



Introduction to CMOS RF Integrated Circuits Design

IV. Mixers

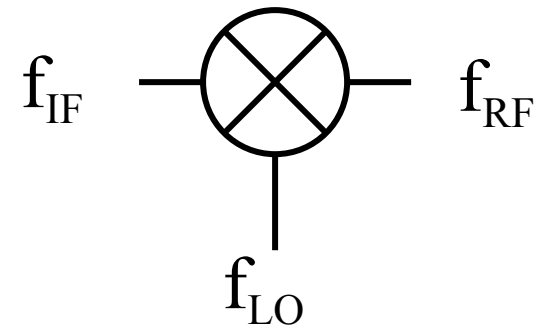
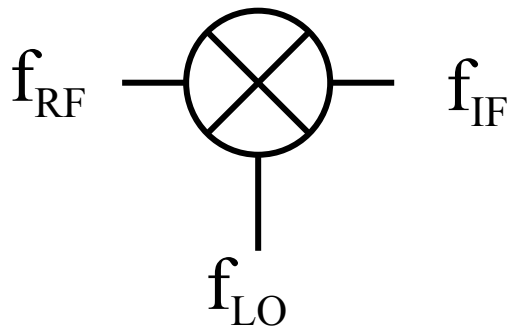


Outline

- Functionality
- Figures of Merit
- Passive Mixer Design
- Active Mixer Design
 - Single-Balanced Mixer
 - Double-Balanced Mixer (Gilbert Cell)
- Design Example

Mixer Functionality

- To perform frequency translation (Up-conversion and Down-Conversion)
- Linearity must be good to avoid SNR degradation due to interference
- Positive gain is preferred



$$v_{IF}(t) = K v_{RF}(t) v_{LO}(t)$$

Frequency Translation

$$v_{\text{OUT}}(t) = K v_{\text{RF}}(t) v_{\text{LO}}(t)$$

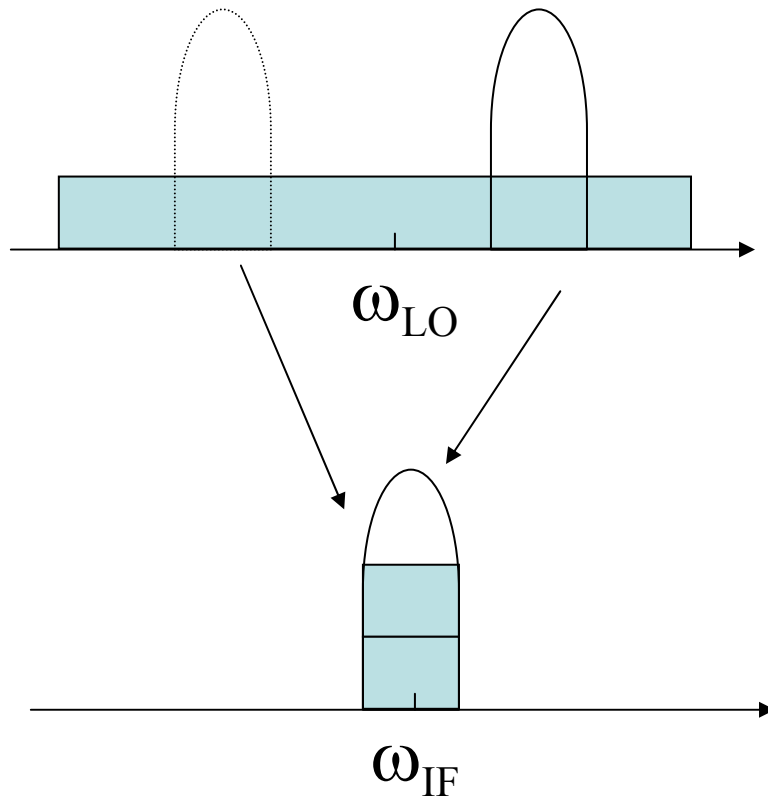
$$v_{\text{RF}}(t) = A(t) \cos(\omega_0 t + \phi(t))$$

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

$$v_{\text{OUT}}(t) = \frac{KA(t)A_{\text{LO}}}{2} \{ \cos((\omega_{\text{LO}} + \omega_0)t + \phi(t)) + \cos((\omega_0 - \omega_{\text{LO}})t + \phi(t)) \}$$

- Low-pass filter for down-conversion
- High-pass filter for up-conversion

Image Rejection



$$|\omega_{LO} - \omega_0| = |\omega_{LO} - \omega_{Image}|$$

We need Image Rejection Filter!

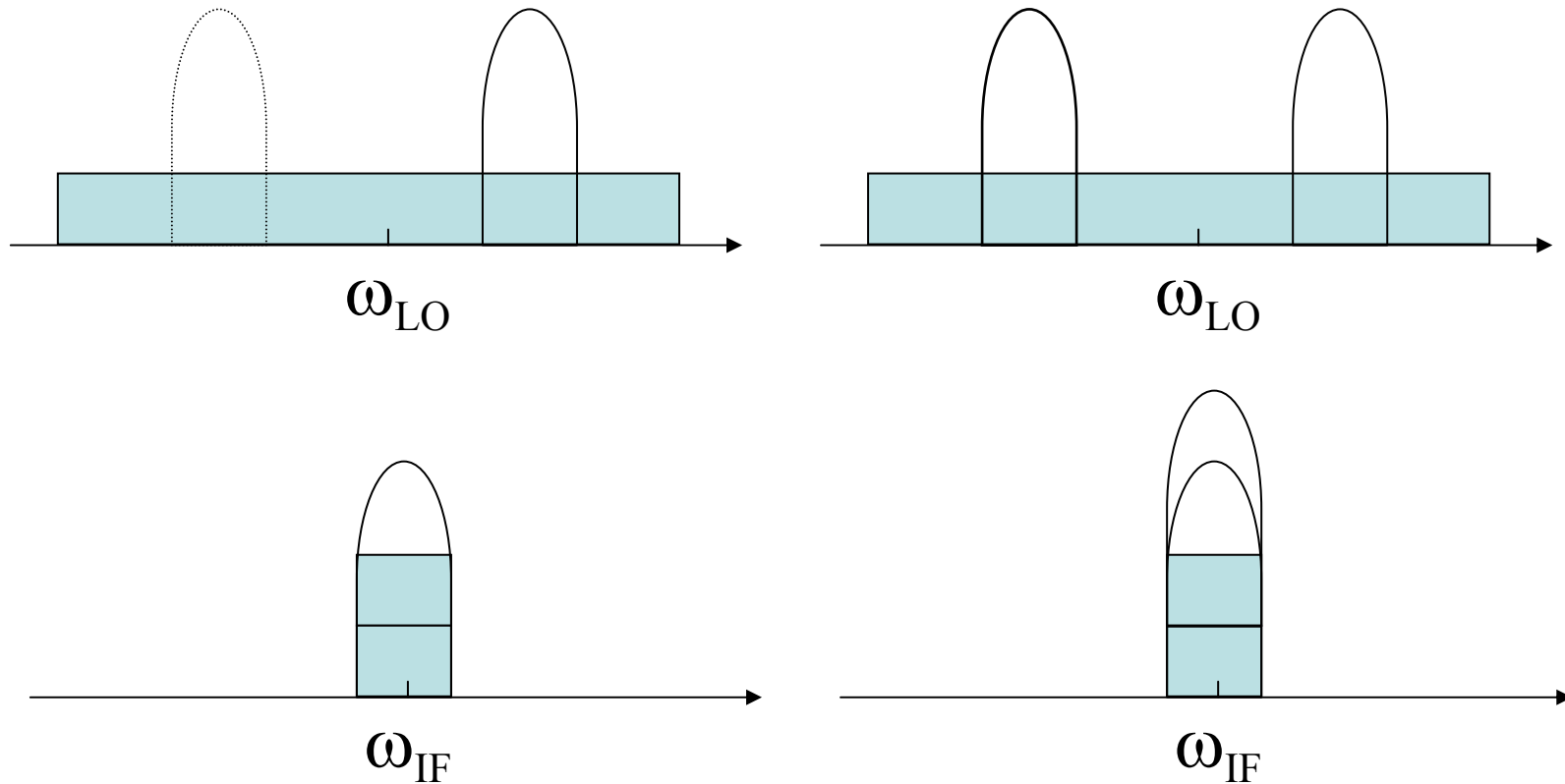
Mixer Figures of Merit

- Frequency and Bandwidth
- Linearity (P-1dB, IIP3)
- Noise Figure
- Conversion Gain
- Power Consumption
- Supply Voltage
- Isolation (RF-LO, LO-RF, LO-IF)

Typical Values

IIP3	~ 10 dBm
P-1dB	~ 0 dBm
Gain	10 dB
NF	~ 12 dB
Port Isolation	< -20 dB
Current	~ 3 mA

Mixer Noise Figure



Single-Sideband (SSB) NF

Double-Sideband (DSB) NF

SSB vs DSB NF

- SSB NF Applied if Desired Signal Exists at Only One Frequency
- DSB NF Applied if Desired Signals Exist at Both Image and Desired Frequencies
- SSB NF = DSB NF + 3 dB
- Typically, Desired Signal Only Exists at One Frequency => SSB NF
- For Direct Conversion, No Image Noise => DSB NF

Input/Output Matching

- Input matching is needed if an off-chip image-rejection filter is used in front to:
 - Maximizes Power Transferred
 - Preserves Characteristics of the Filter
- Output matching is needed if an off-chip channel-selection filter is used

Conversion Gain

The conversion gain may be measured as *voltage* or *power gain*.

Voltage Conversion Gain = rms voltage of the IF signal / rms voltage of the RF signal

Power Conversion Gain = IF Power delivered to the load / rms available RF power from the source

Port-to-Port Isolation

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).

