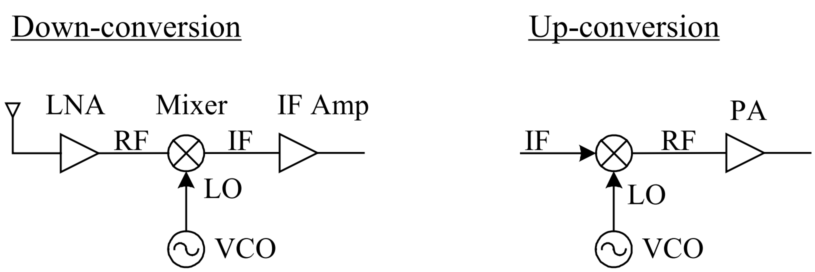
Mixers



important aspects of mixer

* Conversion gain (loss) = G_C

mixers can be passive
so they may show
loss rather than gain

(sometimes passive mixers are better in terms of isolation, linearity, NF)

$$G_C = \frac{IF}{RF}$$ ⟶ conversion gain can be in terms of voltage, current or power

consider a multiplier function :

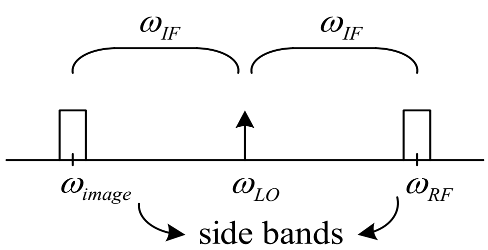
$$(A\cos\omega_{RF}t)(B\cos\omega_{LO}t) = \frac{AB}{2}\left[\underbrace{\cos(\omega_{RF}-\omega_{LO})t}_{\text{IF}} + \cos(\omega_{RF}+\omega_{LO})t\right]$$

high frequency term
that will be filtered out

$$G_C\Big|_{voltage} = \frac{AB/2}{A} = \frac{B}{2} = \underbrace{\frac{1}{2}\ of\ \ LO\ \ amplitude}$$

you expect that conversion gain
be a function of LO power!

<u>* Noise figure</u>



NF definition is tricky because the noise present in both ω_{RF} and ω_{image} band will be down-converted to IF frequency

⟶ most frequently the data (signal) we are interested is at ω_{RF} frequencies. But the noise comes from both ω_{RF} and ω_{image} frequency bands this type of noise figure is called <u>single side band NF</u>

⟶ if data is actually on ω_{RF} and ω_{image} then we can define <u>double-side-band NF</u>

DSB NF is typically 3 dB lower than SSB NF

NF of mixers are typically much higher than LNA's

if it was low we would not have used LNA

typically SSB NF : 10 ~ 15 dB

The reason it is high

1) Noise from frequencies other than RF frequencies will contribute
2) mixers often use switching elements

   a switch transistor operate between active (saturation) and off state

   in linear/sub-threshold state, the transistor is very noisy

*** Mixer linearity**

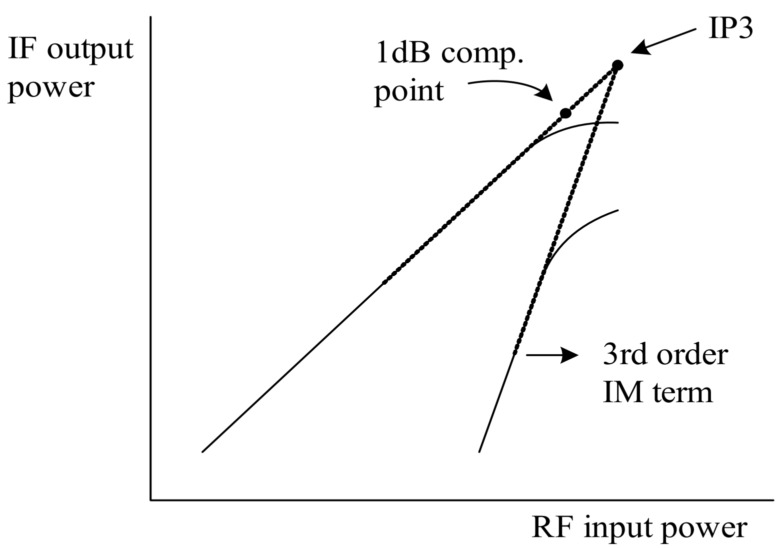
mixer itself is a non-linear element, so what does the linearity of a mixer means?

$$G_C = \frac{IF}{RF} \longleftarrow \text{this gain should be constant}$$

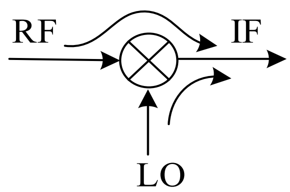
as you go to high input power (RF ↑) gain
starts to drop (saturation)

→ we can define * 1-dB compression point

* IP3



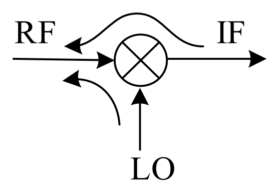
*** Isolation in mixers**



ideally you want

@ IF terminal only IF and not RF or LO → not a big deal since you can filter RF or LO

