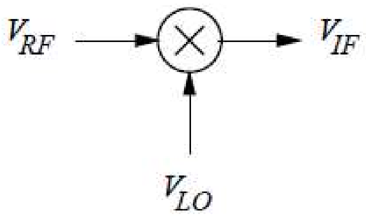
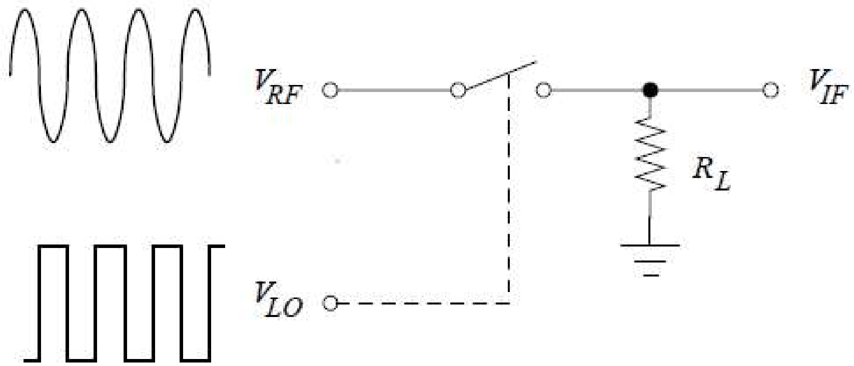
Mixers

General considerations

- Mixer performs frequency translation by multiplying signals
- In down conversion mixer multiplies the LO and RF signals
- Switch mixer is equivalent to the RF signal multiplied by a rectangular waveform see Figure b.
- Switch mixer is linear time variant with respect to the RF port
- Switch mixer is non-linear timevariant with respect to the LO port



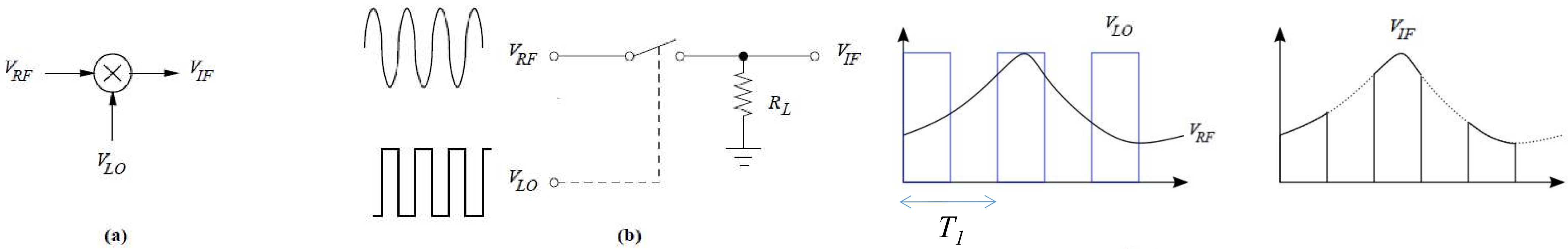
(a)

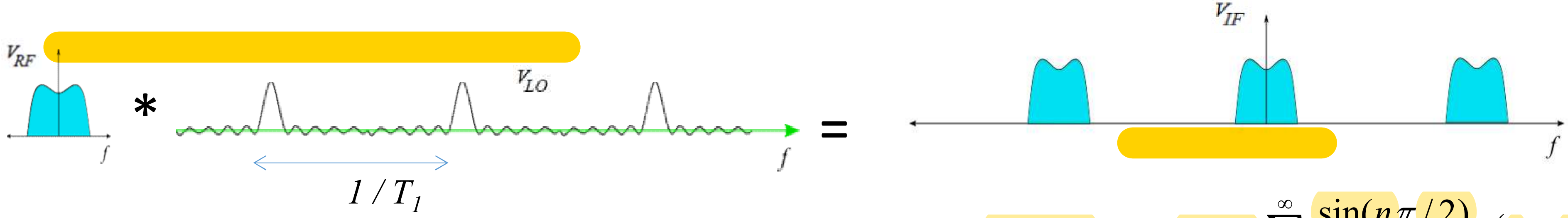


(b)

MOSFET as a Switch Mixer

- A MOS switch contributes a on-resistance which adds noise.
- The on resistance is controlled by the gate overdrive $V_{GS} = V_{LO} - V_{RF}$ which changes with VRF introducing nonlinearity.





- For V_{RF}, the system is linear, time variant.
- For V_{LO}, the system is non linear, time variant.

$$V_{out}(f) = V_{in2}(f) * \sum_{n=-\infty}^{\infty} \frac{\sin(n\pi/2)}{n\pi}\delta(f - n/T_1))$$

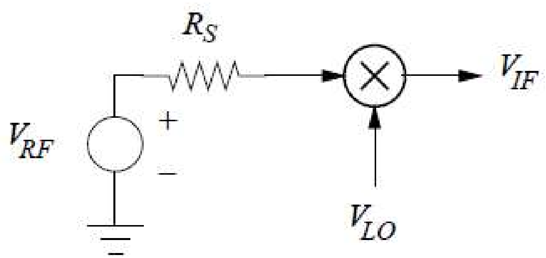
$$= \sum_{n=-\infty}^{\infty} \frac{\sin(n\pi/2)}{n\pi} V_{in2}(f - n/T_1))$$

Typical Mixer Performances

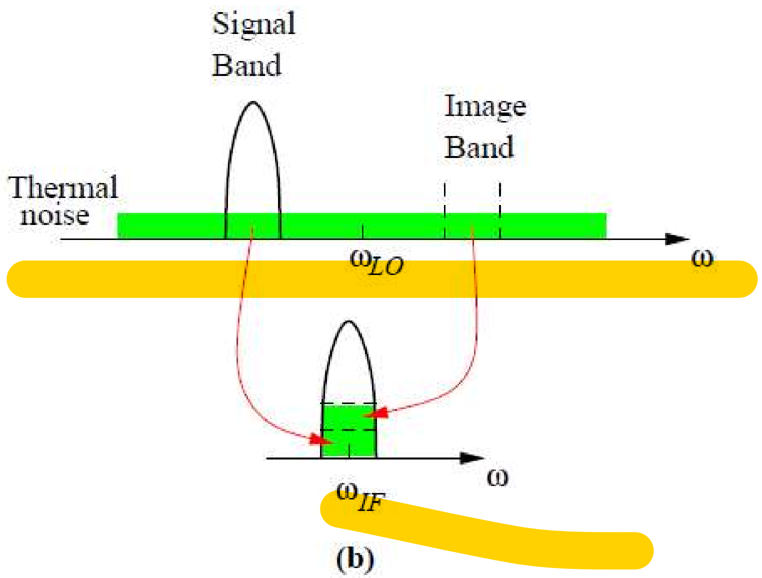
Noise Figure F	12 dB
IIP3	5 dBm
Gain	10 dB
Input Impedance	50 Ω
Port-to-Port Isolation	10-20 dB

Single Side Band (SSB) Noise Figures

- In heterodyne down conversion the thermal noise of R_S in the signal band and the image band are both down converted.
- Thus the output SNR is half the input SNR and the SSB noise Figure of a perfect mixer is 3 dB.