Multiplication: Non-Linearity

The multiplication can be implemented with a multiplier or nonlinear circuit

$$V_{out} = a_0 + a_1 V_{in} + a_2 V_{in}^2 + a_3 V_{in}^3 + a_4 V_{in}^4 + \dots$$

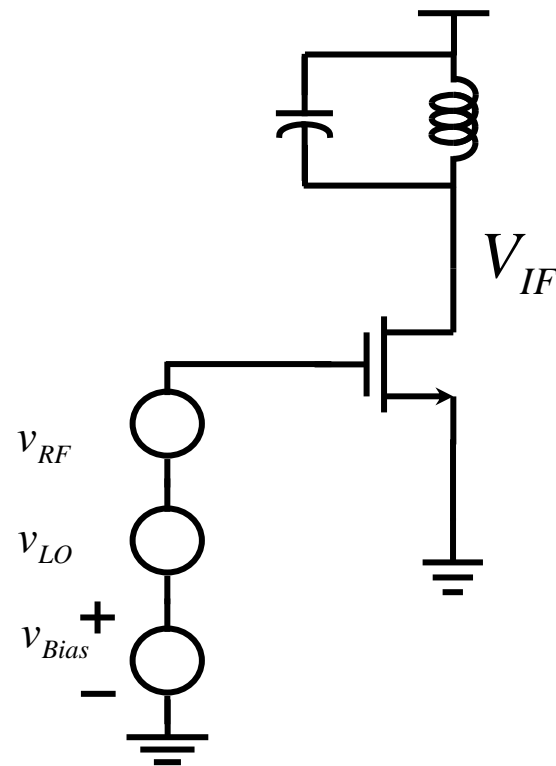
$$v_{in}(t) = V_{RF} \cos(\omega_{RF} t) + V_{LO} \cos(\omega_{LO} t)$$

$$\begin{aligned} v_{out}(t) = & a_1 [V_{RF} \cos(\omega_{RF} t) + V_{LO} \cos(\omega_{LO} t)] \\ & + a_2 [V_{RF}^2 \cos^2(\omega_{RF} t) + V_{LO}^2 \cos^2(\omega_{LO} t)] \\ & + 2 * a_2 [V_{RF} \cos(\omega_{RF} t) V_{LO} \cos(\omega_{LO} t)] + \dots \end{aligned}$$

↙

$$a_2 V_{RF} V_{LO} [\cos(\omega_{RF} + \omega_{LO})t + \cos(\omega_{RF} - \omega_{LO})t]$$

Implementation of a Simple Mixer

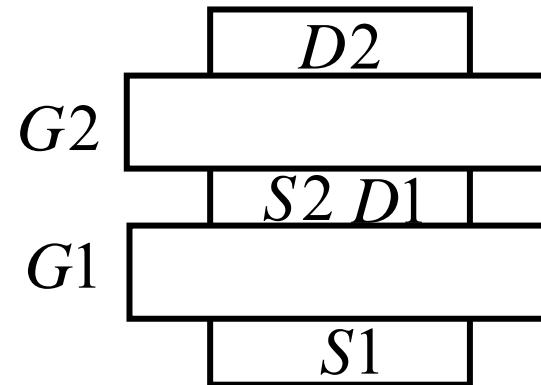
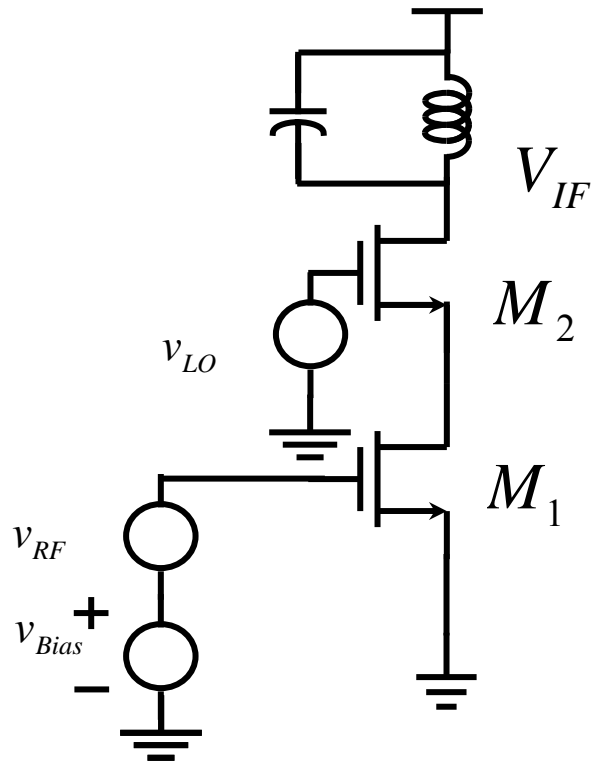


For $V_{LO} \gg V_{dsat}$,

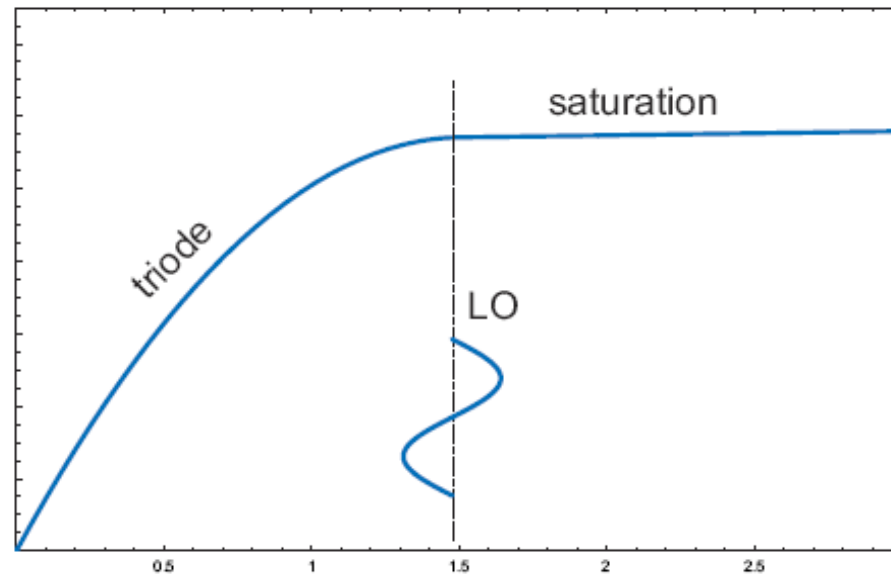
$$G \propto \mu_n C_{OX} \frac{W}{L} V_{LO}$$

*No RF-LO port isolation

Implementation of Dual-Gate Mixer



Dual-Gate Mixer



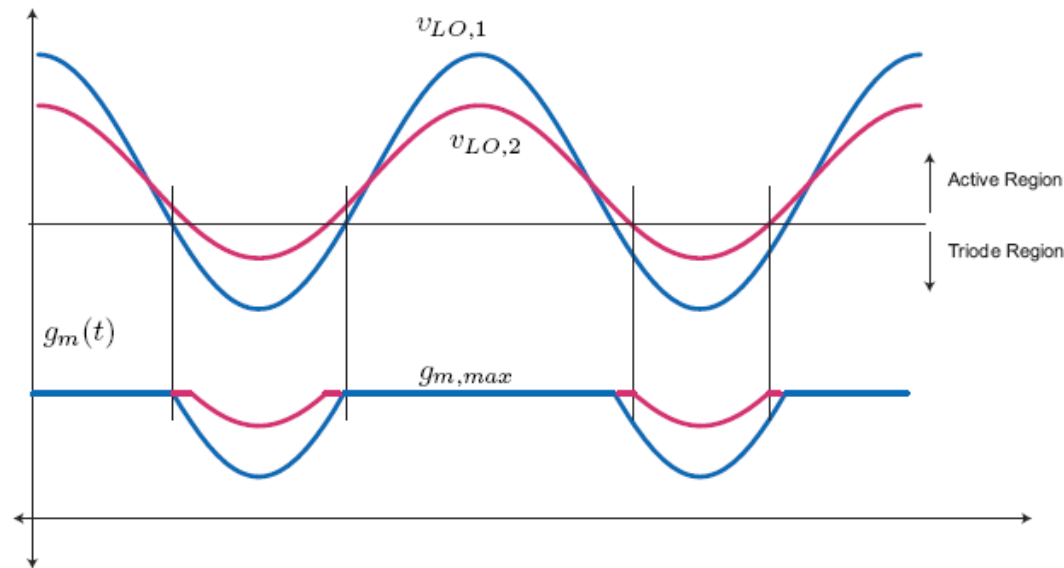
The LO signal is large enough to push $M1$ into triode during part of the operating cycle.

