between R_{DSON} (minimum value of R_{DS}) and ∞ (maximum value of R_{DS})

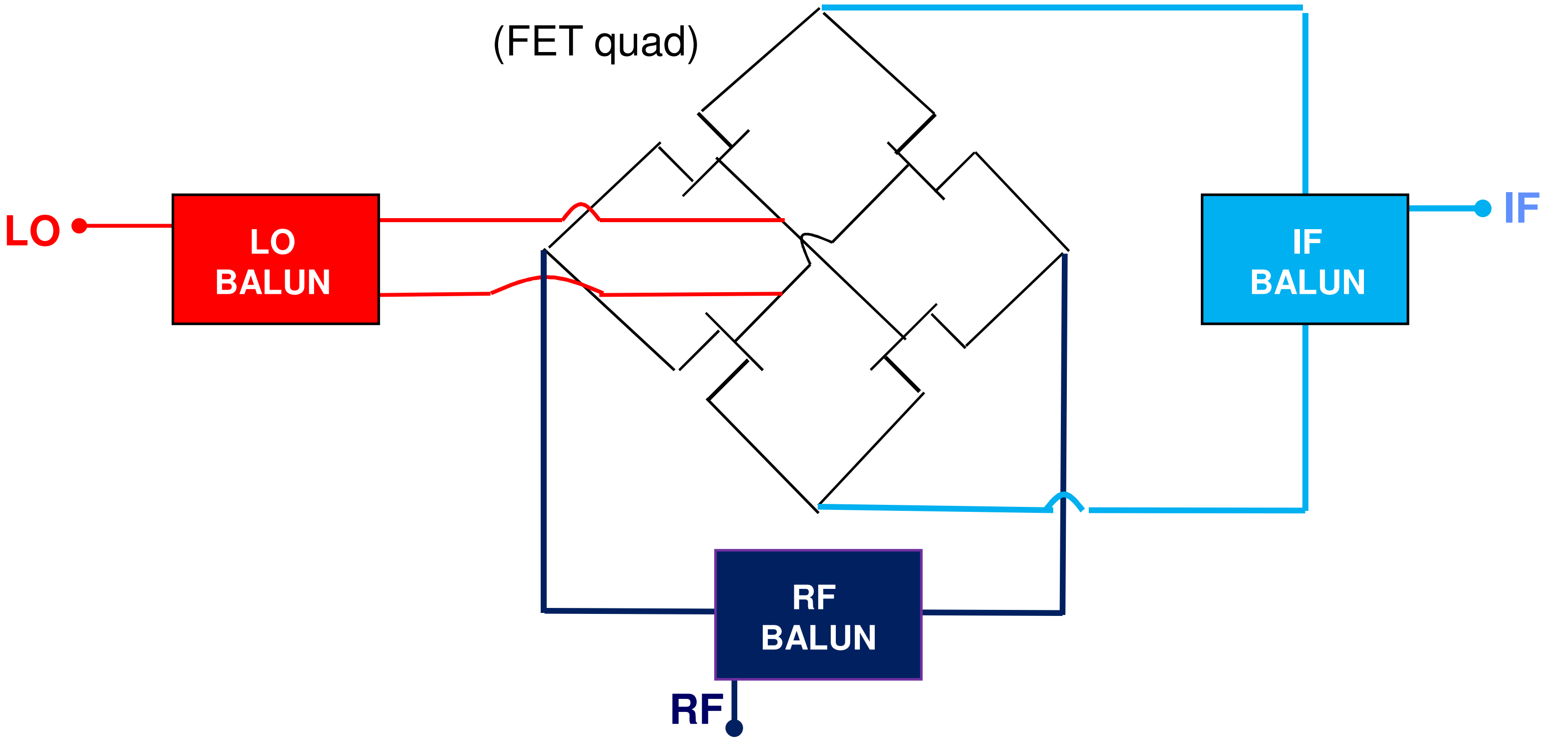




If the transistor size is increased → $(I_{DSMAX}\uparrow)$ → $(R_{DSON}\downarrow)$ → (Conversion losses ↓)