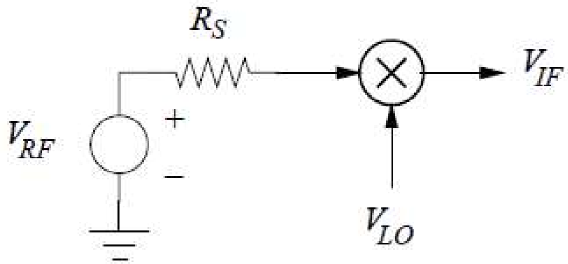
(a)



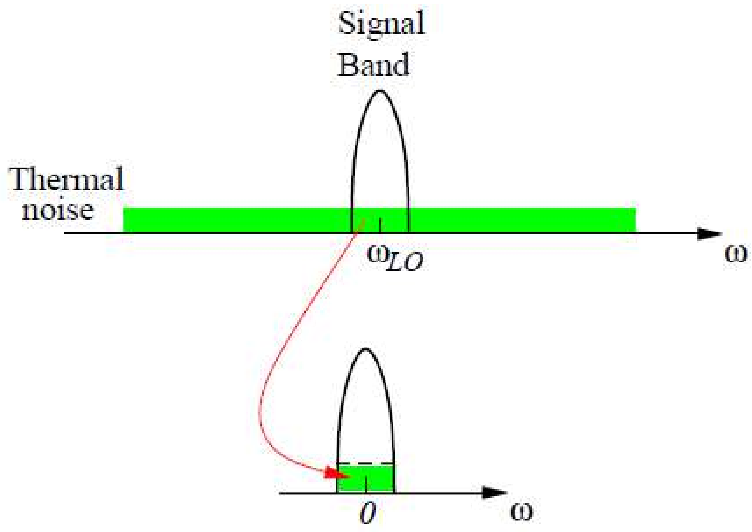
(b)

Double Side Band (DSB) Noise Figures

In homodyne down conversion there is no image band and the thermal noise of R_S is just translated down to baseband Thus the output and input SNRs are the same and the DSB noise Figure of a perfect mixer is 0 dB.

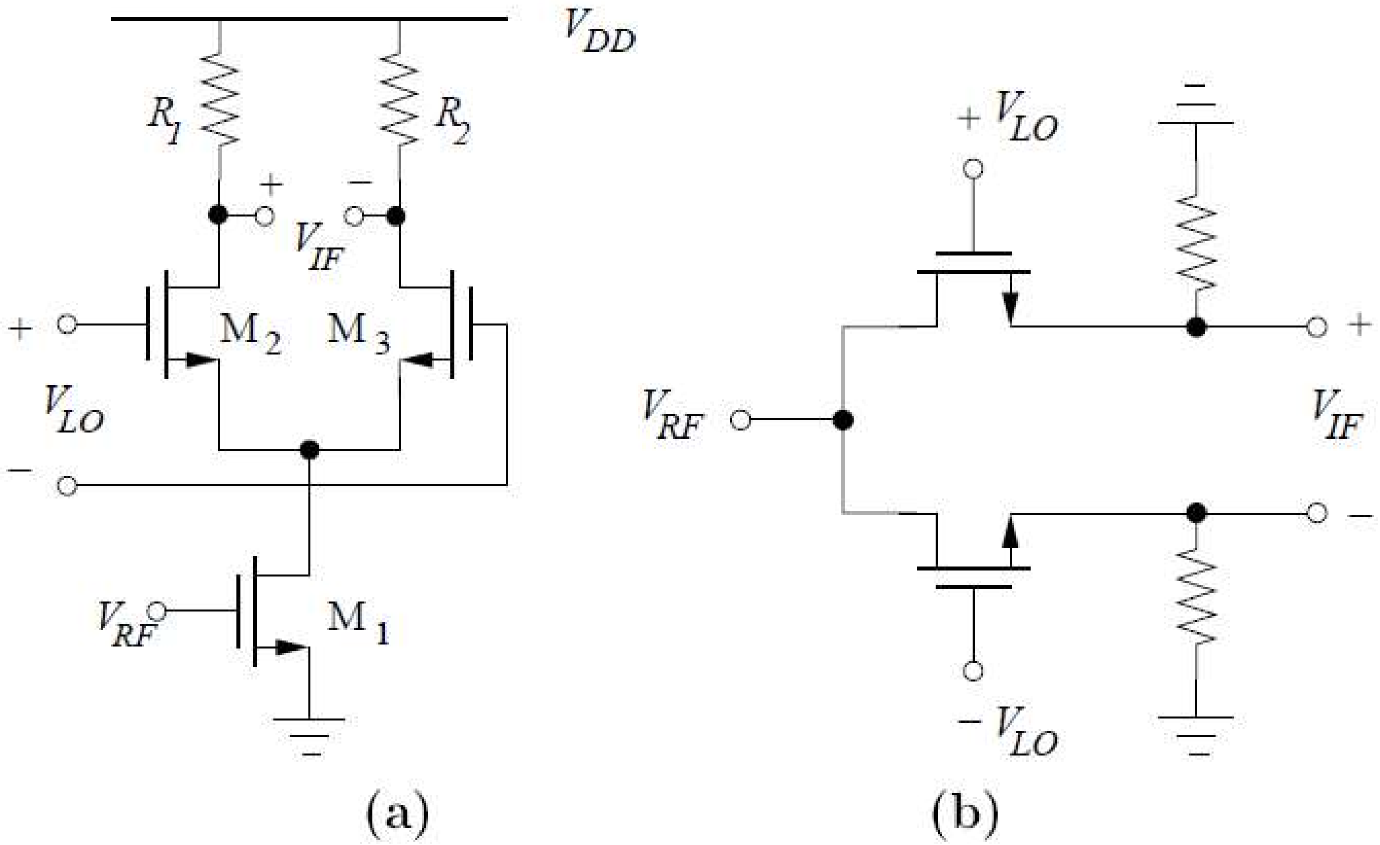


(a)



(b)

Active and Passive Mixers



Return to zero mixer (RZ mixer)

- Active mixers provide gain Fig (a): conversion gain
- Passive mixers do not provide gain Fig (b)
  - conversion loss (for ideal switch: $2/\pi$ amplitude of fundamental of LO)
  - more linear but conversion loss magnifies NF of IF stage

Noise and Linearity

- LNA Mixer combined NF must be low and linearity high.
- Linearity is essential for reducing mixing spurs
- Mixer IP2 is critical as this causes feedthroughs.
- For up conversion mixers NF is important only if inband noise of Rx must be low.
- Also for up conversion mixer linearity is determined by type of modulation and baseband signal swing.

Conversion Gain

- Input RF and output IF impedances are usually different
- Then the power gain conversion and voltage gain conversion are different
- Matching of the RF input is required to avoid reflection in the image reject filter
- The IF load impedance of the mixer is *not* equal to 50 Ω: the IF filter impedance is typically 500 to 1000 ohms.
- In homodyne impedance might even be higher to maximize the voltage gain.

Conversion Gain(..Contd)

- Voltage conversion gain = $V_{rms,IF}$ / $V_{rms,RF}$
- Power conversion gain = $P_{L,IF}$ / P_{AVS}
- Voltage conversion gain = power conversion gain, if Z_{in} = Z_L= Z_S=50 ohms
- In homodyne voltage conversion gain not equal to power conversion gain due to wide variation of impedances between RF and baseband.
- In heterodyne they may be equal if impedances of IF stage (like first IF) is same as that of RF stages.
- In modern mixers voltage gain preferred as impedances can vary over Tx/Rx chain.
- Down conversion mixers need to have power gain as high as possible however due to low supply voltages in vlsi processes.
- To maintain linearity it is difficult to achieve more than 10 dB gain.
- In direct conversion transmitters maximize gain to relax PA gain requirement.
- In heterodyne transmitters IF mixers must provide moderate gain so as not compress RF mixers.