The g_m of $M1$ is therefore modulated periodically

$$g_m|_{sat} = \frac{\mu_n C_{OX} W}{L} (V_{GS} - V_T)$$

$$g_m|_{Triode} = \frac{\mu_n C_{OX} W}{L} V_{DS}$$

Implementation of Dual-Gate Mixer



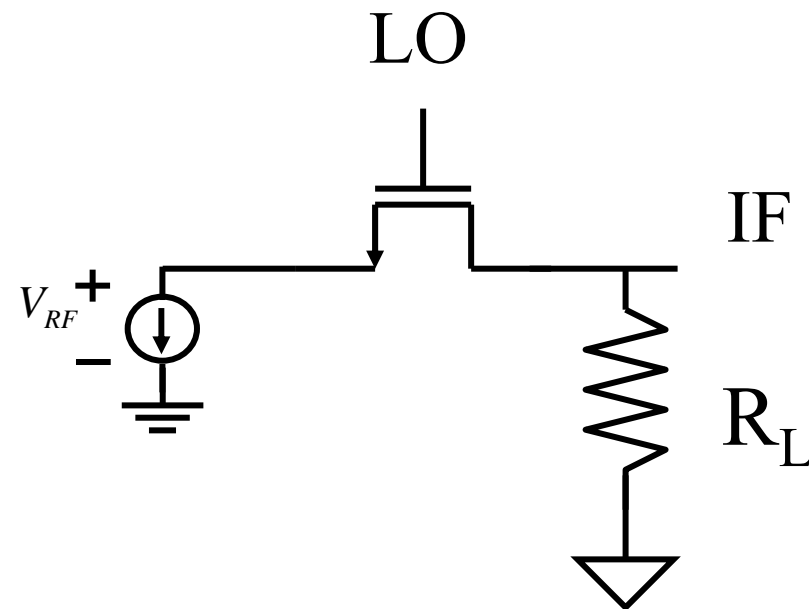
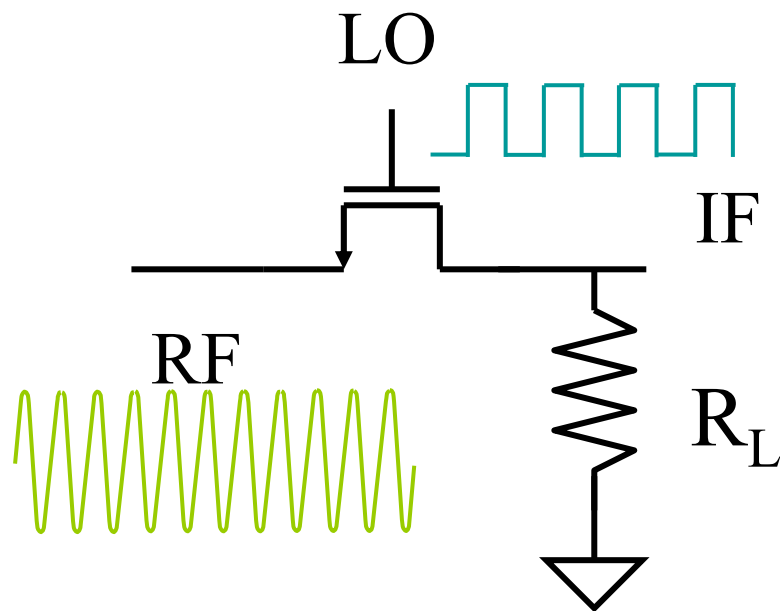
V_{GS2} is roughly constant since $M1$ acts like a current source.

$$V_{D1} = v_{LO} - V_{GS2} = V_{B2} + V_0 \cos \omega_0 t - V_{GS2}$$

$$g(t)|_{V_{D1} > V_{GS} - V_T} = \frac{\mu_n C_{OX} W}{L} (V_{GS1} - V_T)$$

$$g(t)|_{V_{D1} < V_{GS} - V_T} = \frac{\mu_n C_{OX} W}{L} (V_{B2} - V_{GS2} - |V_0 \cos \omega_0 t|)$$

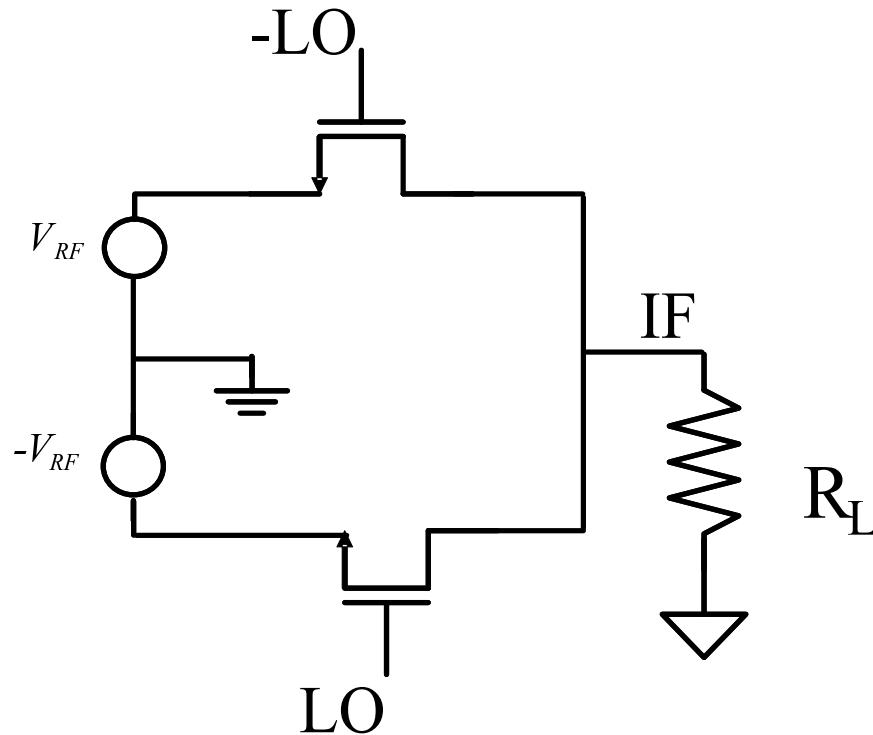
Passive vs Active Mixers



Passive Mixers

- MOS Devices Operate in Triode Region
- High Linearity
- High Frequency
- No Gain or even Loss
- In Practice, Buffer Needed to Isolate or to Convert Output Current to Voltage

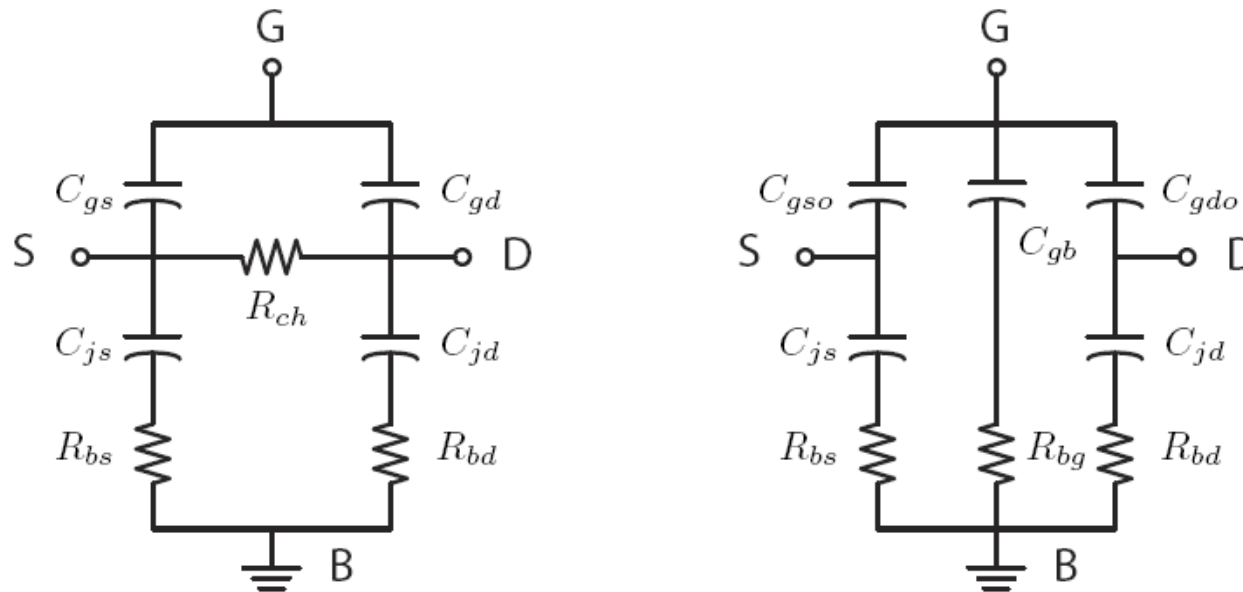
Voltage Switching Mixers



- Switching of voltage
- Requires good switches that turn on hard (low resistance) and turn off well (good insulation)

During the +LO cycle, feeds the RF to the output directly. In the -LO cycle, feeds an inverted RF signal to the output. We see that the RF signal is effectively multiplied by ± 1 with a rate determined by the LO signal. A differential RF signal is created using a balun or fed directly from a balanced LNA.

Voltage Switching Mixers



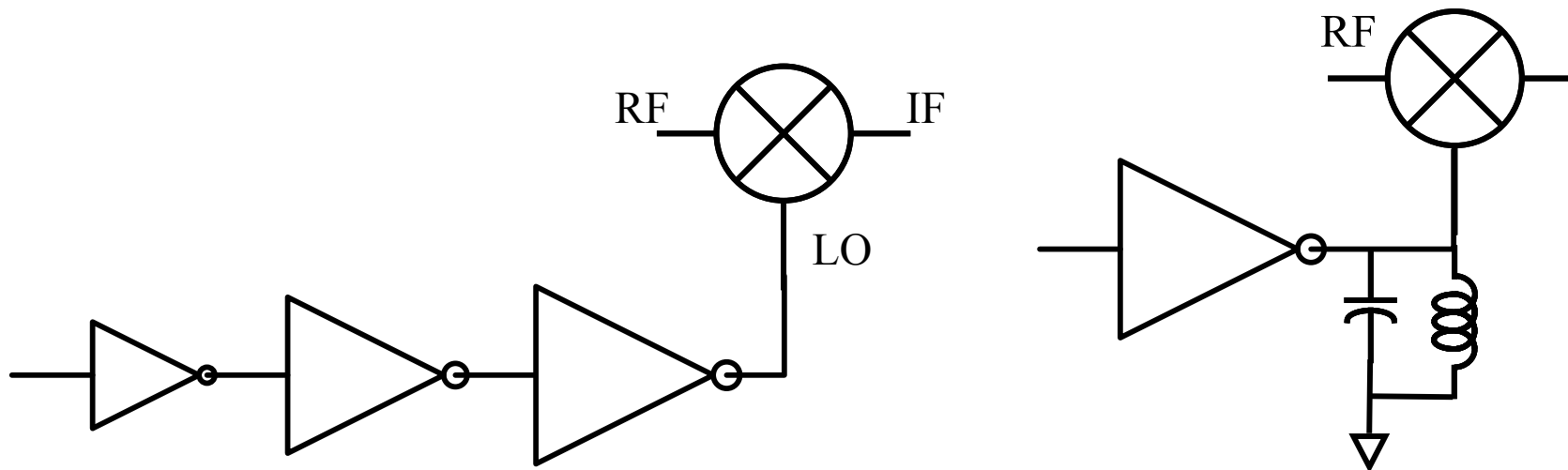
When the device is “on”, it’s in the triode region. Due to the low on-resistance, the coupling through the substrate and LO path is minimal.

