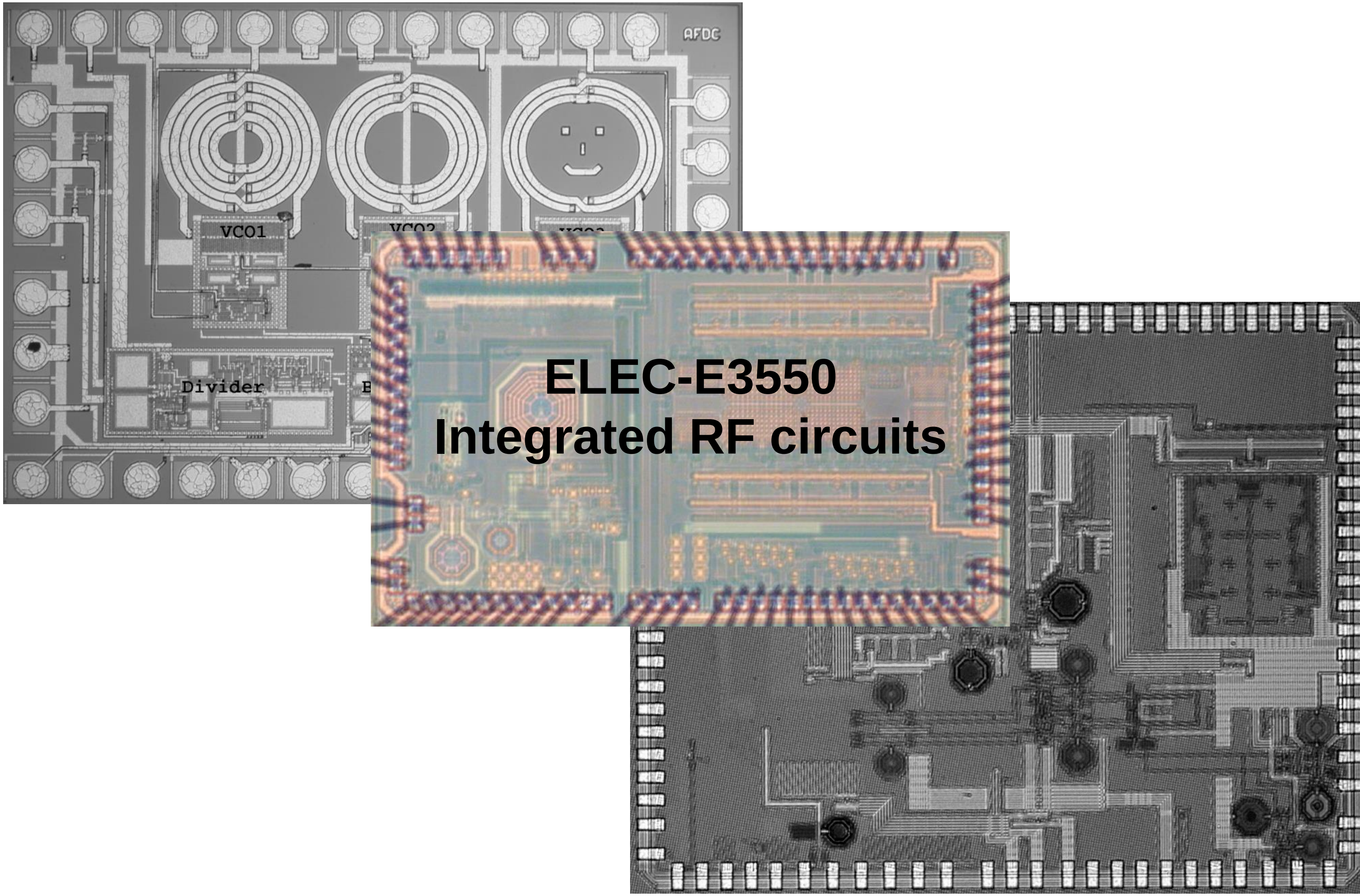


ELEC-E3550
Integrated RF circuits

Aalto University
School of Electrical Engineering

Department of Electronics and Nanoengineering
Kari Stadius, Saeed Naghavi, Jian Gao