@ RF terminal only RF and not IF or LO



IF → can be filtered but LO presence is a problem since

LO → can leak to input → radiate from antenna

→ can result in self-mixing → dc term (that is not really a dc)

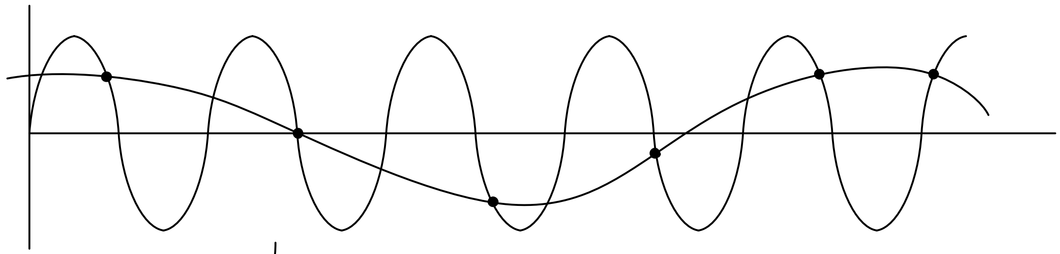
@ LO terminal only LO and not RF or IF

→ filter

→ usually weak signal unlike LO, but it can also cause problem

RF/LO isolation → 40 ~ 60 dB is desired

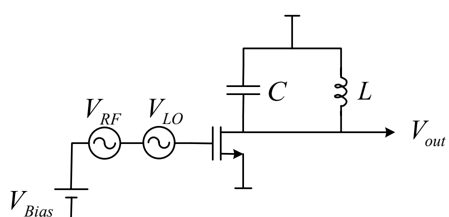
Mixers
- mixers using non-linear devices
- multiplier-based mixers
- sub-sampling mixers → sample RF at much lower freq. (LO does not need to be high-freq.)



noise at sampler input folds into the IF band

these type of mixers are very noisy
SSB NF ~ 25 dB

Mixers using non-linear devices



$$V_{out} = C_1 V_{in} + C_2 V_{in}^2$$

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

$$V_{out} = V_{DC} + V_{fund} + V_{square} + V_{cross}$$

$$V_{fund} = C_1\left[V_{RF}\cos(\omega_{RF}t) + V_{LO}\cos(\omega_{LO}t)\right]$$

$$V_{square} = C_2\left[V_{RF}^2\cos^2(\omega_{RF}t) + V_{LO}^2\cos^2(\omega_{LO}t)\right]$$

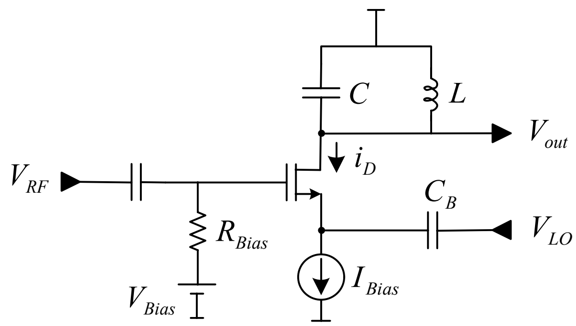
$$V_{cross} = 2C_2 V_{RF} V_{LO}\left[\cos(\omega_{RF}t)\cos(\omega_{LO}t)\right]$$

$$\cos(\omega t)^2 = \frac{1}{2}\left[1 + \cos 2\omega t\right]$$

$$V_{cross} = C_2 V_{RF} V_{LO}\left[\cos(\omega_{RF} - \omega_{LO})t + \cos(\omega_{RF} + \omega_{LO})t\right]$$

$$G_C = \frac{C_2 V_{RF} V_{LO}}{V_{RF}} = C_2 V_{LO}$$

to isolate RF and LO better (still not very well isolated)



$$i_D = \frac{k'W}{2L}\left(V_{gs} - V_{Th}\right)^2$$

$$i_D = \frac{k'W}{2L}\left[V_{Bias} + V_{RF}\cos(\omega_{RF}t) - V_{LO}\cos(\omega_{LO}t) - V_{Th}\right]^2$$

transconductance $\left(\frac{i_{DIF}}{V_{RF}}\right)$ $\longrightarrow$ $G_C = \frac{k'W}{2L}V_{LO}$

long-channel MOS are more nonlinear
than short-channel devices (velocity saturation makes them linear)

Long-channel MOS are better for mixer applications

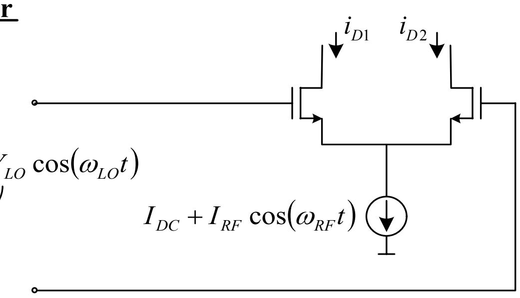
Multiplier-based Mixers

* better performance than non-linear mixing
  as you can get only multiplication function
  and less other harmonics