When the device is “off”, the RF and LO leak into the IF through the overlap and substrate capacitances.

Voltage Switching Mixers

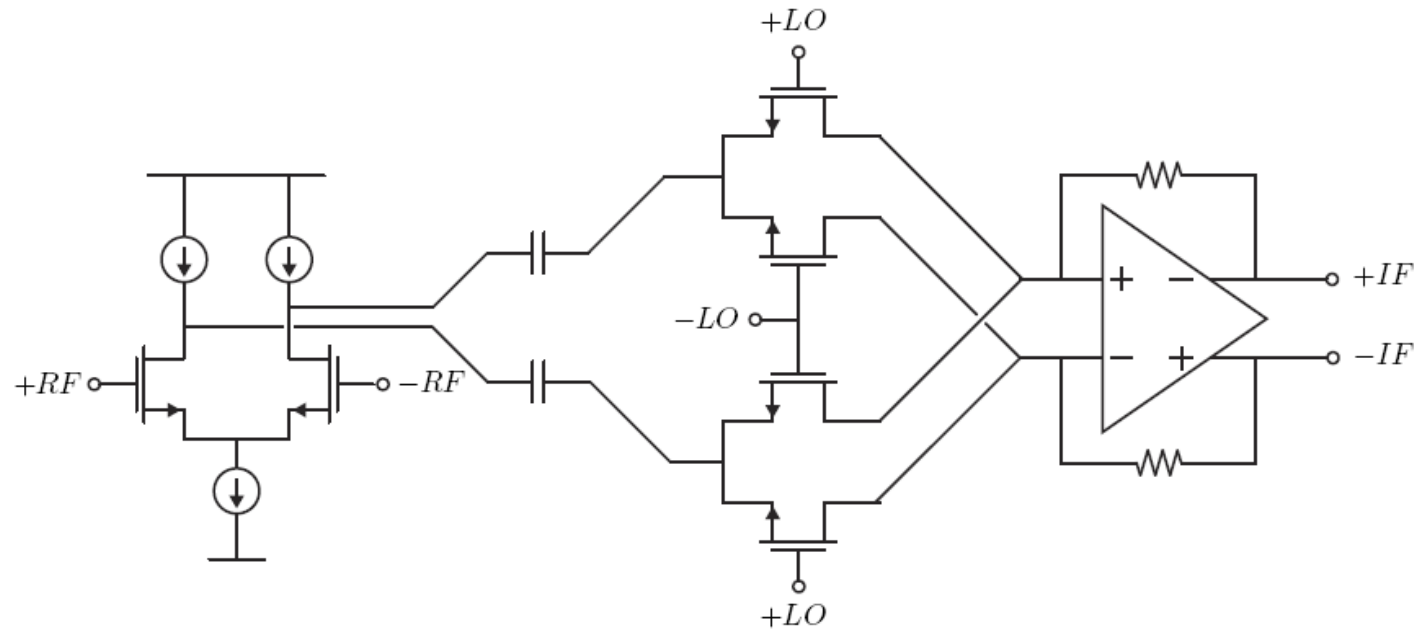
- MOS passive mixer is very linear. The device is either “on” or “off” and does not impact the linearity too much. Since there is no transconductance stage, the linearity is very good.
- The downside is that the MOS mixer is passive, or lossy.
- There is no power gain in the device.
- Need large LO drive to turn devices on/off Need to create a differential RF and LO signal. This can be done using baluns or by using a differential LNA and LO buffer.

Passive Mixer LO Power



- Large capacitive load $\rightarrow P = CV^2_{LO} f_{LO}$ large power
- Large inverters or tuned buffer

Passive Current Mixer



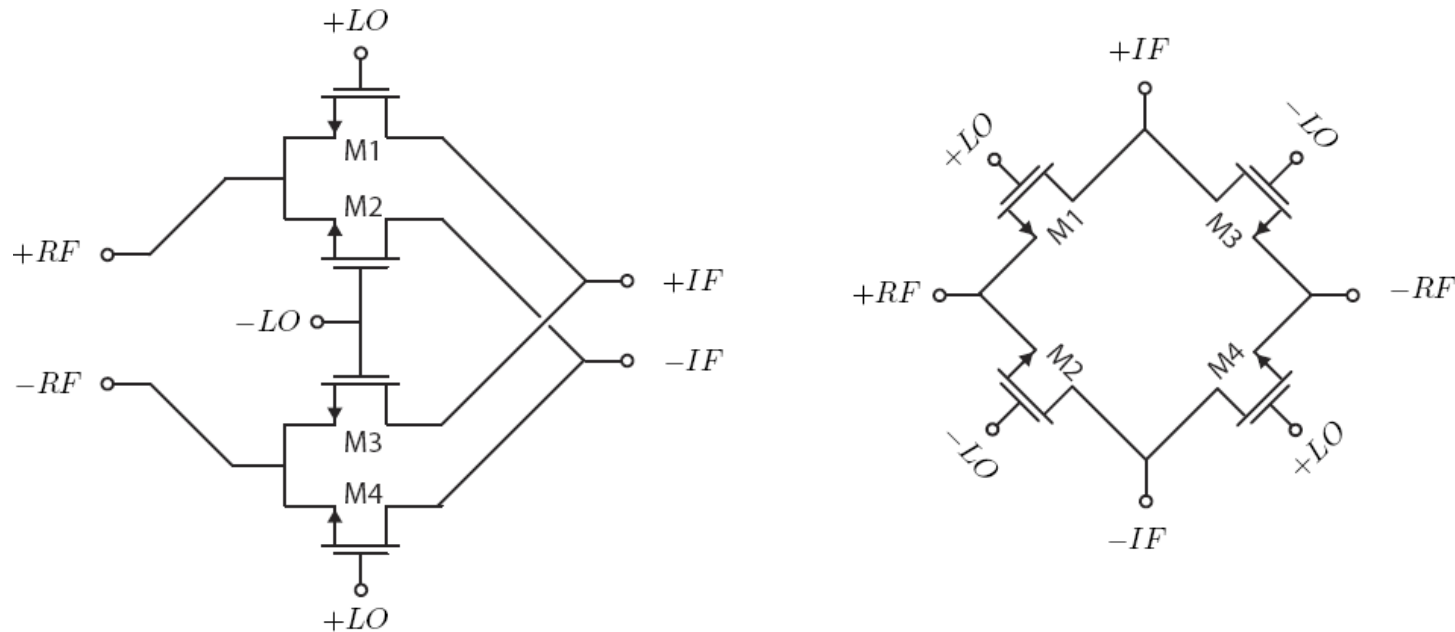
- The input stage is a Gm stage similar to a Gilbert cell mixer. The Gilbert Quad, though, has no DC current and switches on/off similar to a passive mixer.
- The output signal drives the virtual ground of a differential op-amp. The current signal is converted into a voltage output by the op-amp.

Passive Current Mixer

- 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)

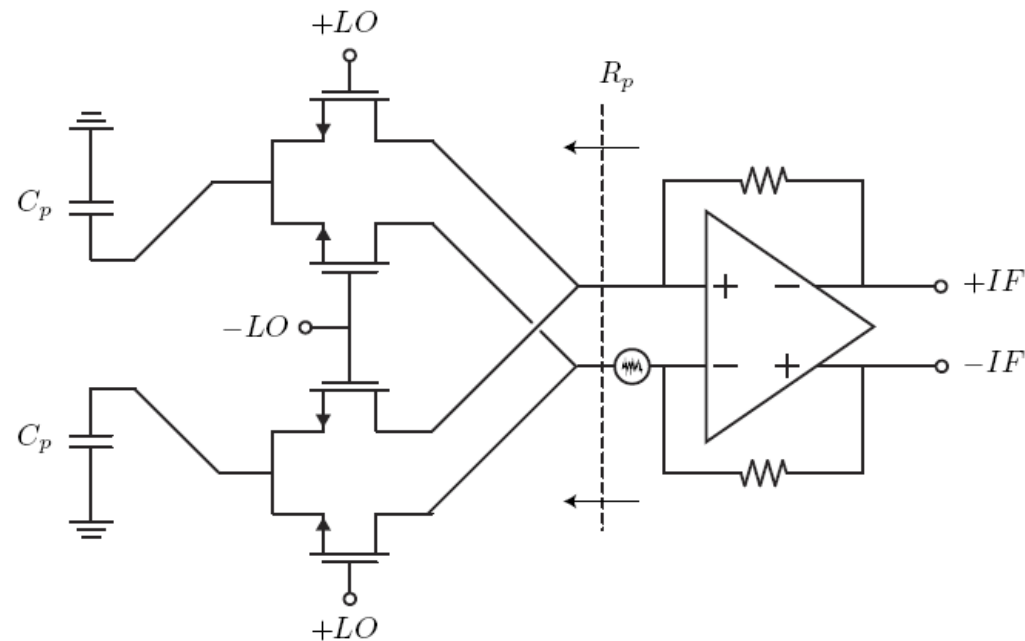
- Need large LO drive compared to the active Gilbert cell mixer.
- Need an op-amp. This requires extra power consumption and introduces additional noise.
- Need a common mode feedback circuit at the input of the op-amp.