Integrated RF circuits
Spring 2022

Previous Topics

Basic Amplifiers

- Biasing schemes

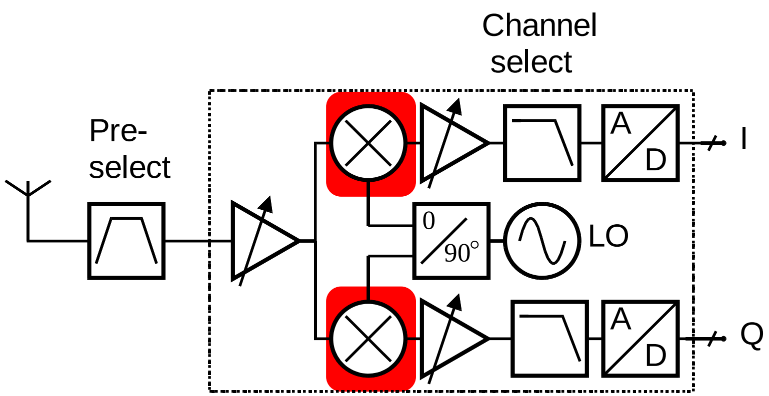
Low-Noise Amplifiers

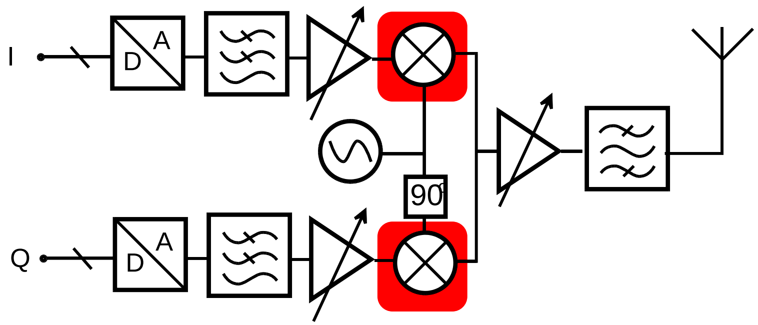
- Concepts
- Resistively terminated
- Parallel feed-back
- Common gate
- Inductively degenerated
- Wide bandwidth - - low noise ?? →Noise cancelling

Power Amplifiers

- Concepts
- Current mode: A, B, C
- Switch mode: D, E, F

Mixers





Focus on specific RF IC mixers

- Down-conversion (RX)
- Up-conversion (TX)

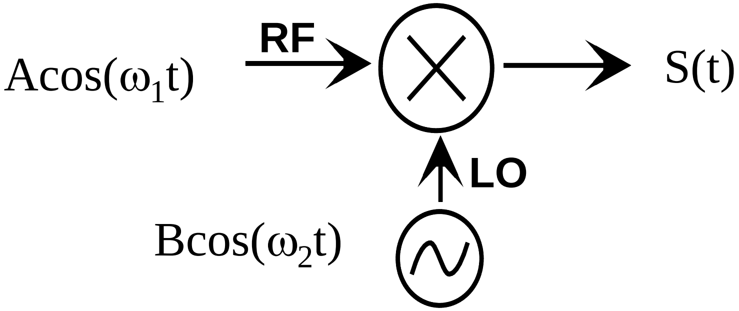
TX and RX mixers are quite similar
→ RX only for simplicity

- Active mixers (Gilbert cell)
- Passive mixers
- Advanced cases / examples

Exercises & Homework

- Self-access learning material
- CAD-exercise
- Homeworks

Ideal Multiplier / Mixer

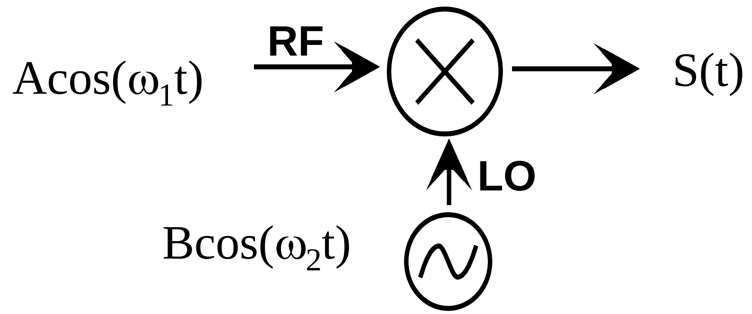


$$S(t) = A\cos(\omega_1 t) B\cos(\omega_2 t) = \frac{AB}{2}\left(\cos(\omega_1 - \omega_2)t + \cos(\omega_1 + \omega_2)t\right)$$