* separate port for LO, RF and IF $\longrightarrow$ better isolation

* well implemented in CMOS since CMOS is a good switch

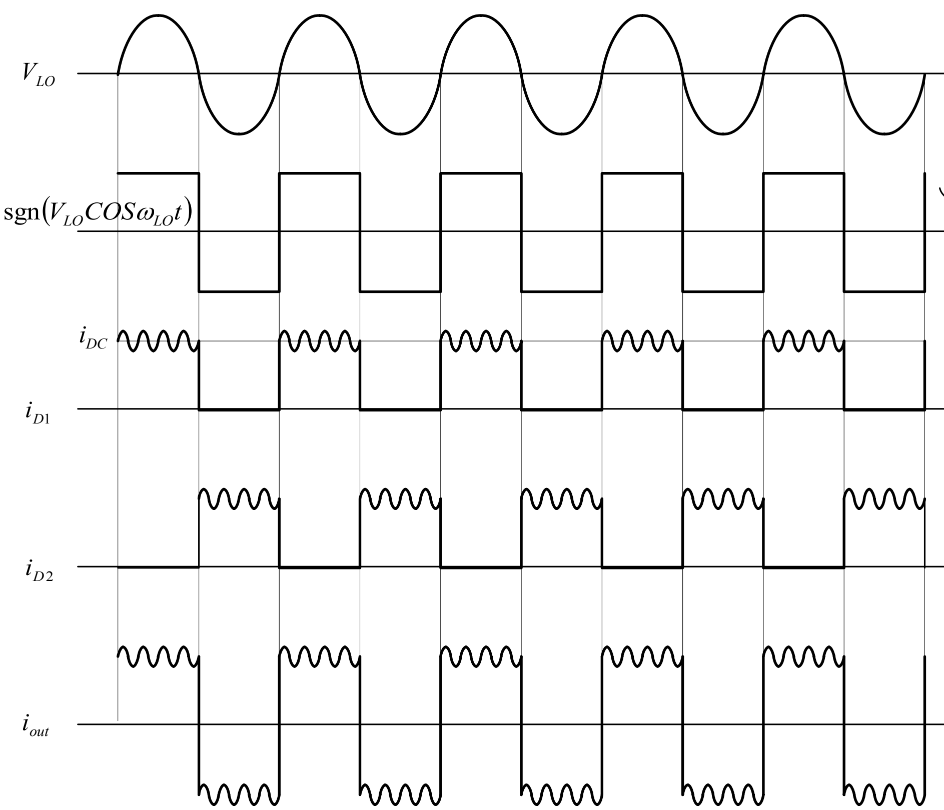
→ **Single balanced Mixer**



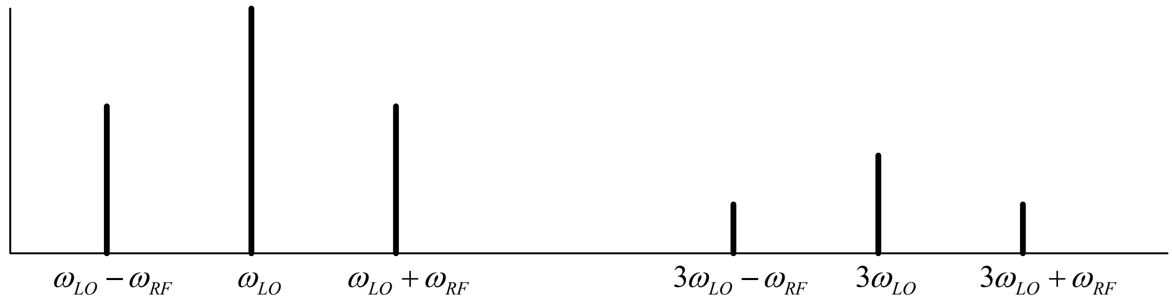
→ gilbert-cell mixer

VLO
large enough
such-that it
commutates the
different pair
(switch them on
and off alternatively)

$$i_{out}=i_{D2}-i_{D1}=\operatorname{sgn}[\cos\omega_{LO}t][I_{Bias}+I_{RF}\cos\omega_{RF}t]$$



contains
odd harmonics
of LO

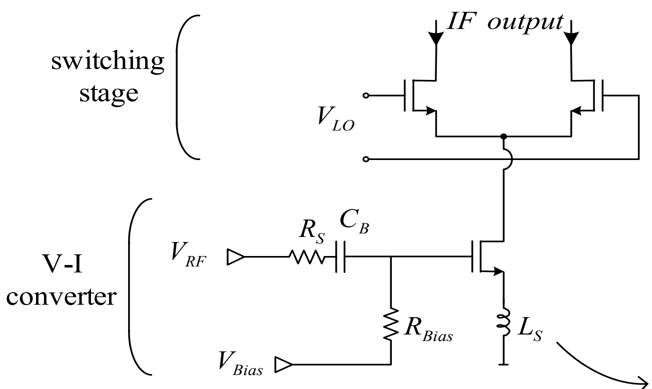


since LO + it's odd harmonics are present at the output

this type of mixer is referred to as single balanced mixers

* to make a linear $I_{Bias} + I_{RF} COS\omega_{RF} t$ We need a linearized transconductance stage

example of single-balanced mixer with linearized transconductance



assuming perfect switch under high LO signal

perfect square wave fundament amplitude $= \frac{4}{\pi}$ sq. wave amplitude

is preferred over R as it has
* lower noise
* better for low-power low-voltage
* gain at harmonic