Port to Port Isolation

The isolation between the ports of a mixer is critical:

- LO - RF feedthrough leads to LO leakage to the LNA(dc offset) and antenna(unwanted radiation).
- RF - LO feedthrough allows strong interferers pulling on local oscillator.
- RF - IF feedthrough might transmit beat components due to 2^{nd} order non linearity.

The leakage can be mitigated by filtering or the isolation enhanced using a double balanced mixer.

Down conversion mixer vs Up conversion mixer

Down conversion Mixer

NF $\longrightarrow$ Important
Conversion gain $\longrightarrow$ Important
Linearity $\longrightarrow$ very important
IM2 $\longrightarrow$ DC offset $\longrightarrow$ SNR degradation
IM3 $\longrightarrow$ Amplitude degradation (interferers)
Port-to-port isolation $\longrightarrow$ Important

- LO to RF Isolation
- RF to LO isolation
- RF to IF isolation

For direct conversion receivers

- LO to IF isolation $\longrightarrow$ for heterodyne receivers (if LO and IF frequencies are nearby)

UP conversion Mixer

NF $\longrightarrow$ Not Important
Conversion gain $\longrightarrow$ Not Important but eases requirement on PA. For heterodyne IF mixers should not have too high gain otherwise RF mixers can get compressed.
Linearity $\longrightarrow$ very important
- IM2 $\longrightarrow$ dc offset $\longrightarrow$ saturation of next stage
- IM3 $\longrightarrow$ Amplitude degradation (spreading)
- Spurious frequencies

Port-to-port isolation $\longrightarrow$ Important

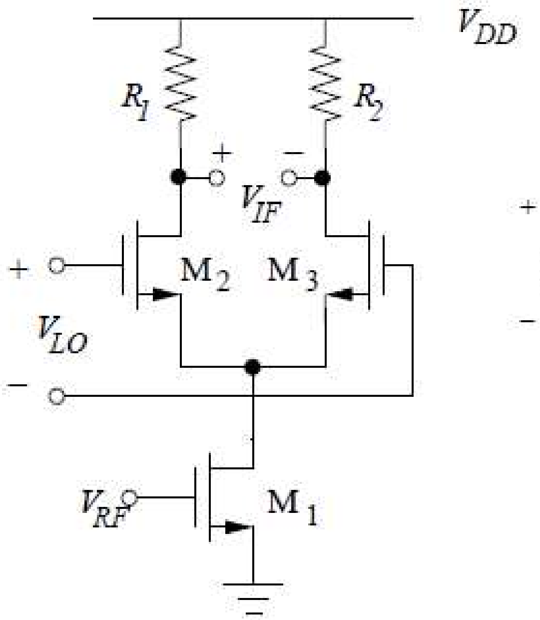
- LO to o/p Isolation
- o/p to LO isolation

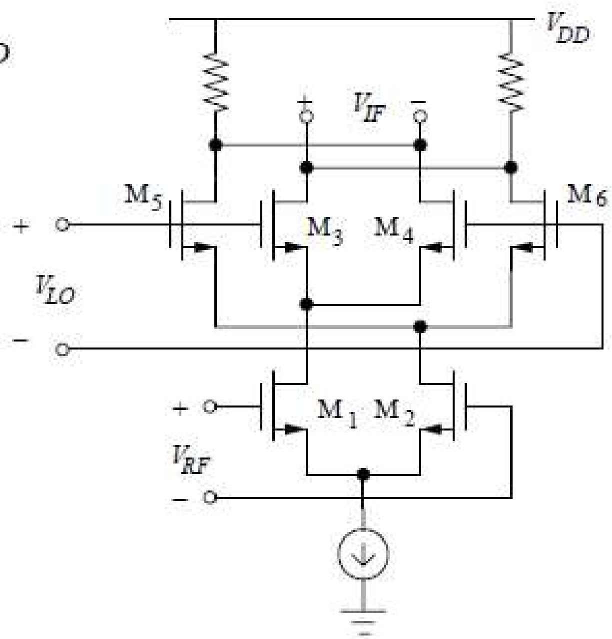
For direct conversion receivers

- IF to LO isolation $\longrightarrow$ for heterodyne receivers (if LO and IF frequencies are nearby)

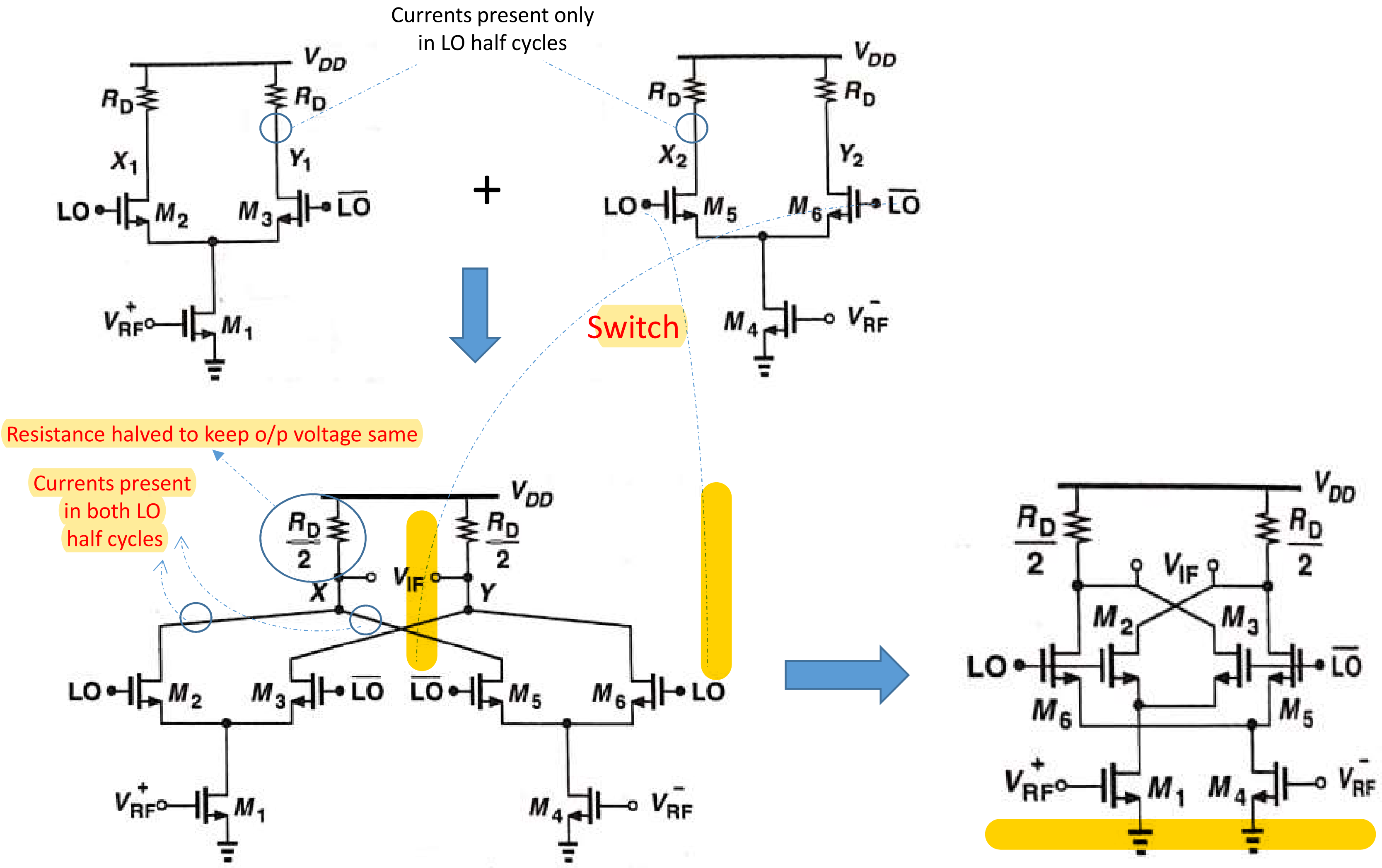
Single and Double Balanced Mixers

- Single balanced mixer accommodates a single ended RF signal and a double ended LO signal.
- Double balanced mixer accommodates a double ended RF signal and a double ended LO signal e.g. Gilbert cell