Passive Current Mixer



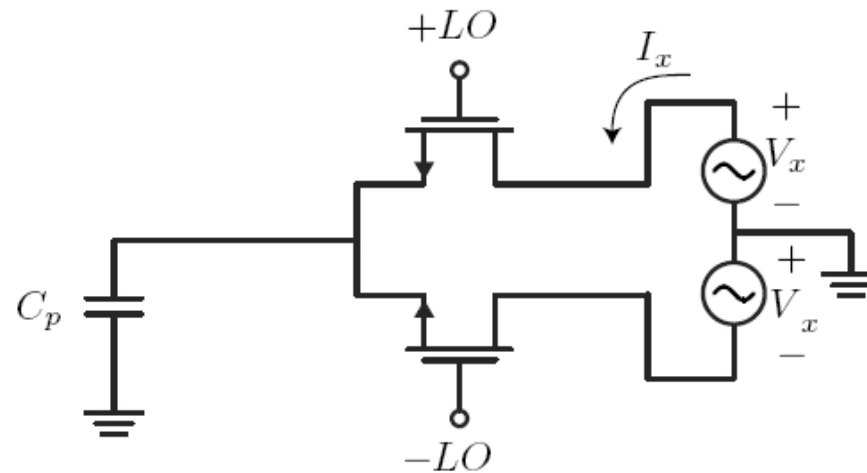
Note that the Gilbert quad is really a folded ring. Thus the passive and active mixers are very similar. The main difference is how the quad devices are biased. In the Gilbert cell they are biased nominally in saturation and have DC current. In the passive mixers, they are biased near the threshold.

Passive Current Mixer



The op-amp input referred noise is amplified to IF. The resistance seen at the op-amp input terminals is actually a switched capacitor resistor! The parasitic capacitance at the output of the transconductance stage is charged and discharged at the rate of the LO.

Passive Current Mixer



Note that the parasitic capacitances are charged at the rate of the LO to the input voltage V_x , and then to the $-V_x$, every cycle.

The total charge transferred during a period is given by

$$Q_{\text{tot}} = C_p V_x - (-C_p V_x) = 2C_p V_x$$

The net current is given by

$$I_x = Q_{\text{tot}}/T_{\text{LO}} = 2C_p V_x f_{\text{LO}}$$

Passive Current Mixer

Since there are two differential pairs connected to the op-amp terminals in parallel, the total charge is twice. So the effective resistance seen at this node is given by:

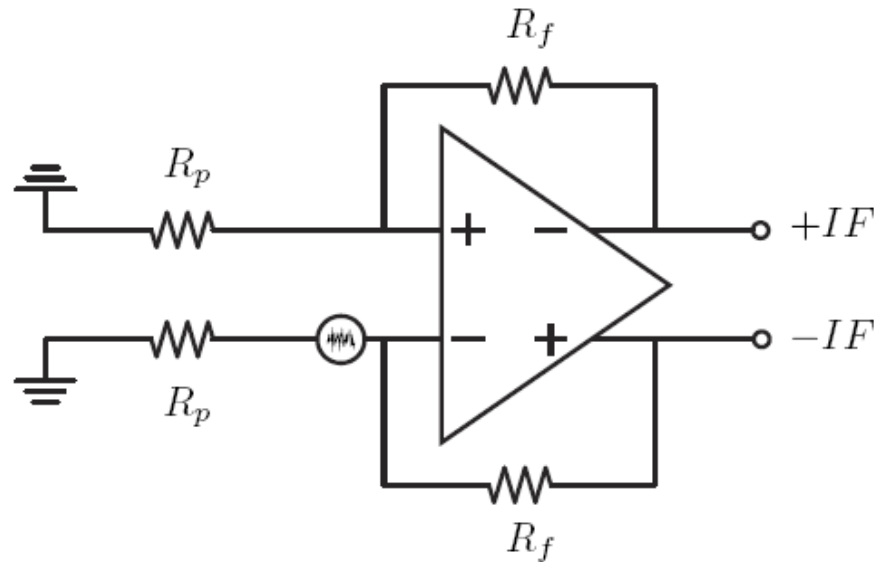
$$R_p = V_x / 2I_x$$

The effective resistance is therefore given by:

$$R_p = 1/4f_{LO}C_p$$

This is a switched capacitor “resistors”.

Passive Current Mixer

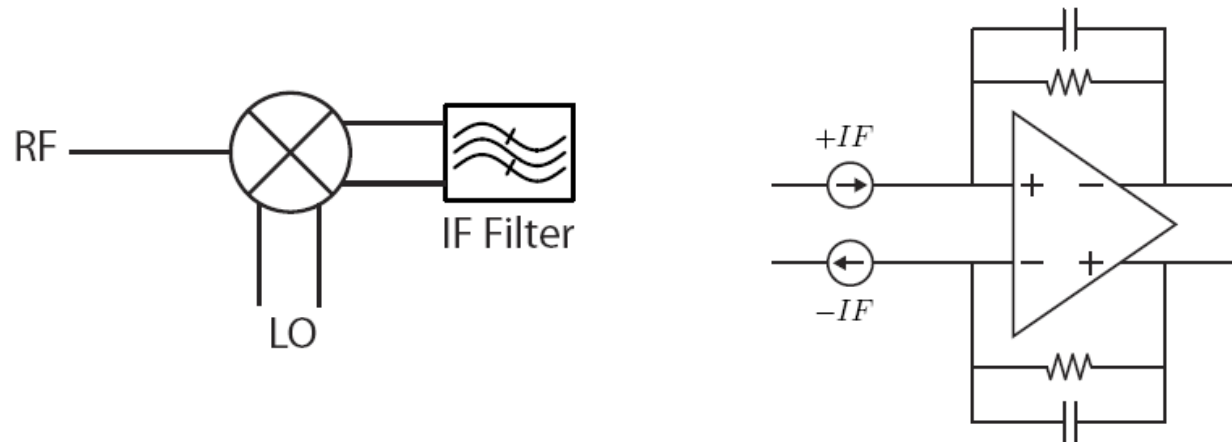


The noise is thus transferred to the output with transfer function given by:

$$\overline{v_o^2} = \left(1 + \frac{R_f}{R_p}\right)^2 \overline{v_{amp}^2}$$

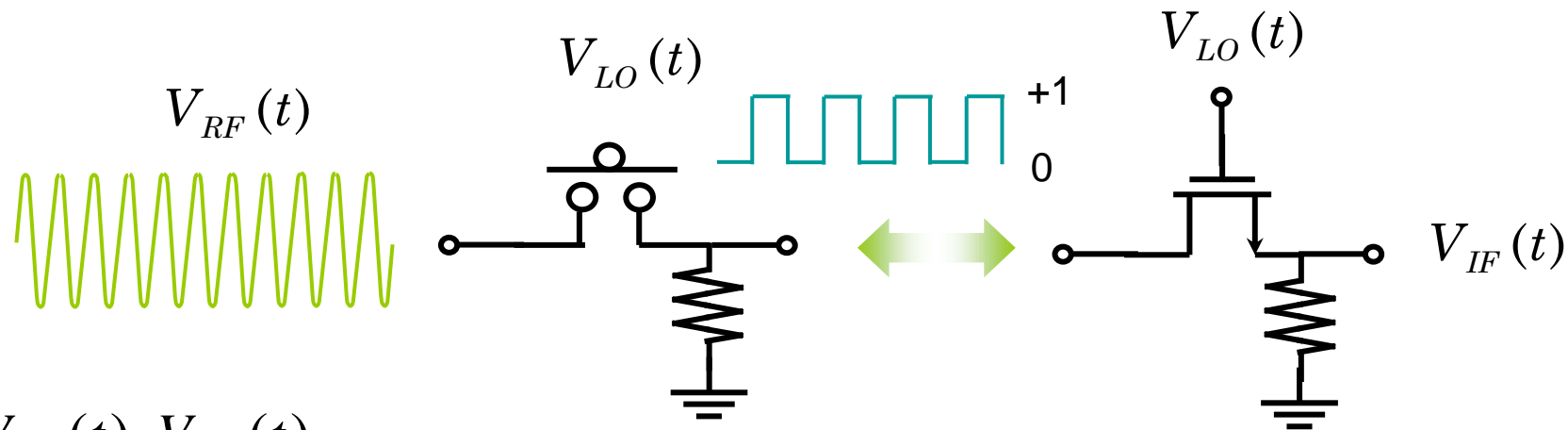
To minimize this noise, we have to minimize the parasitic capacitance C_p and the op-amp noise.