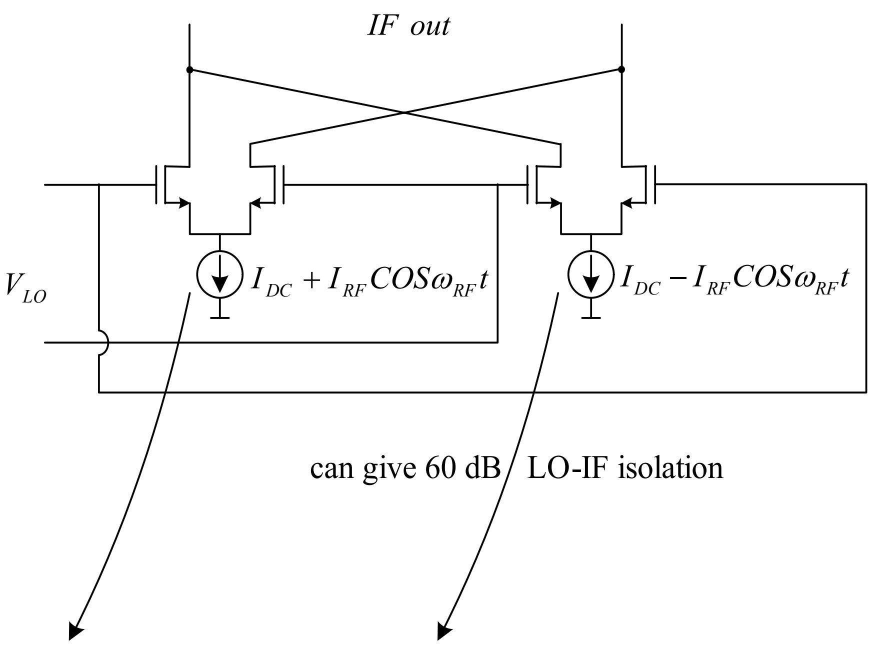
transconductance I_{IF}/V_{RF} $\leftarrow$ $G_C = \frac{2}{\pi} g_m$ $\rightarrow$ $$\frac{2g_m}{\pi\left[1-\omega^2 C_{gs} L_s + j\omega\left(L_s g_m + R_S C_{gs}\right)\right]}$$

g_m: transconductance of V-I converter

Double balanced mixers

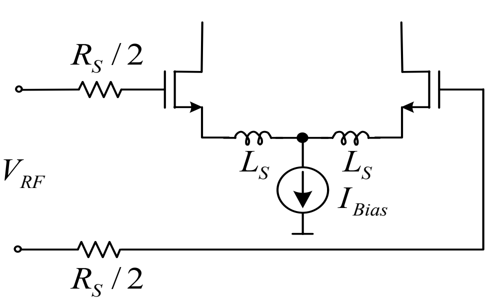
removes LO at the IF port

two single-balanced may be combined to remove LO



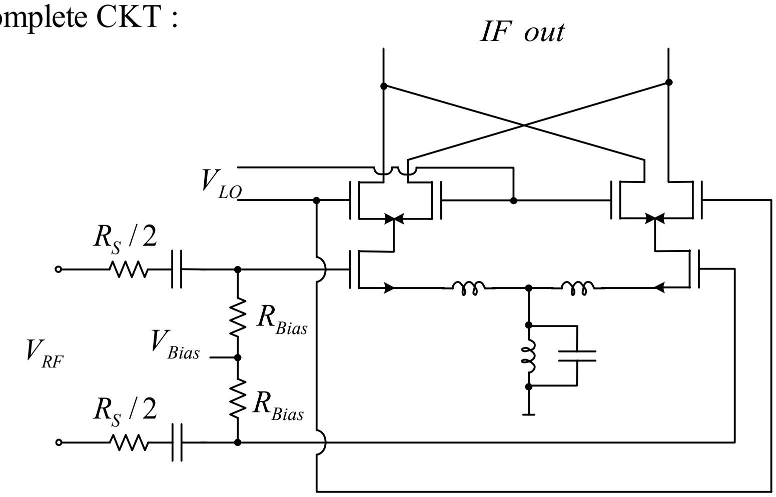
can give 60 dB LO-IF isolation

use a linearized transconductance stage



or use minimum supply headroom by using an LC tank instead of I $_{bias}$ current source

Complete CKT :



Noise figure of gilbert-cell mixers

⟶ mainly NF of V-I transconductance stage

+ 3dB (since ½ signal is at $(\omega_{LO} + \omega_{RF})$)