Double Balanced MOSFET based Gilbert cell



Comparison of Single and Double Balanced Mixers

Single balanced Mixer:

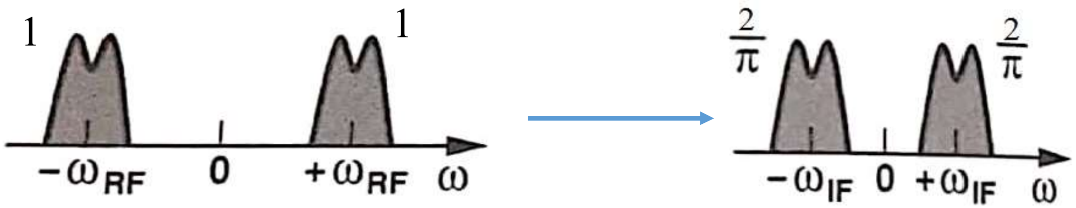
- exhibits less input referred noise
- more susceptible to noise in LO signal
- LO-IF feedthrough is larger
- RF-IF feedthrough is larger

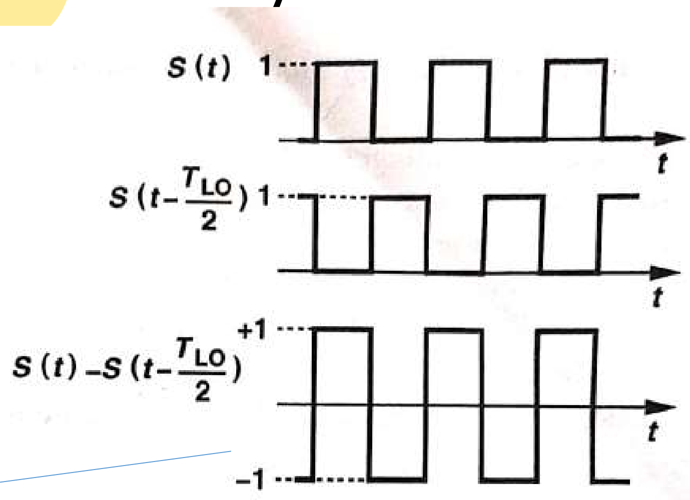
Double balanced Mixer:

- generates less even-order distortion (relax half IF issue, beat frequency).
- higher conversion gain.
- LO-IF feedthrough is reduced (balanced topology).

Note: High frequency RF-IF feedthrough is usually not important (can be removed by LPF). Low frequency RF-IF feedthrough of beat (due to LNA non-linearities) is a problem for the homodyne receiver.
Note: Advantages of double balance mixers disappear if used as single ended.

Single Balanced RZ (passive) Mixer Analysis





Considering only fundamental component of LO voltage,

$$V_{out1} = V_{RF}(t)\cdot \underbrace{\frac{1}{2}}_{\text{half since differential LO i/p}} \cdot \underbrace{\frac{4}{\pi}\cos\ (\omega_{LO}\ t)}_{\text{fundamental component of LO}} \cdot \frac{R_L}{R_L+R_{on}} = V_{RF}(t)\cdot\frac{2}{\pi}\cos\ (\omega_{LO}\ t)\cdot\frac{R_L}{R_L+R_{on}}$$

V_{LO}

$V_{RF}(t)\times\cos(\omega_{LO}\ t)$ will produce components like,

$$\frac{1}{2}\cos(\omega_{RF}-\omega_{LO}) + \underbrace{\frac{1}{2}\cos(\omega_{RF}+\omega_{LO})}_{\text{filtered out}}$$

$$\Rightarrow V_{out1}(t) = |V_{RF}|\cdot\frac{1}{\pi}\cos\ (\omega_{RF}-\omega_{LO})\ t\cdot\frac{R_L}{R_L+R_{on}}$$

Similarly,

$$V_{out2}(t) = -|V_{RF}|\cdot\frac{1}{\pi}\cos\ (\omega_{RF}-\omega_{LO})\ t\cdot\frac{R_L}{R_L+R_{on}}$$

Hence,

$$V_{IF}(t) = V_{out1}(t) - V_{out2}(t)$$

$$= |V_{RF}|\cdot\underbrace{\frac{2}{\pi}\cdot\frac{R_L}{R_L+R_{on}}}_{\text{Voltage Gain}}\cdot\cos\ (\omega_{RF}-\omega_{LO})\ t$$

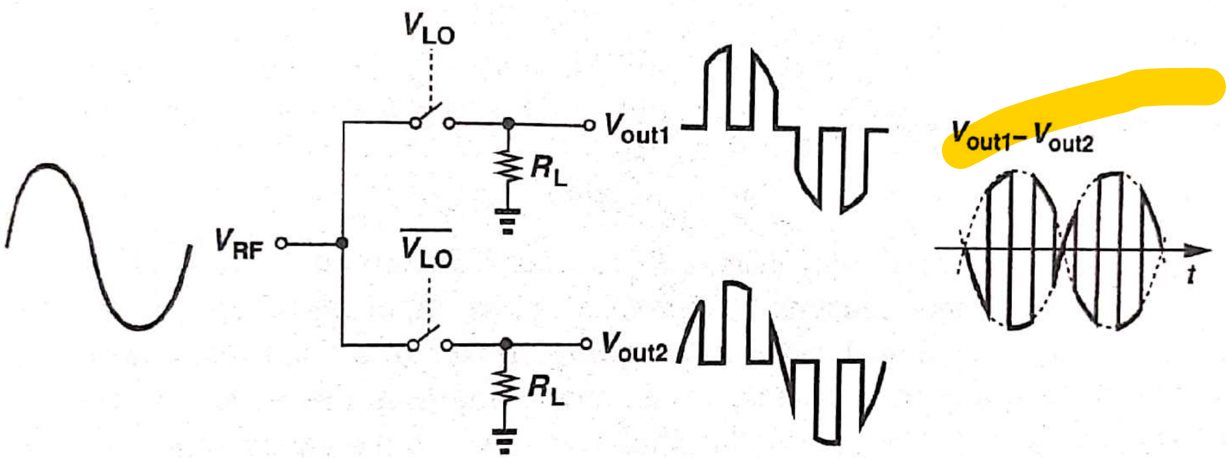
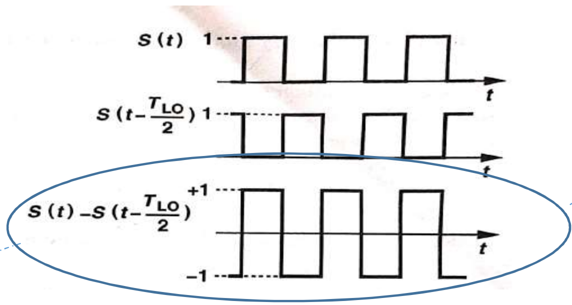