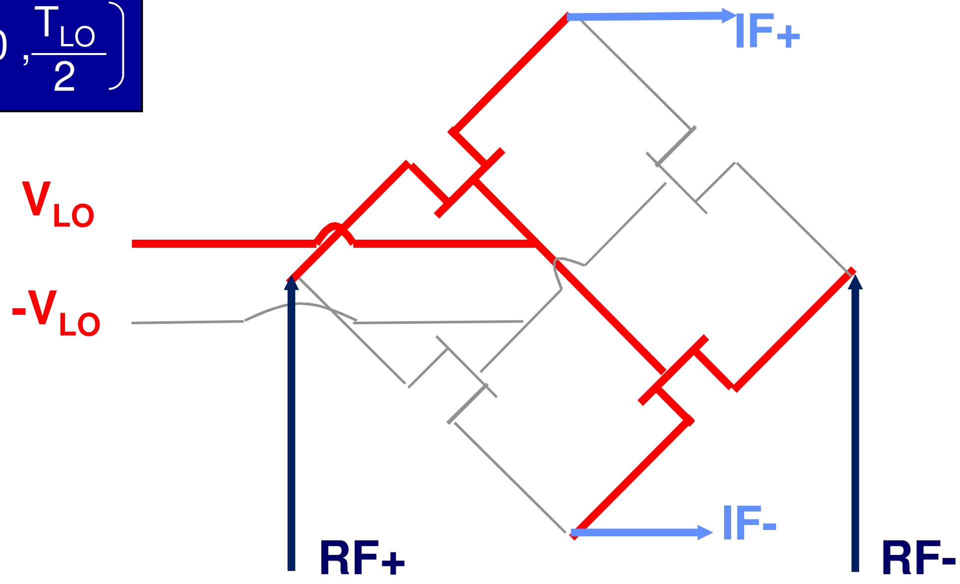
However → $(C_{GS}\uparrow)$ → (Frequency limitation ↑)