+ additional noise in the switching stage

+ noise of LO

Linearity of gilbert-cell mixers

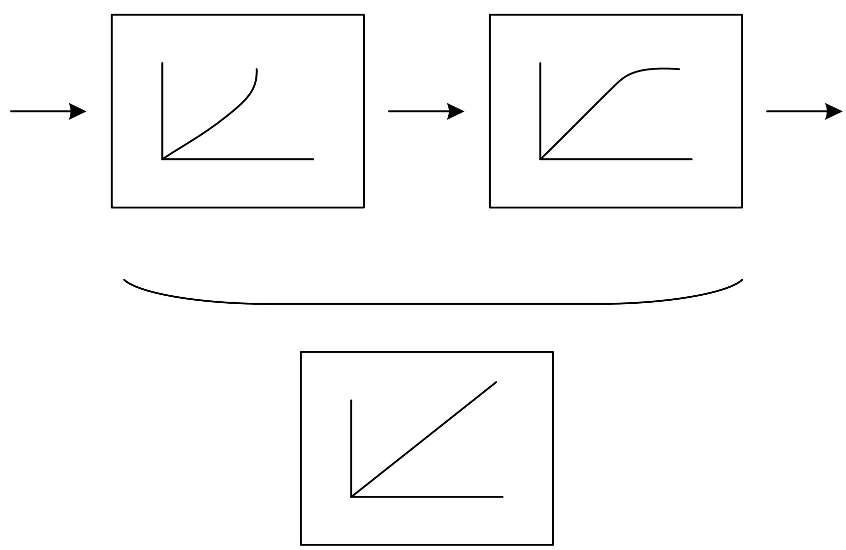
⟶ mainly linearity of V-I transconductance stage
(almost same IP3 or I-dB compression)

as long as LO switching stage is close to ideal switch

More on linearization

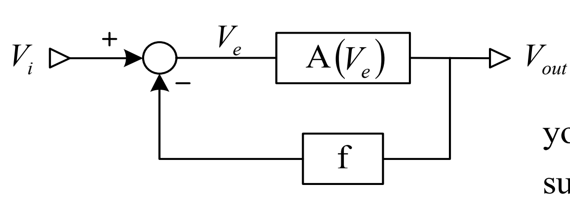
Predistortion

⟶ combine to non-linearities such that they cancel each other



Negative feedback

⟶ closed loop bandwidth is smaller than inherent bandwidth ⟶ makes the ckt slow



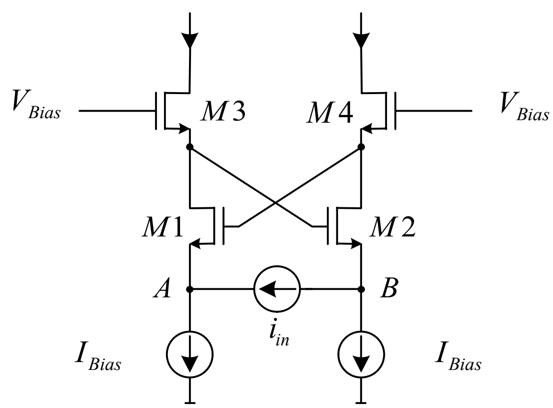
you have to wait for this cycle such that error signal is meaningful

Positive feedback (feed-forward)

→ as long as you do not have gain you can use the feedback without being worried about instability

Example

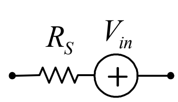
Cross-quad



$$\begin{cases} V_A = V_{Bias} - (V_{gs4} + V_{gs1}) \\ V_B = V_{Bias} - (V_{gs3} + V_{gs2}) \end{cases}$$

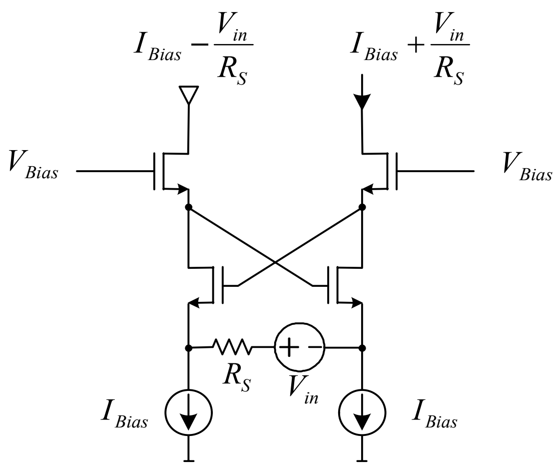
$$\left.\begin{aligned} V_{gs3} &= V_{gs1} \\ V_{gs2} &= V_{gs4} \end{aligned}\right\}$$ since they have same current