Passive Current Mixer



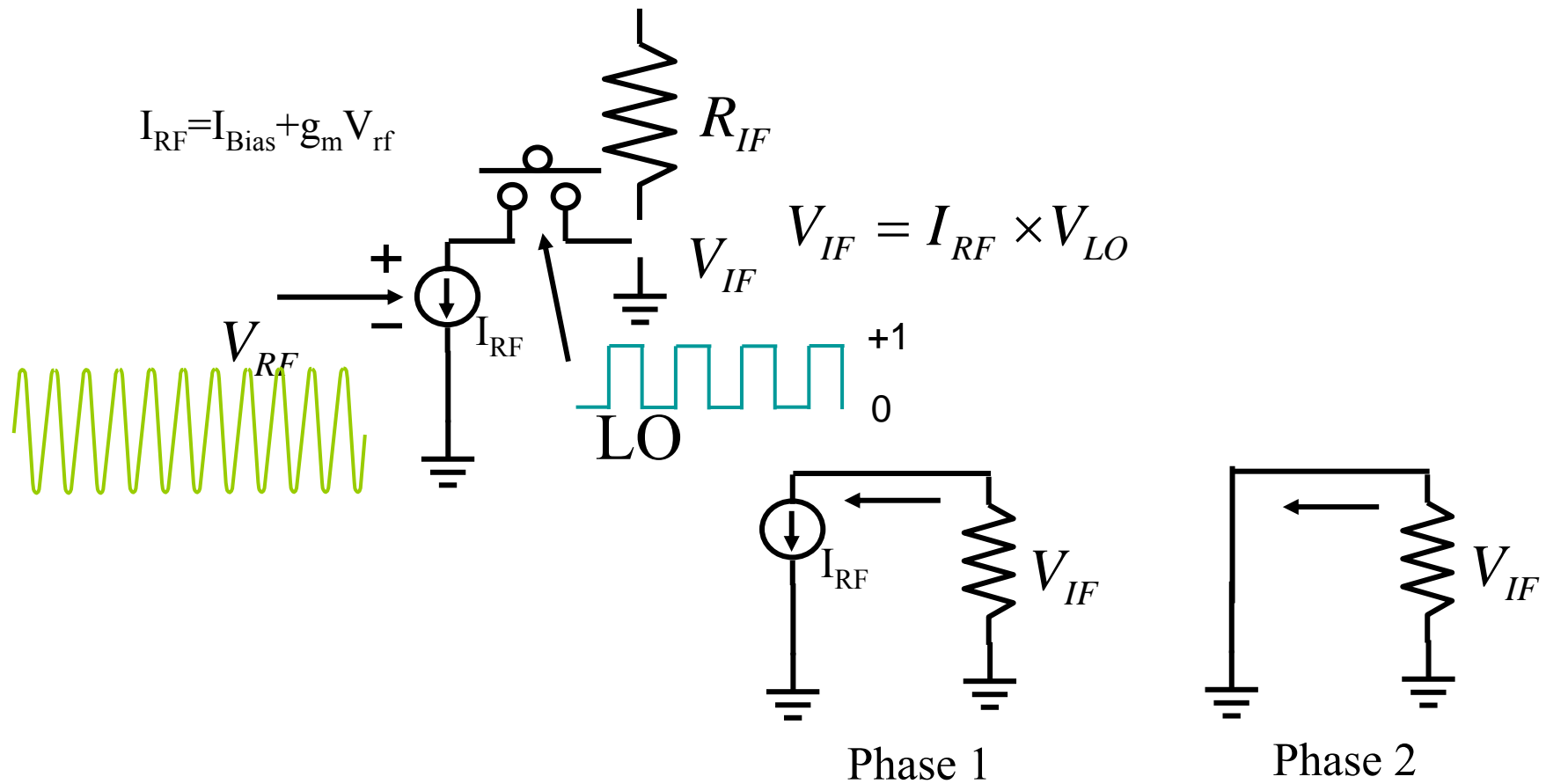
Since a down-conversion mixer will naturally drive a filter, we see that the output current can be used directly to drive a current mode filter. For instance, the op-amp can be absorbed into the first stage of a multi-stage op-amp RC *IF* filter. The feedback resistor R_f is shunted with a capacitor C_f to produce a pole.

Implementation of Active Mixer



$$\begin{aligned}
 & V_{RF}(t) \cdot V_{LO}(t) \\
 &= A_{RF} \cos(\omega_{RF} t) \times sq(\omega_{LO} t) \\
 &= A_{RF} \cos(\omega_{RF} t) \times \left[\frac{1}{2} + \frac{2}{\pi} \sum_{n=1,3,5,\dots}^{\infty} \frac{1}{n} \cos(n\omega_{LO} t) \right] \\
 &= \frac{1}{2} A_{RF} \cos(\omega_{RF} t) + \frac{1}{\pi} A_{RF} \left[\cos(\omega_{RF} \pm \omega_{LO}) t + \frac{1}{3} \cos(\omega_{RF} \pm 3\omega_{LO}) t + \dots \right]
 \end{aligned}$$

Multiplier-Based Mixers



Multiplier-Based Mixers

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

$$I_{IF} = \frac{I_{bias}}{2} \left[1 + \frac{4}{\pi} \cos \omega_{LO} t + \frac{4}{3\pi} \cos 3\omega_{LO} t + \frac{4}{5\pi} \cos 5\omega_{LO} t + \dots \right] + \frac{g_m}{2} A_{RF} \cos \omega_{RF} t$$

$$+ g_m A_{RF} \left[\frac{1}{\pi} \cos(\omega_{LO} - \omega_{RF}) t + \frac{1}{\pi} \cos(\omega_{LO} + \omega_{RF}) t \right]$$

$$+ g_m A_{RF} \left[\frac{1}{3\pi} \cos(3\omega_{LO} - \omega_{RF}) t + \frac{1}{3\pi} \cos(3\omega_{LO} + \omega_{RF}) t \right]$$

$$+ g_m A_{RF} \left[\frac{1}{5\pi} \cos(5\omega_{LO} - \omega_{RF}) t + \frac{1}{5\pi} \cos(5\omega_{LO} + \omega_{RF}) t \right]$$

DC ω_{RF} $n \omega_{LO}$
 $n=1,3,5$

$n \omega_{LO} \pm \omega_{RF}$ $n=1,3,5$

Multiplier-Based Mixers

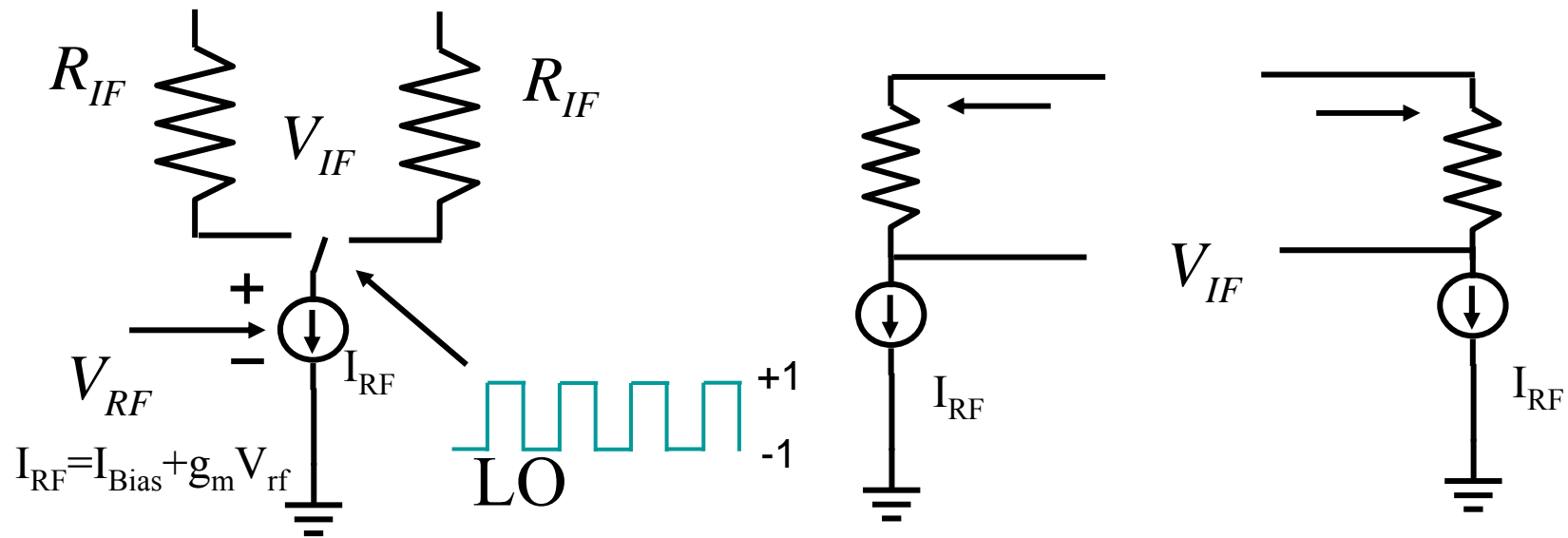
- LO-IF feedthrough

A spectra component at ω_{LO} appears at the IF-port. If the LO frequency is not far enough from the desired RF, it may be difficult to attenuate the LO component enough via filtering.

- RF-IF feedthrough (or *direct feedthrough*).

An RF spectra components shows at the IF-port. Direct feedthrough worsens the NF of the mixer because it allows the noise at the RF-port at the desired IF frequency to leak to the IF-port.

Single-Balanced Mixers



Switching between I_{RF} and $-I_{RF}$

Single-Balanced Mixers

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

$$I_{IF} = I_{bias} \left[\frac{4}{\pi} \cos \omega_{LO} t + \frac{4}{3\pi} \cos 3\omega_{LO} t + \frac{4}{5\pi} \cos 5\omega_{LO} t + \dots \right]$$

$$+ g_m A_{RF} \left[\frac{2}{\pi} \cos(\omega_{LO} - \omega_{RF}) t + \frac{2}{\pi} \cos(\omega_{LO} + \omega_{RF}) t \right]$$