Figure 6.19 *Waveforms for passive mixer gain computation.*

Common Emitter and Common Base Bipolar Mixers

- CE mixer has high input impedance : $Z_{in} = r_\pi + R_E + \beta R_E \approx \beta R_E$ better suited for homodyne receiver.
- CB mixer has a lower input impedance $Z_{in} \approx R_E + 1/g_m$



$$I_{c1}(t) \approx \frac{-V_{RF}(t)}{R_S + R_E + 1/g_{m1}}$$

For LO square wave signal with 50% duty cycle,

the fundamental will have a component $(2/\pi)$

for a differential amplifier this will be $(4/\pi)$

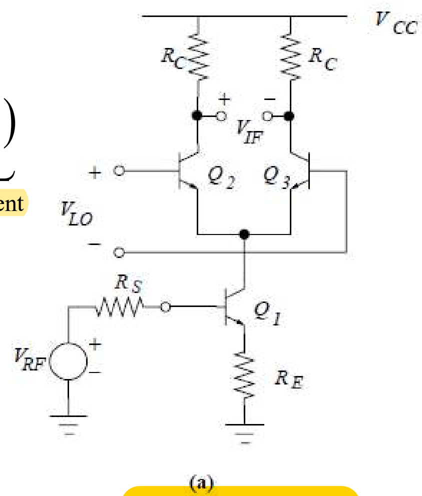
Fundamental component

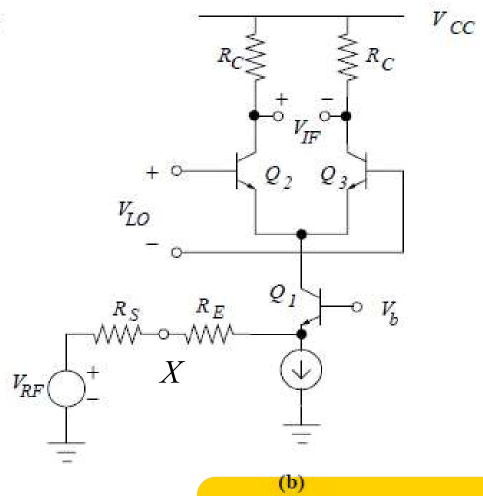
Hence, $V_{out}(t) = \dfrac{V_{RF}(t) \times R_C}{R_S + R_E + 1/g_{m1}} \cdot \underbrace{2}_{\text{since differential o/p taken}} \cdot \underbrace{\frac{1}{2}}_{\text{half since differential LO i/p}} \cdot \underbrace{\frac{4}{\pi}\cos(\omega_{LO} t)}_{\text{fundamental component of square wave}}$

$V_{RF}(t) \times \cos(\omega_{LO} t)$ will produce components like,

For differential

$$\frac{1}{2}\cos(\omega_{RF} - \omega_{LO}) + \underbrace{\frac{1}{2}\cos(\omega_{RF} + \omega_{LO})}_{\textit{filtered out}}$$





Hence, $V_{IF}(\omega) = \dfrac{|V_{RF}|}{R_S + R_E + 1/g_{m1}} \cdot \dfrac{2R_C}{\pi}$, Here V_{IF} and V_{RF} represent peak power.

Common Emitter and Common Base Bipolar Mixers

The voltage conversion gain:

$$A_V = \frac{V_{IF}}{V_{RF}\big|_{\text{node X}}} = \frac{\frac{|V_{RF}|}{R_S + R_E + 1/g_{m1}} \cdot \frac{2R_C}{\pi}}{|V_{RF}| \cdot |Z_{in}| / \left(|Z_{in}| + R_S\right)} = \frac{\frac{|V_{RF}|}{R_S + R_E + 1/g_{m1}} \cdot \frac{2R_C}{\pi}}{|V_{RF}| \cdot \left(R_E + 1/g_{m1}\right) / \left(R_E + 1/g_{m1} + R_S\right)} = \frac{2}{\pi} \cdot \frac{R_C}{R_E + 1/g_{m1}}$$

For matched i/p, $R_S = R_E + 1/g_{m1}$

$$\Rightarrow A_V = \frac{1}{\pi} \frac{2R_C}{R_S}$$

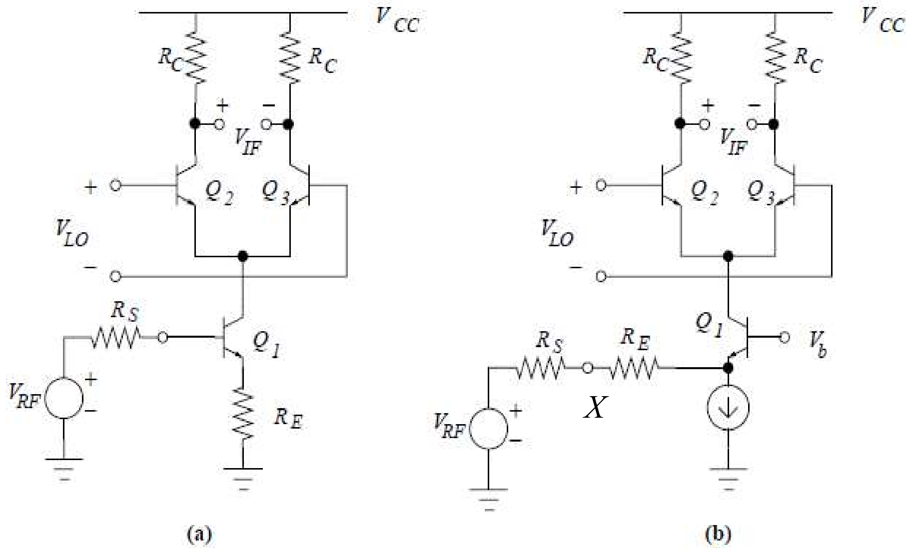
The average IF power delivered to the load:

$$P_{IF} = 2 \times \frac{(V_{IF}/2)^2}{R_C} = \frac{V_{IF}^2}{2R_C}$$

$$= \frac{|V_{RF}|^2 \cdot R_C^2}{\left(R_S + R_E + 1/g_{m1}\right)^2} \cdot \frac{4}{\pi^2} \cdot \frac{1}{2R_C} = \frac{|V_{RF}|^2 \cdot R_C}{\left(R_S + R_E + 1/g_{m1}\right)^2} \cdot \frac{2}{\pi^2}$$

$$= \frac{|V_{RF}|^2 \cdot R_C}{(2R_S)^2} \cdot \frac{2}{\pi^2}$$

$$P_{AVS} = |V_{RF} / 2R_S|^2 \times R_S = \frac{|V_{RF}|^2}{4R_S}$$



Conversion power gain (with i/p matched), $A_P = P_{IF} / P_{AVS} = \dfrac{\frac{|V_{RF}|^2 \cdot R_C}{4R_S^2} \cdot \frac{2}{\pi^2}}{\frac{|V_{RF}|^2}{4R_S}} = \dfrac{R_C}{R_S} \cdot \dfrac{2}{\pi^2}$

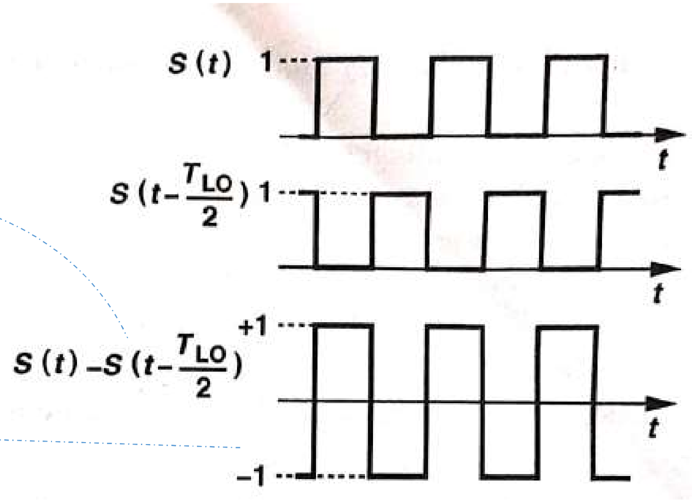
In practice A_P is lower due to parasitics.