$V_A = V_B$

Substitute i in with 

→ $i_{in} = \dfrac{V_{in}}{R_S}$ as $V_A = V_B$

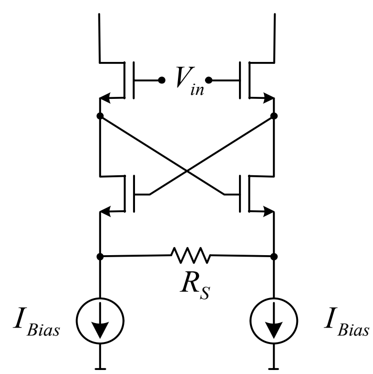
→ perfect transconductance stage with linearity of a resistor



cross-quad
transconductance

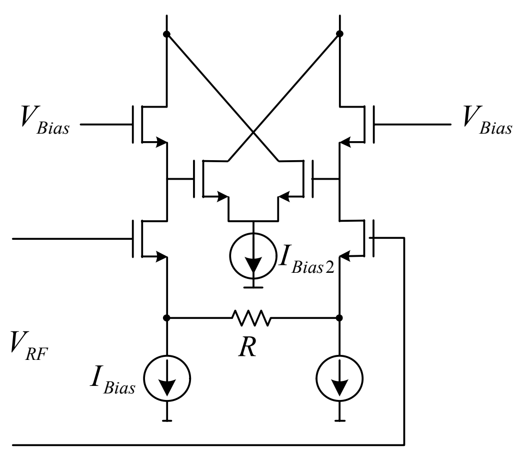
$\equiv$

alternative
connection
for
cross-quad
transconductance



Alternative feedforward linearization technique

MOSFET cascomp

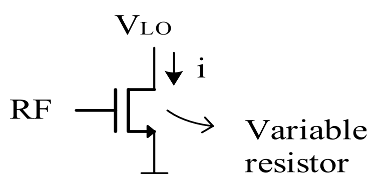


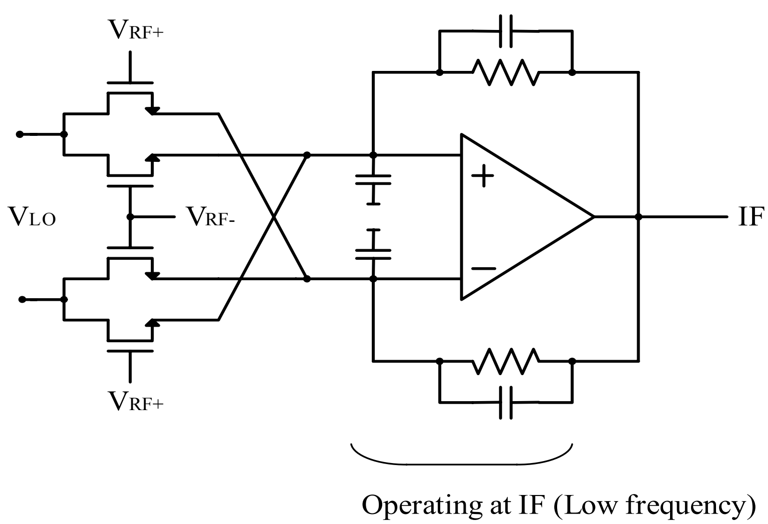
Potentiometric Mixers

Unlike Gilbert mixers(transistors as switch), use transistors as variable resistors

V_{ds} varies with LO
V_{gs} is controlled by RF

$$i = \frac{V_{LO}}{r_{ds}} \approx V_{LO}\frac{k'W}{L}\left(V_{RF} - V_T - V_{LO}\right) \approx kV_{LO}V_{RF}$$





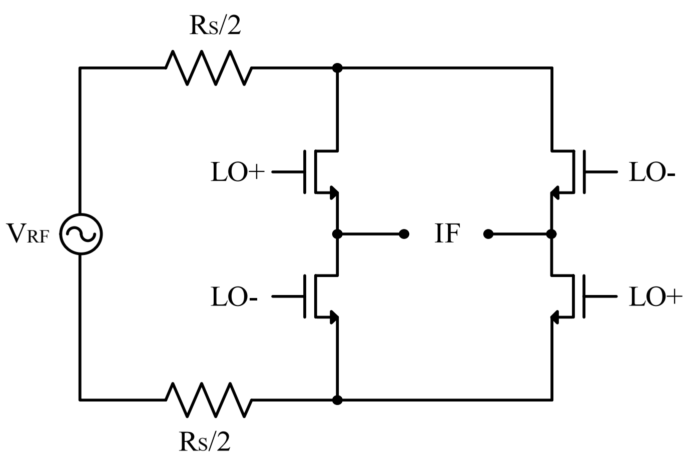
- Good linearity (IIP3~40dB)
- High noise (NF ~30dB) : due to resistive operation