up-conversion

down-conversion

Ideal Multiplier / Mixer



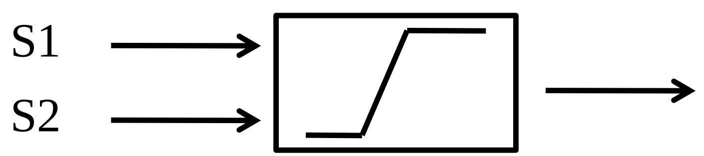
up-conversion

$$S(t) = A\cos(\omega_1 t)B\cos(\omega_2 t) = \frac{AB}{2}\left(\cos(\omega_1 - \omega_2)t + \cos(\omega_1 + \omega_2)t\right)$$

down-conversion

”*mixing*” = multiplication in time-domain = frequency shift in frequency domain

Any nonlinear element can act as a mixer



S_{OUT} = f(S1,S2)

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Reminder: IIP3 Analysis

- Nonlinear circuit with 2nd and 3rd order nonlinearity

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

- Inputs: $A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t) \rightarrow$ Output

$$v_{out}(t) = \frac{1}{2}\alpha_2\left(A_1^2 + A_2^2\right) + \left(\alpha_1 A_1 + \alpha_3\frac{3A_1^3 + 6A_1A_2^2}{4}\right)\cos(\omega_1 t) + \left(\alpha_1 A_2 + \alpha_3\frac{3A_2^3 + 6A_1^2A_2}{4}\right)\cos(\omega_2 t)$$

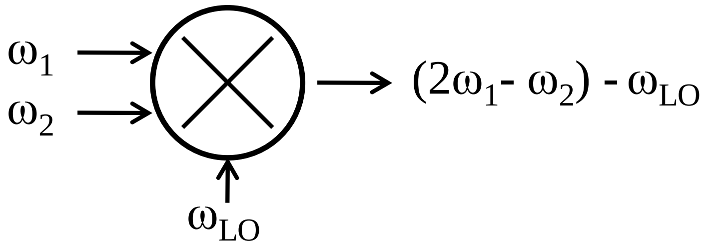
$$+ \tfrac{1}{2}\alpha_2 A_1^2\cos(2\omega_1 t) + \tfrac{1}{2}\alpha_2 A_2^2\cos(2\omega_2 t) + \tfrac{1}{4}\alpha_3 A_1^3\cos(3\omega_1 t) + \tfrac{1}{4}\alpha_3 A_2^3\cos(3\omega_2 t)$$

$$+ \alpha_2 A_1 A_2\left[\cos(\omega_1 t - \omega_2 t) + \cos(\omega_1 t + \omega_2 t)\right] + \tfrac{3}{4}\alpha_3 A_1^2 A_2\cos(2\omega_1 t + \omega_2 t) + \tfrac{3}{4}\alpha_3 A_1 A_2^2\cos(\omega_1 t + 2\omega_2 t)$$

$$+ \tfrac{3}{4}\alpha_3 A_1^2 A_2\cos(2\omega_1 t - \omega_2 t) + \tfrac{3}{4}\alpha_3 A_1 A_2^2\cos(2\omega_2 t - \omega_1 t)$$