Analysis of Single Balanced Mixer

Considering only fundamental component of LO vol tage,

$$V_{out}(t) = I_{RF}(t)\, R_D \cdot \underbrace{2}_{\text{due to differential o/p}} \cdot \underbrace{\frac{1}{2}}_{\text{half since differential LO i/p}} \cdot \underbrace{\frac{4}{\pi}\cos(\omega_{LO}\, t)}_{\text{fundamental component}}$$

Fundamental component



$$I_{RF}(t) = g_{m1} V_{RF} \cos\omega_{RF} t$$

$$I_{RF}(t) \times \cos(\omega_{LO}\, t) \text{ will produce components like,}$$

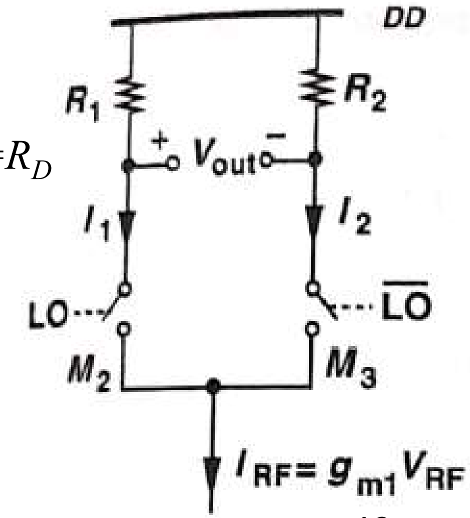
V_{LO}

$$\frac{1}{2}\cos(\omega_{RF} - \omega_{LO}) + \underbrace{\frac{1}{2}\cos(\omega_{RF} + \omega_{LO})}_{\text{filtered out}}$$

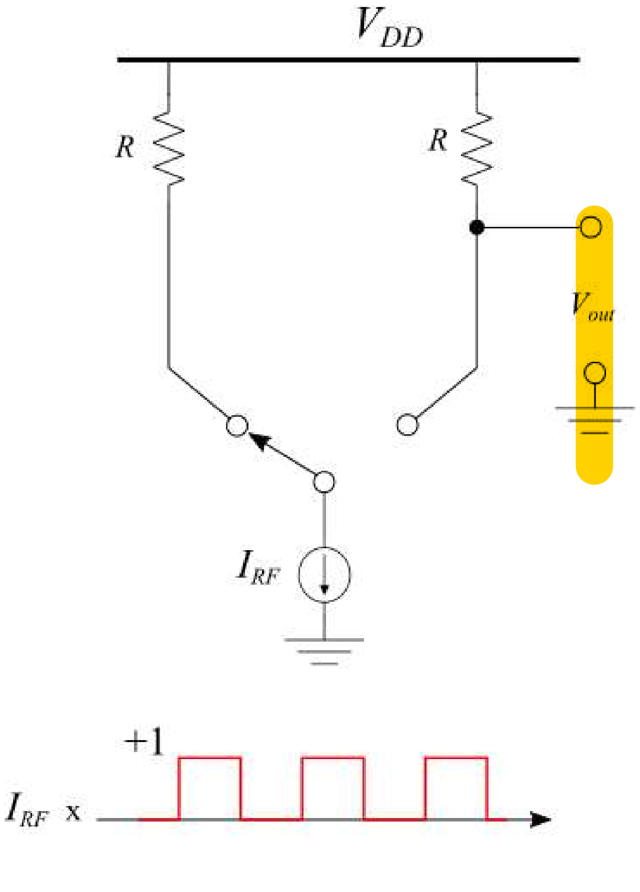
$$\Rightarrow V_{IF}(t) = \frac{2}{\pi} g_{m1} R_D\; V_{RF} \cos\;(\omega_{RF} - \omega_{LO})\, t$$

$$\text{Voltage gain, } A_V = \frac{|V_{IF}|}{|V_{RF}|} = \frac{2}{\pi} g_{m1} R_D$$