Cold-FET « Switch Mode Mixer » : Ring DBM



Operating principle of the ring Cold-FET DBM

$\left[0, \frac{T_{LO}}{2}\right]$



In the ideal case

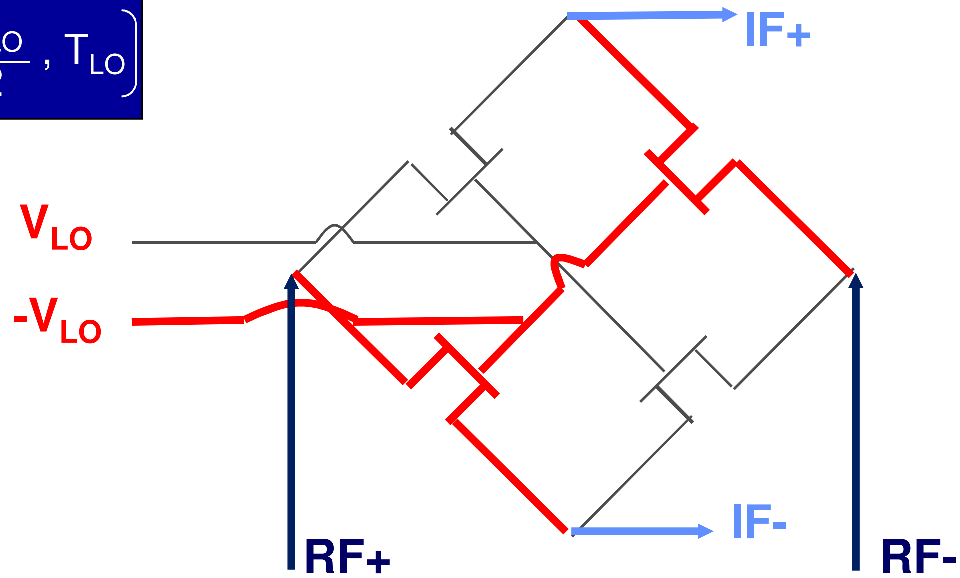
$Rds_{ON} = 0$ / $Rds_{OFF} = \infty$

$IF^{+} \approx RF^{+}$

$IF^{-} \approx RF^{-}$

Input signal is copied

$\left[\frac{T_{LO}}{2}, T_{LO}\right]$



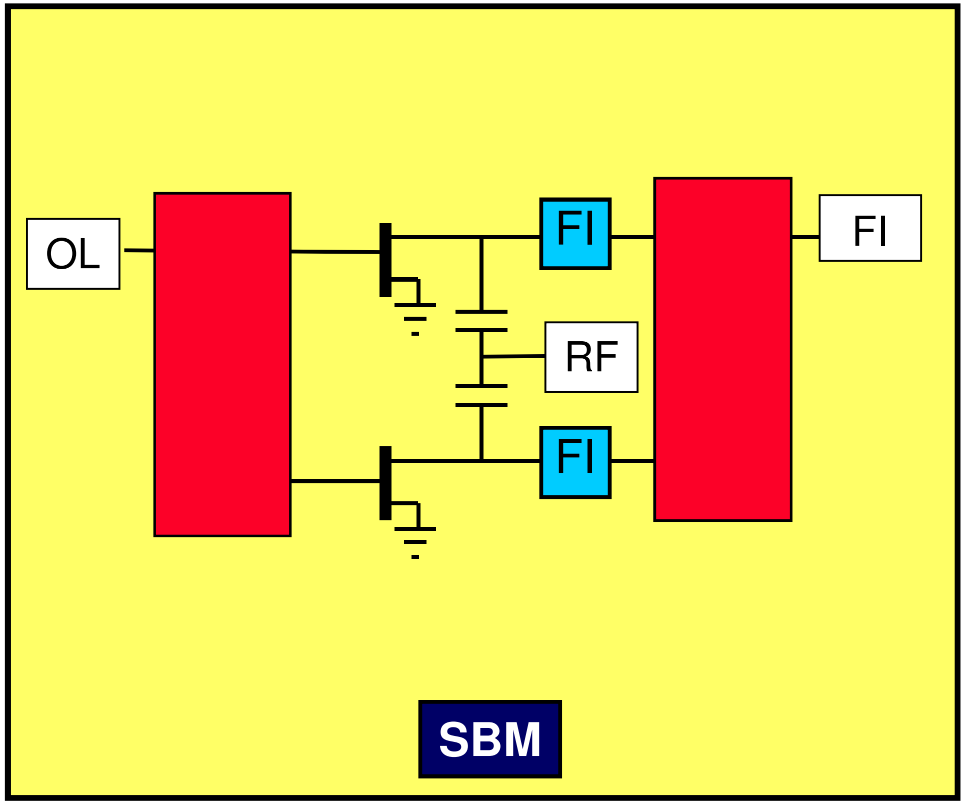