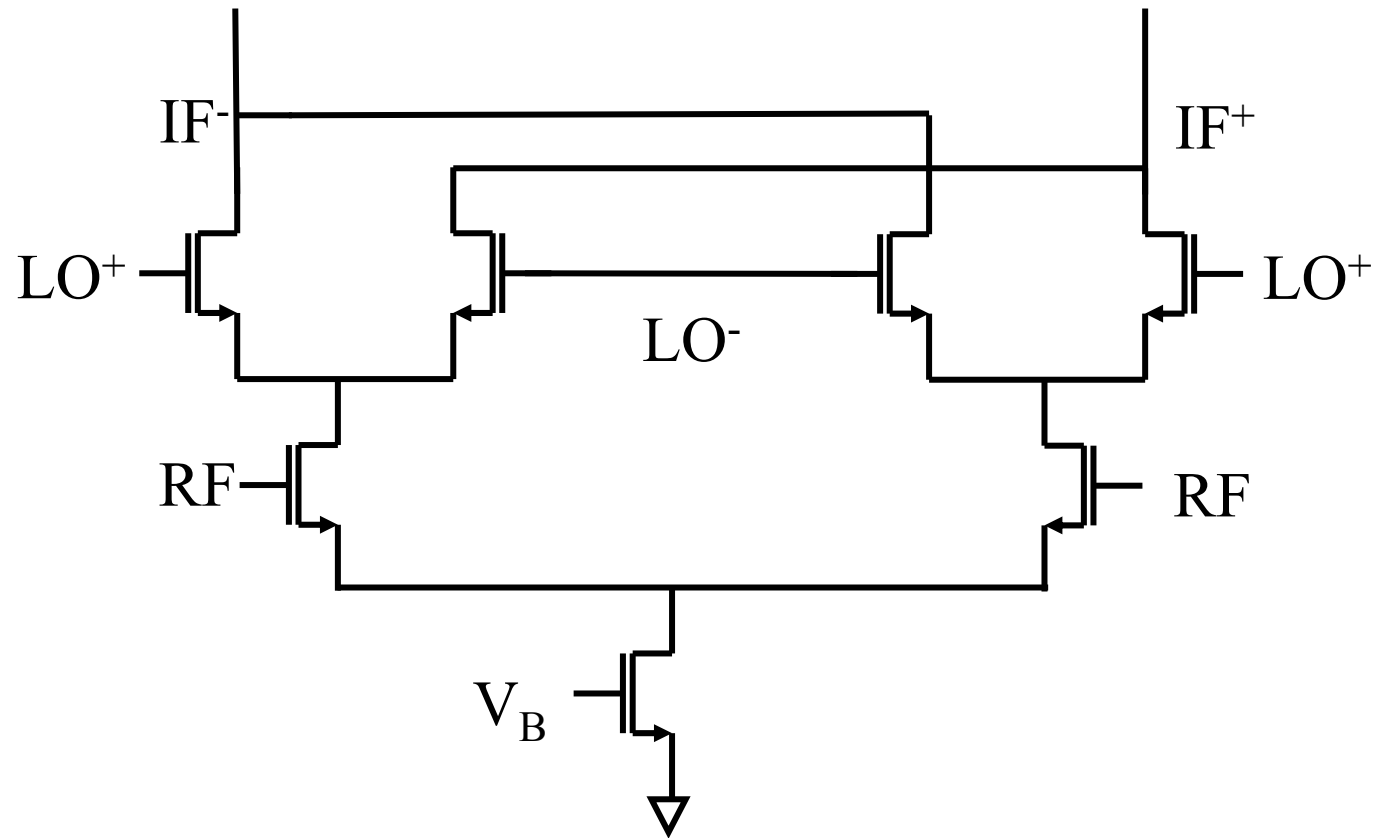
$$+ g_m A_{RF} \left[\frac{2}{3\pi} \cos(3\omega_{LO} - \omega_{RF}) t + \frac{2}{3\pi} \cos(3\omega_{LO} + \omega_{RF}) t \right]$$

$$+ g_m A_{RF} \left[\frac{2}{5\pi} \cos(5\omega_{LO} - \omega_{RF}) t + \frac{2}{5\pi} \cos(5\omega_{LO} + \omega_{RF}) t \right]$$

$n \omega_{LO}$
 $n=1,3,5$

$n \omega_{LO} \pm \omega_{RF} \quad n=1,3,5$

Double-Balanced Mixers



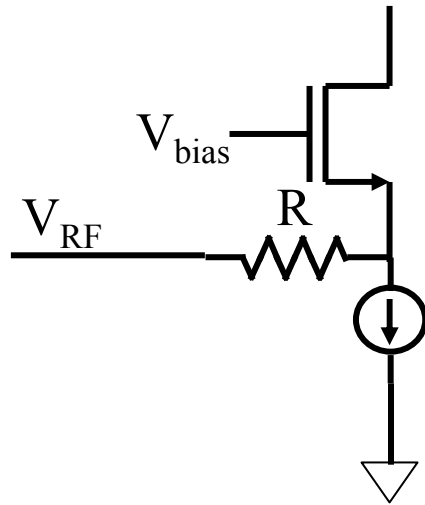
Double-Balanced Mixers

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

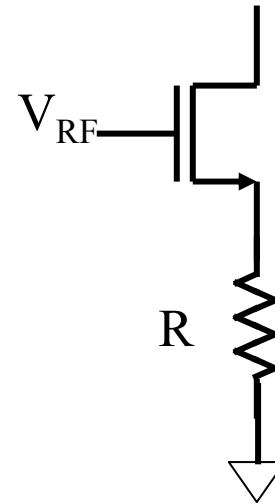
$$I_{IF} = g_m A_{RF} \left[\frac{2}{\pi} \cos(\omega_{LO} - \omega_{RF}) t + \frac{2}{\pi} \cos(\omega_{LO} + \omega_{RF}) t \right]$$
$$+ g_m A_{RF} \left[\frac{2}{3\pi} \cos(3\omega_{LO} - \omega_{RF}) t + \frac{2}{3\pi} \cos(3\omega_{LO} + \omega_{RF}) t \right]$$
$$+ g_m A_{RF} \left[\frac{2}{5\pi} \cos(5\omega_{LO} - \omega_{RF}) t + \frac{2}{5\pi} \cos(5\omega_{LO} + \omega_{RF}) t \right]$$

$$n \omega_{LO} \pm \omega_{RF} \quad n=1,3,5$$

Linearization



Common-Gate Input



Common-Source Input

Linearization

Common-Gate Linearization:

- The transconductance of the common-gate at the RF port is:

$$G_m = IM_{RF}/V_{RF} = g_m / (1 + g_m R) \rightarrow 1/R$$

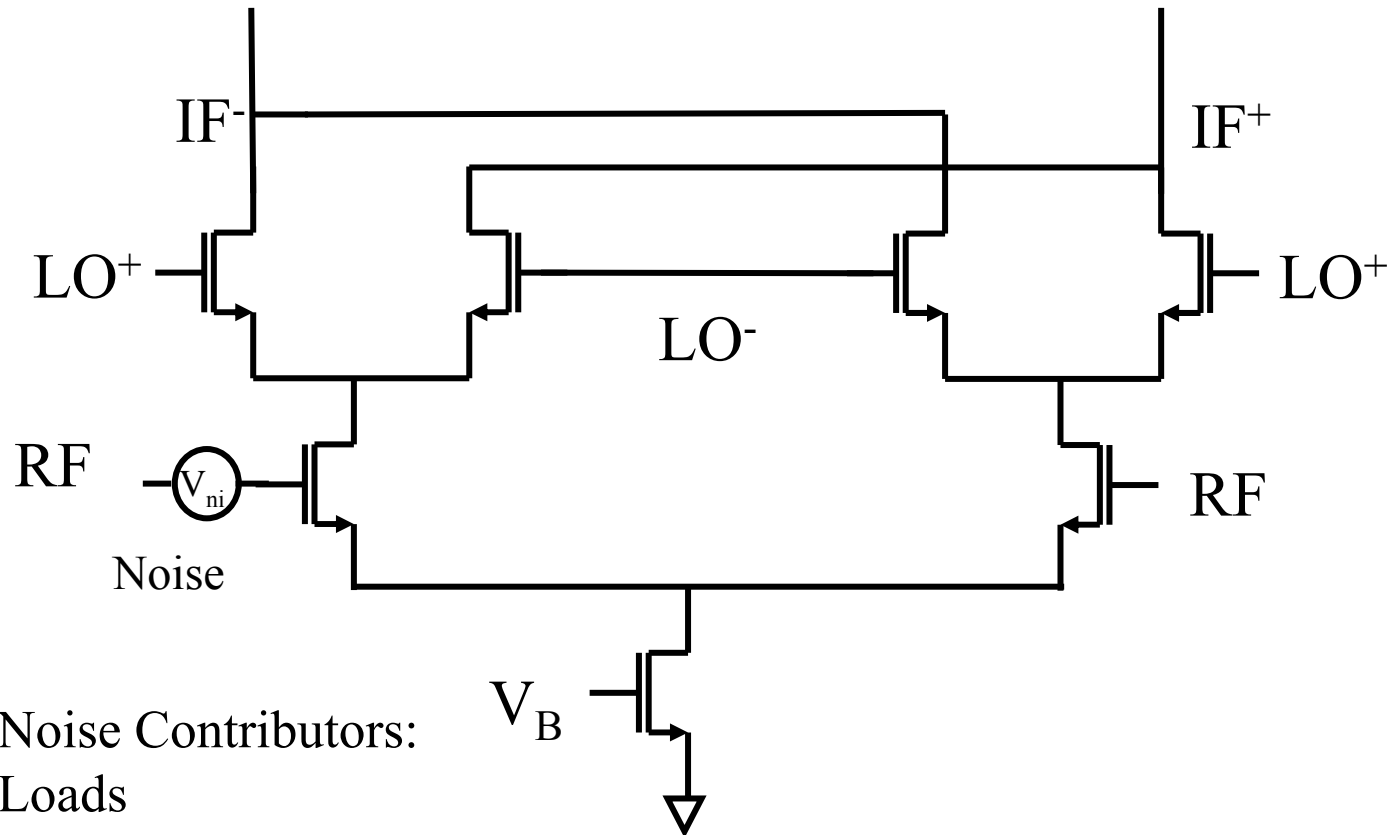
can be made is R is large enough

The disadvantage is the additional noise due to R.