Passive double-balanced Mixer

Passive Mixers → low power

Switch RF signal directly in voltage domain instead of curren

driven by local oscillator



$$G_C = \frac{2}{\pi} \approx -3.9dB$$ → for square wave LO drive

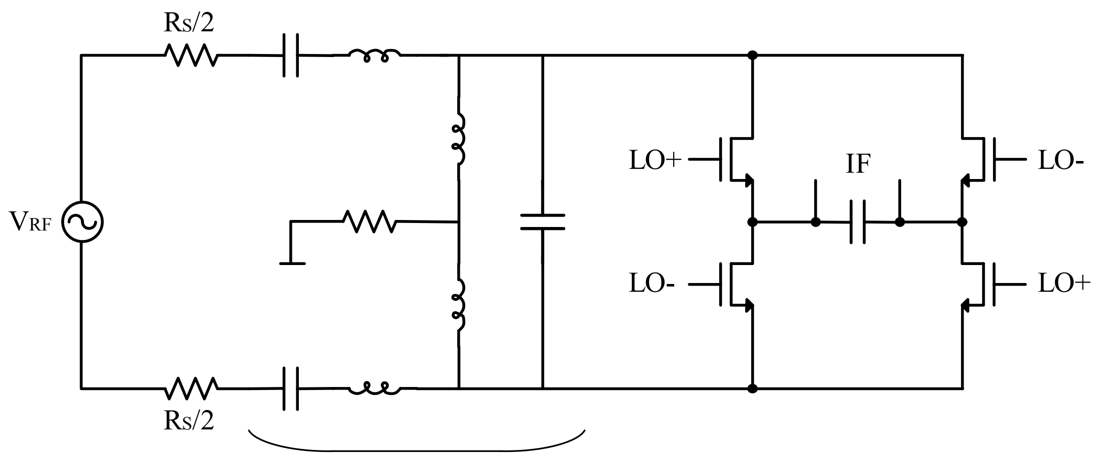
In practice conversion gain is lower due to transistors finite switching time

/

For sinusoidal drive conversion gain is actually higher

$$G_C = \frac{\pi}{4} \approx -2.1dB$$

Alternative approach → low-noise passive double-balanced mixer

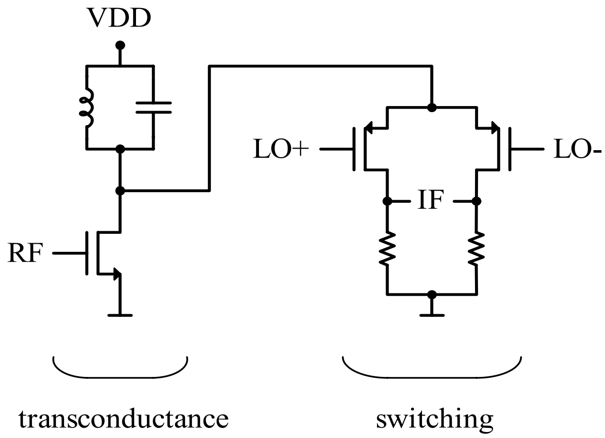


Narrowband matching → L-match can boost IP3
(trade conversion gain for IP3)

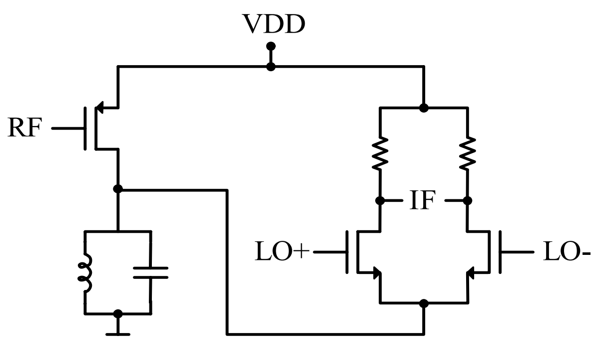
- IIP3 ~ 10dBm
- NF ~ 10dB

- No dc bias → no 1/f noise → good for direct conversion receivers
- to decrease LO power, resonate input caps with inductors → narrowband LO power ↓ $1/Q^2$

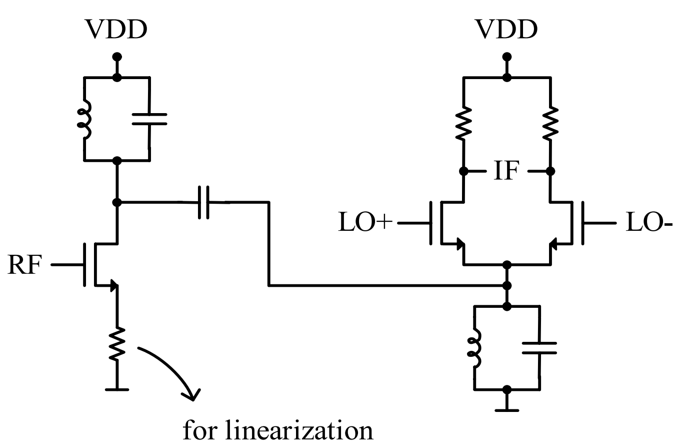
Some typical single-balanced mixers in literature