$R_1 = R_2 = R_D$

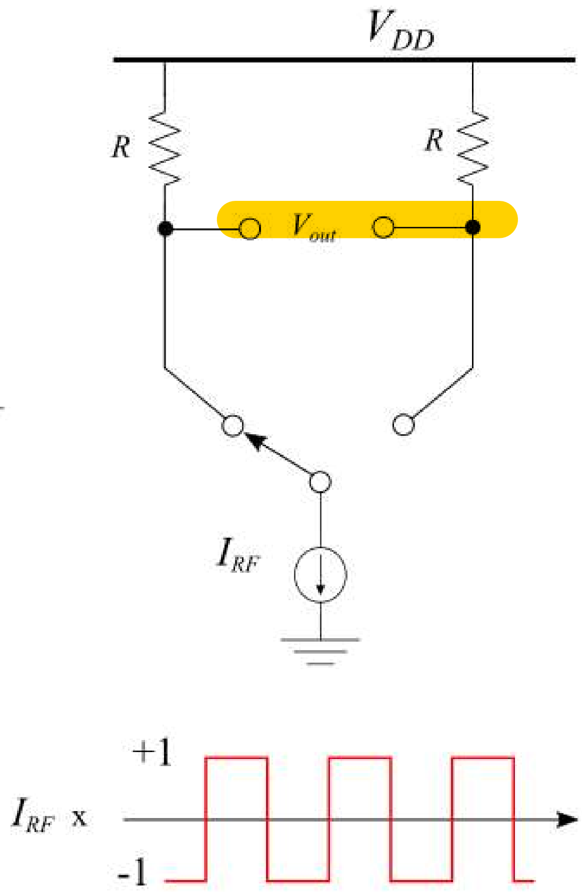


Direct Feedthrough



DC value not zero

V_{out} has a direct component of $I_{RF}(t)$

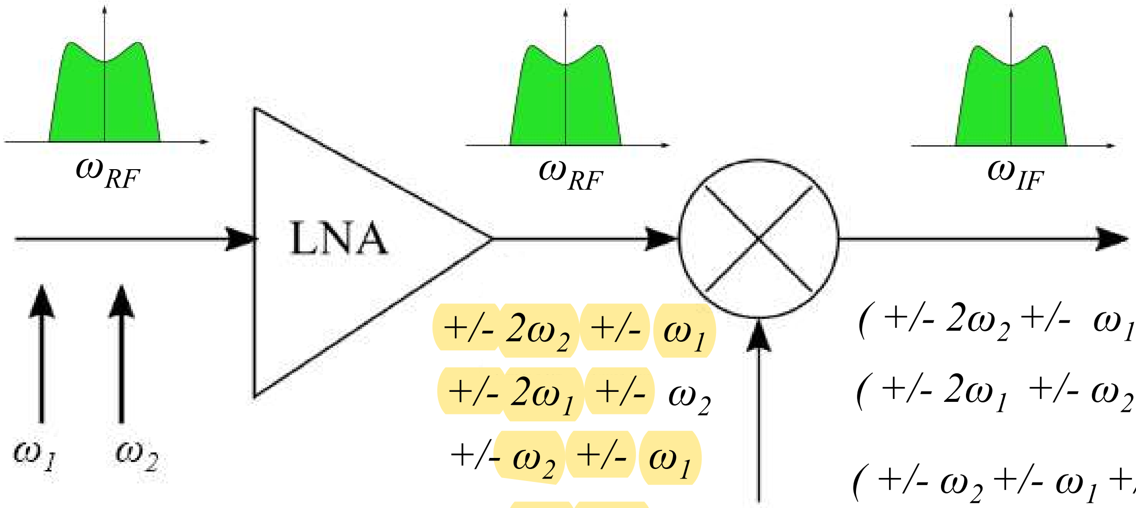


DC value zero

V_{out} has no direct component of $I_{RF}(t)$

- Important in homodyne receivers since second order beat components can pass through to baseband.
- Not so important in heterodyne receivers since IF frequency far from baseband.

Mixer Spurs



$+/- \, 2\omega_2 +/- \, \omega_1$

$+/- \, 2\omega_1 +/- \, \omega_2$

$+/- \, \omega_2 +/- \, \omega_1$

$+/- \, 2\omega_1$

$+/- \, 2\omega_2$

$(+/- \, 2\omega_2 +/- \, \omega_1 +/- \, \omega_{LO})$

$(+/- \, 2\omega_1 +/- \, \omega_2 +/- \, \omega_{LO})$

3rd order non linearity

$(+/- \, \omega_2 +/- \, \omega_1 +/- \, \omega_{LO})$ → Second order non linearity

$+/- \, 2\omega_1 +/- \, \omega_{LO}$

$+/- \, 2\omega_2 +/- \, \omega_{LO}$

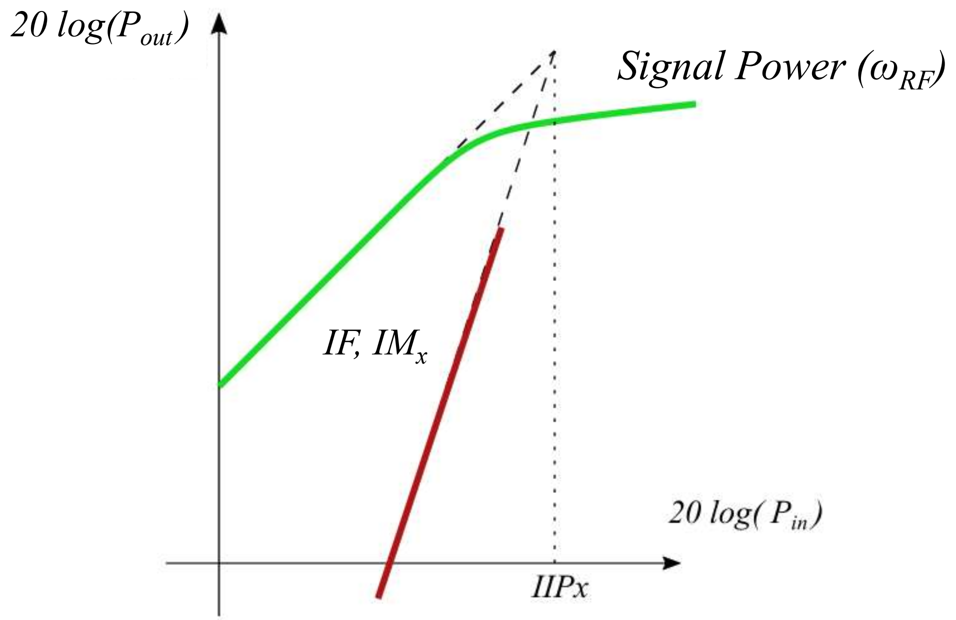
$+/- \, 2(\omega_1 +/- \, \omega_{LO}) +/- \, (\omega_2 +/- \, \omega_{LO})$

$+/- \, 2(\omega_2 +/- \, \omega_{LO}) +/- \, (\omega_1 +/- \, \omega_{LO})$

3rd order Intermodulation products

$+/- \, (\omega_2 +/- \, \omega_{LO}) +/- \, (\omega_1 +/- \, \omega_{LO})$ → 2nd order beat frequencies

Mixer Linearity

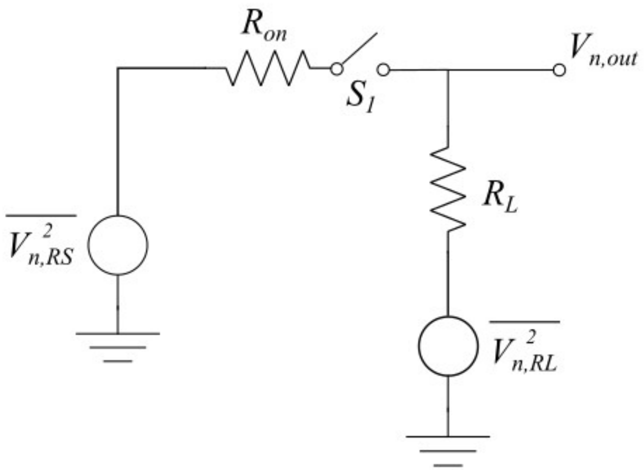


Noise in Mixers

Noise in mixer is difficult to calculate due to the frequency translation and time variance.

- What is noise in RF before down-conversion ?
- What is noise in IF after down-conversion ?
- need time-domain noise analysis since noise exhibits time-varying statistics due to switching.

Passive Mixer Noise calculation



Assuming 50% duty cycle of the LO, the o/p contains half of $4kT(R_{on} \parallel R_L)$ and half of $4kTR_L$.

Hence,

$$\overline{V^2_{n,out}} = 2kT[(R_{on} \parallel R_L) + R_L]$$

$$\Rightarrow \overline{V^2_{n,in}} = \overline{V^2_{n,out}} / \left(\underbrace{\frac{1}{\pi} \cdot \frac{R_L}{R_L + R_{on}}}_{\text{voltage gain}} \right)^2$$

$$= 2\pi^2 kT \frac{(R_{on} + R_L)(2R_{on} + R_L)}{R_L}$$

Source of Noise

In RF path

- Drain current noise of M2 & M3 .
- Drain current noise of M1.

In IF path:

- Drain Resistance R_D.