- The conversion transconductance is

$$G_c = 2G_m / \pi$$

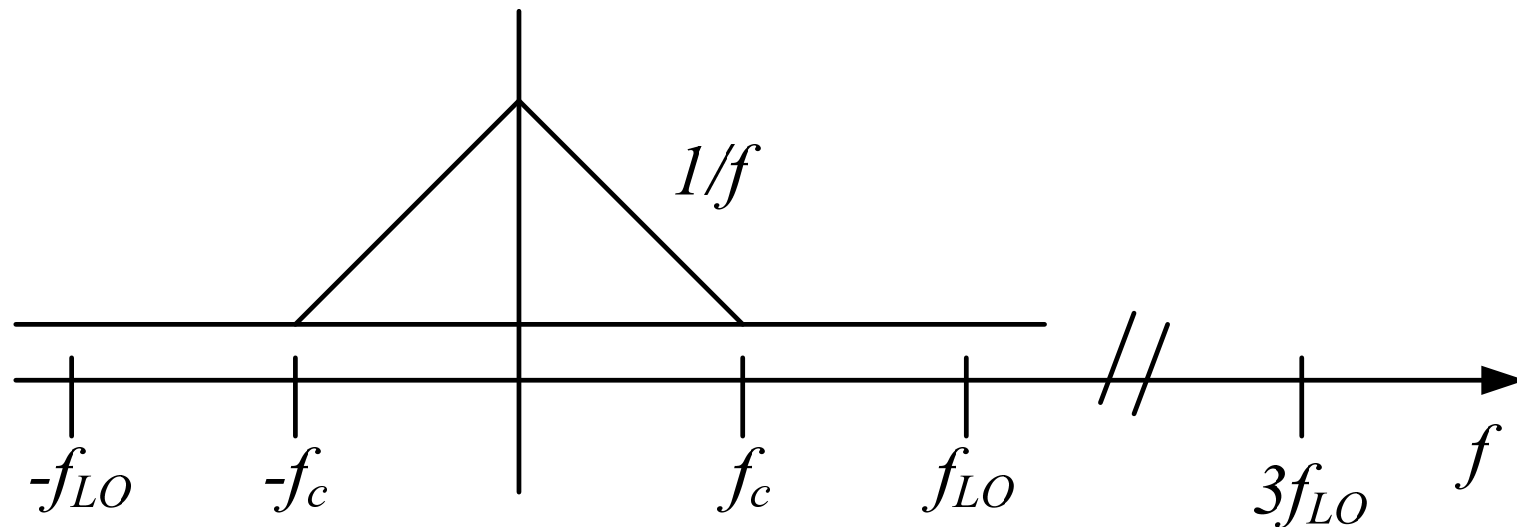
Noise in Mixers



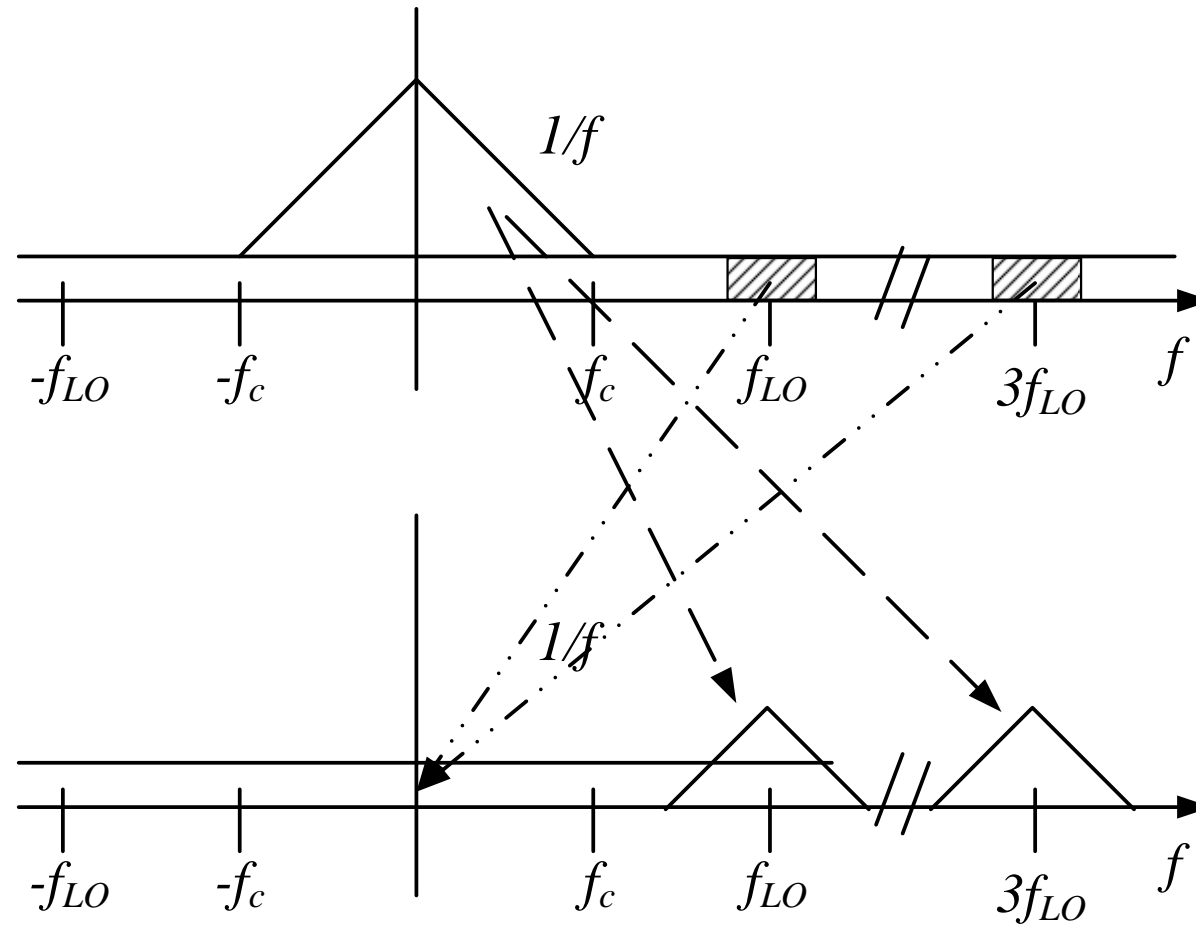
- Noise Contributors:
- Loads
- Transconductance FETs
- Switches

Noise in Mixers

- Loads
1/f noise
- Transconductance FETs
1/f noise and white noise



Noise in Mixers



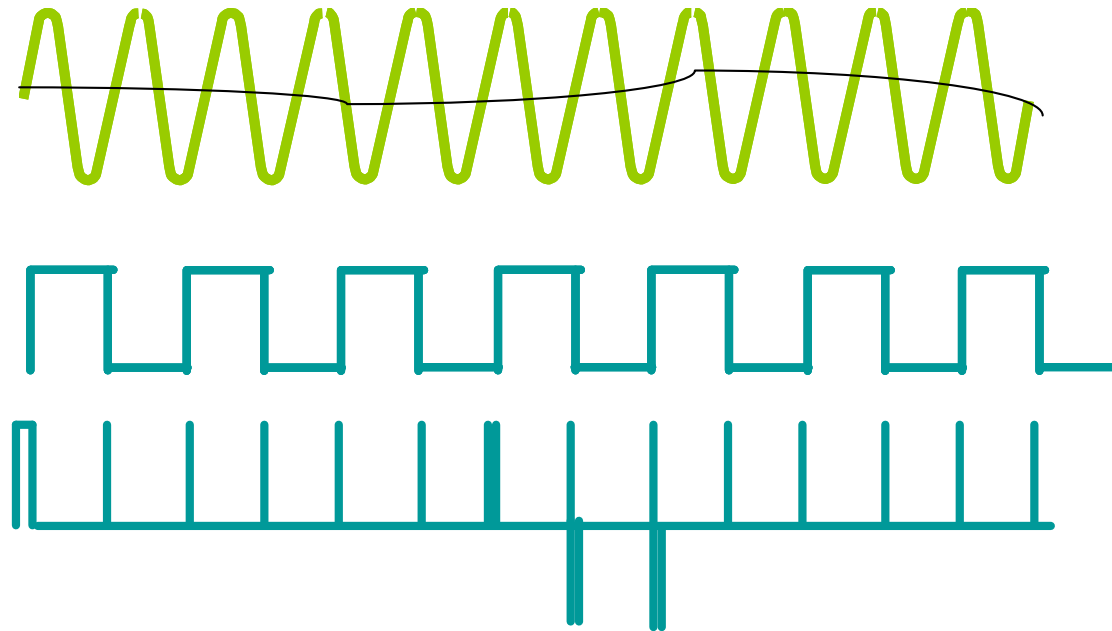
Noise in Mixers

- Switch Noise

Assume that all input phase noise is reflected to one side of the differential pair and is given by:

$$v_{id} = v_n(t) + 2A \sin \omega_{LO} t$$

Each time the V_{id} crosses zero the i_{od} switches from $-I$ to I or vice-versa.



Noise in Mixers

Random current pulses due to $v_n(t)$. The width of each pulse is:

$$\Delta t = v_n(t)/s$$

S is the slope of LO

And its height = $2I$

Frequency = $2f_{LO}$

The average current noise pulses is:

$$i_{0,nav} = \frac{2I_0 t}{T/2} = \frac{2IV_n(t)}{sT/2} = \frac{IV_n(t)}{\pi A} \quad s = 2\pi f A \times 2$$

Noise in Mixers

SNR due to the switch noise:

$$\text{SNR} = i_0 / i_{no}$$

$$\text{signal} = G_m \times V_{in} = \frac{2g_m V_{in}}{\pi}$$

$$\text{SNR} = \frac{2g_m V_{in}}{\pi} \frac{1}{\frac{1}{\pi} \frac{IV_n}{A}} = \frac{2A}{V_{GS} - V_T} \frac{V_{in}}{V_n}$$

$$g_m = V_{GS} - V_T$$

The SNRs can be improved by:

- Increase LO swing
- Trade off with frequency
- (reduce over-ride voltage)
- (Reduce N_n by increase WL of the switch)

Simulation of Mixers in Spectre-RF

- Periodic Transfer Function (PXF)
conversion gain
- Periodic Steady State (PSS)
1dB compression point and conversion gain
- Periodic Distortion (Pdisto) analysis
IIP3
- Periodic Noise (Pnoise)
noise figure.