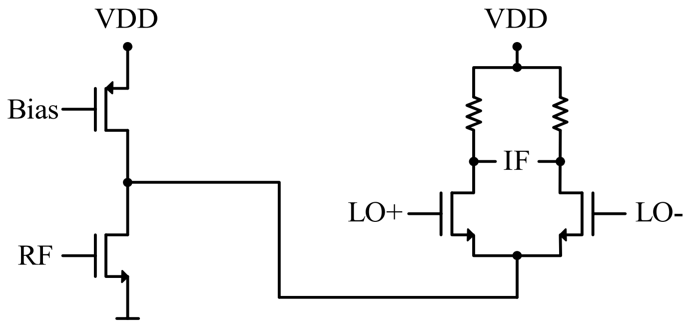
Change nmos to pmos and vice versa



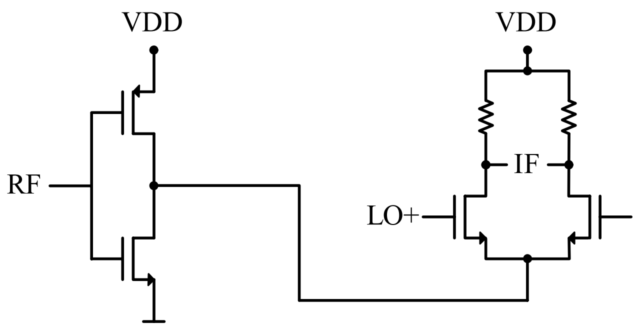
More linearized transconductance



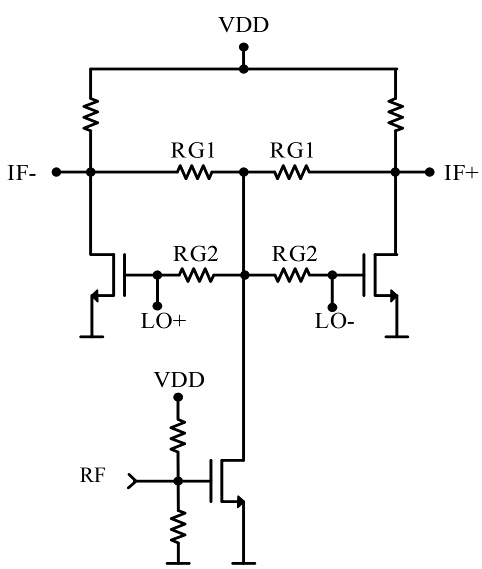
Current source instead of the tank (wideband frequency)

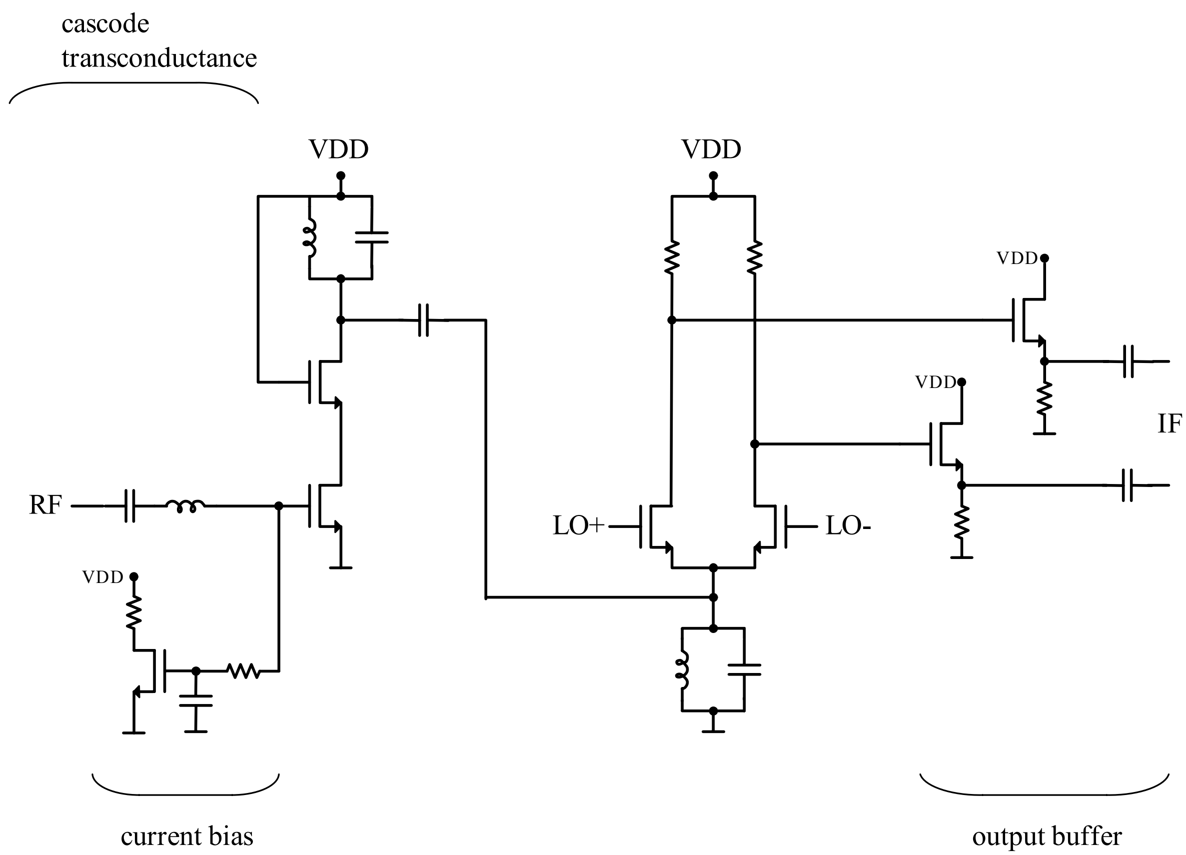


Inverter as transconductance



Linearization using feedback

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transconductance
VDD
VDD
VDD
VDD
RF
LO+
LO-
IF
VDD
current bias
output buffer