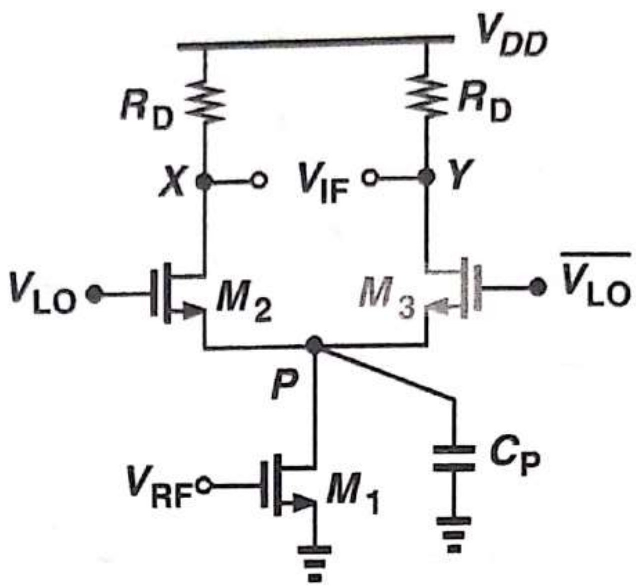


Figure 6.49 *Loss of RF current to ground through C_P.*

Criteria Affecting the Noise Performance

The LO signal is not usually a square wave and the transistors M2 and M3 are simultaneously on for part of the period. During this time M2 and M3 injects their noise at the output.

Note: while M2 and M3 are simultaneously on, the noise from M1 appears as a common mode component and does not contribute to the output.

Mixed Bag Solutions:

- Use larger LO swing (reduces time for which M2 and M3 are simultaneously 'ON' (section 6.3.1 new edition, razavi))
- Lower C_P (smaller W of transistor)

Quantitative Analysis

Methodology:

- For each source of noise calculate a conversion gain.
- Multiply the magnitude of each noise by the corresponding conversion gain and add up all the resulting powers.
- Divide the output by the overall conversion gain to get the input referred noise voltage $\overline{V_{ni}^2}$.
- Calculate the mixer noise figure: $F = \dfrac{\overline{V_{ni}^2}}{4kTR_s}$

Single balanced active Mixer Noise calculation

Oscillator noise Ignored here

In IF

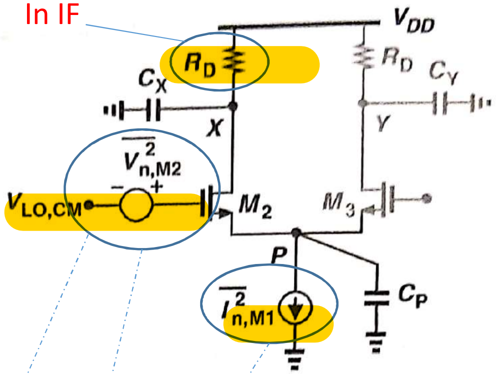


Figure 6.57 *Noise of input device and one switching device in an active mixer.*

In RF

Oscillator noise also present here.

$$\overline{V^2_{n,R_D}} = 4kTR_D,\ \underbrace{\overline{I^2_{n,M_1}} = 4kT(\gamma)\,g_{m1}}_{\text{drain current noise of } M_1},\ \underbrace{\overline{V^2_{n,M_2}} = \frac{4kT(\gamma)}{g_{m2}}}_{\text{i/p referred noise voltage representing drain current noise of } M_2}$$

$$\overline{V^2_{n,X}} = \underbrace{\frac{1}{2}}_{\text{Indicating noise injected during 50\% duty cycle of LO}} \left(\overline{I^2_{n,M_1}}R_D^2 + \underbrace{\overline{V^2_{n,M_2}}\,C_P^2\omega^2 R_D^2}_{\text{noise current injected by M2 into node X see example 5.10 (new edition)}} \right) + 4kTR_D$$

$$\text{Hence, } \overline{V^2_{n,in,single\ balanced}} = \frac{\underbrace{2}_{\text{taken twice due to 2 o/ps in a differential configuration}} \cdot \left[\frac{1}{2} \cdot \left(\overline{I^2_{n,M_1}}R_D^2 + \overline{V^2_{n,M_2}}\,C_P^2\omega^2 R_D^2 \right) + 4kTR_D \right]}{\underbrace{\frac{1}{\pi^2} g_{m1}^2 R_D^2 \frac{g_{m2}^2}{C_P^2\omega^2 + g_{m2}^2}}_{\text{single ended voltage conversion gain see Eqn 6.76 in new edition}}}$$

$$= \pi^2 \left(\frac{C_P^2\ \omega^2}{g_{m2}^2} + 1 \right) kT \left(\frac{4(\gamma)}{g_{m1}} + \frac{4(\gamma)\ C_P^2\omega^2}{g_{m2}g_{m1}^2} + \frac{8}{g_{m1}^2 R_D} \right)$$

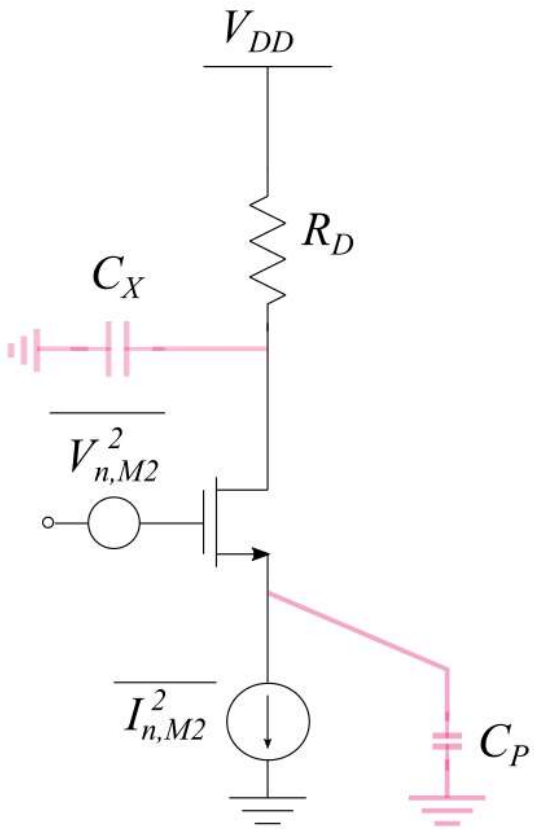
Single balanced active Mixer Noise calculation

For, single ended mixer, $\overline{V_{n,X}^2} = \frac{1}{2}\left(\overline{I_{n,M_1}^2} R_D^2 + \overline{V_{n,M_2}^2}\, C_P^2 \omega^2 R_D^2\right) + 4kTR_D$

$$\overline{V_{n,in,single\ ended}^2} = \frac{\left[\frac{1}{2}\cdot\left(\overline{I_{n,M_1}^2} R_D^2 + \overline{V_{n,M_2}^2}\, C_P^2 \omega^2 R_D^2\right) + 4kTR_D\right]}{\frac{1}{\pi^2} g_{m1}^2 R_D^2 \frac{g_{m2}^2}{C_P^2\ \omega^2 + g_{m2}^2}}$$

$$= \pi^2\left(\frac{C_P^2\ \omega^2}{g_{m2}^2} + 1\right) kT \left(\frac{2(\gamma)}{g_{m1}} + \frac{2(\gamma)\ C_P^2 \omega^2}{g_{m2} g_{m1}^2} + \frac{4}{g_{m1}^2 R_D}\right)$$

$$\Rightarrow V_{n,in,single\ ended}^2 < V_{n,in,single\ balanced}^2$$



MOS Mixers Versus Bipolar Mixers

- MOS mixers require typically 1 V of differential LO drive to experience complete switching: M2 and M3 are simultaneously on for a greater fraction of the period: injecting more noise at the output.
- The channel noise is typically several times lower than the bipolar shot noise. So MOS and BJT have approximately the same noise performance in mixers.
- As M2 and M3 are simultaneously on for a greater fraction of the period, the conversion gain of MOS might be lower, because when both are ON only common mode gain is provided and not differential gain.