$IF^{+} \approx RF^{-}$

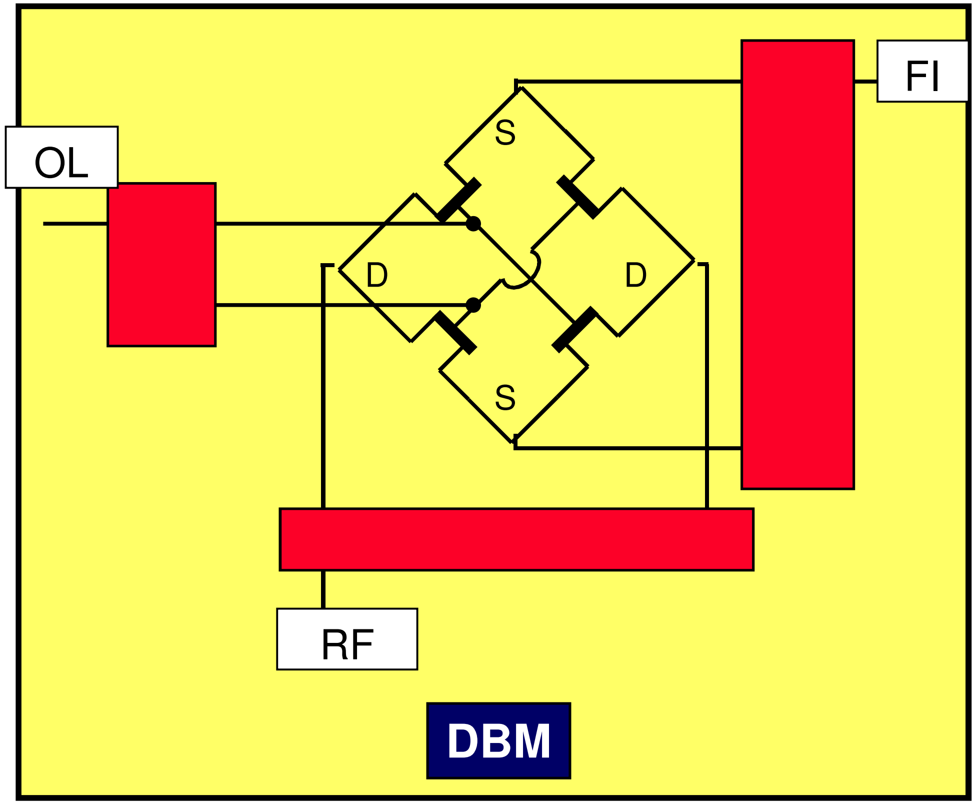
$IF^{-} \approx RF^{+}$

Input signal is reversed

Main Cold-FET mixer architectures

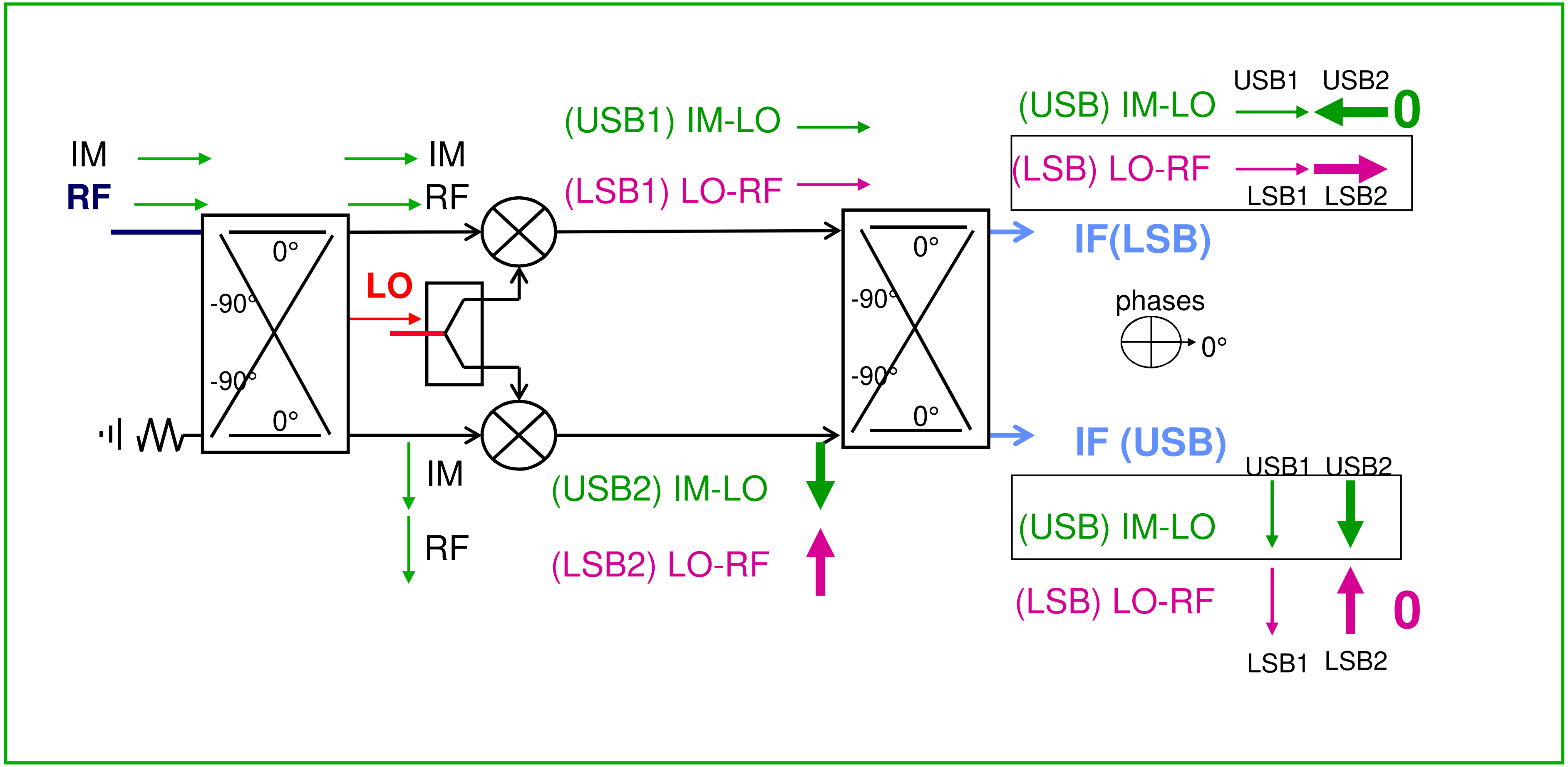
- Cold-FET Mixers





Example of IRM (Image Rejection Mixer)

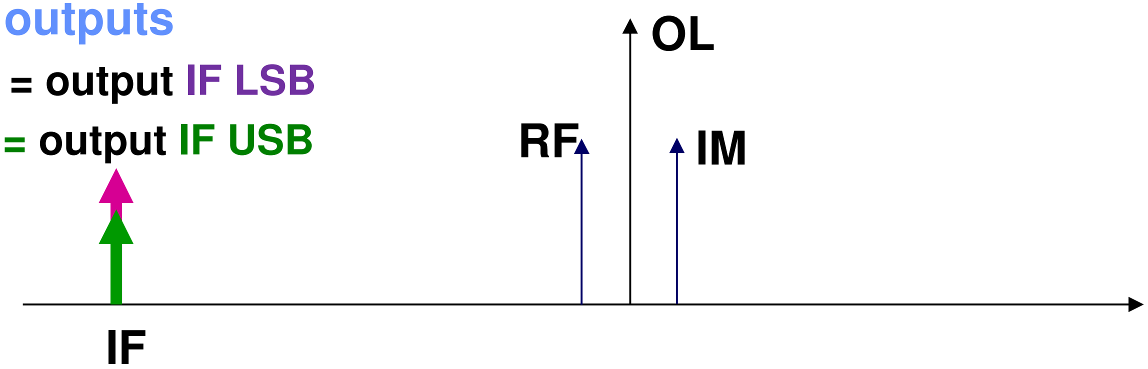
Example of IRM



IF outputs

= (LO-RF) = output IF LSB

= (IM-LO) = output IF USB



Mixer