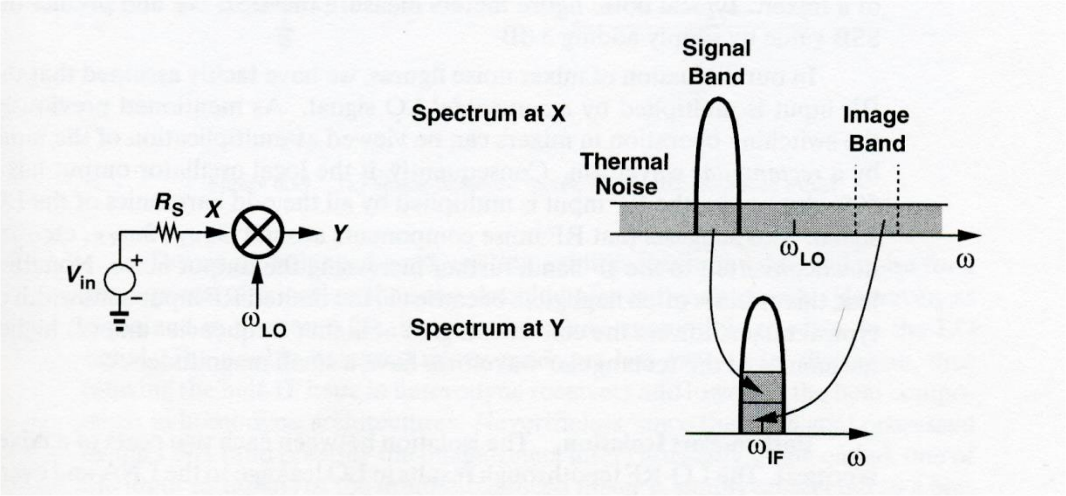
Concepts

- Conversion gain $= V_{IF} / V_{RF}$
- Noise Figure
  - Single-sideband (SSB)
  - Double-sideband (DSB)
- Linearity
  - IIP2
  - IIP3; in-band / out-of-band



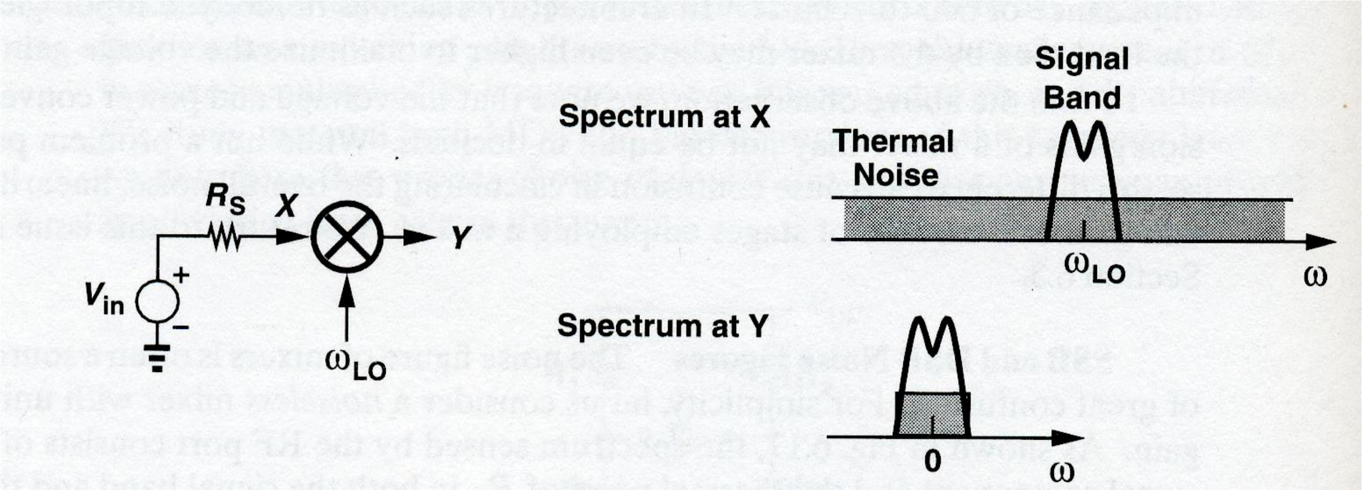
- Compression point (ICP)
- Port-to-port isolation

Mixer Noise Figure; SSB



- In single-sideband mixer ($f_{RF} \neq f_{LO}$)
  - Noise is on both sidebands
  - Signal is on ONE sideband
- The NF of ”noiseless SSB mixer” is 3 dB
- Heterodyne receivers: image filter before mixer

Mixer Noise Figure; DSB



- In double-sideband mixer
  - Noise is on both sidebands
  - Signal is on both sideband
- The NF of ”noiseless DSB mixer” is 0 dB
- Valid parameter for **direct-conversion receivers**

Simple Mixer Example: MOSFET Drain Current

MOSFET drain current with two input signals:

$$I_{DS} = \frac{K_n^{'} W}{2L}\left(V_{GS0} - V_T + v_{RF} + v_{LO}\right)^2$$

$$= \frac{K_n^{'} W}{2L}\left[\left(V_{GS0} - V_T\right)^2 - 2\left(V_{GS0} - V_T\right)\left(v_{RF} + v_{LO}\right) + v_{RF}^2 + v_{LO}^2 + 2 v_{RF} v_{LO}\right]$$

Simple Mixer Example: MOSFET Drain Current

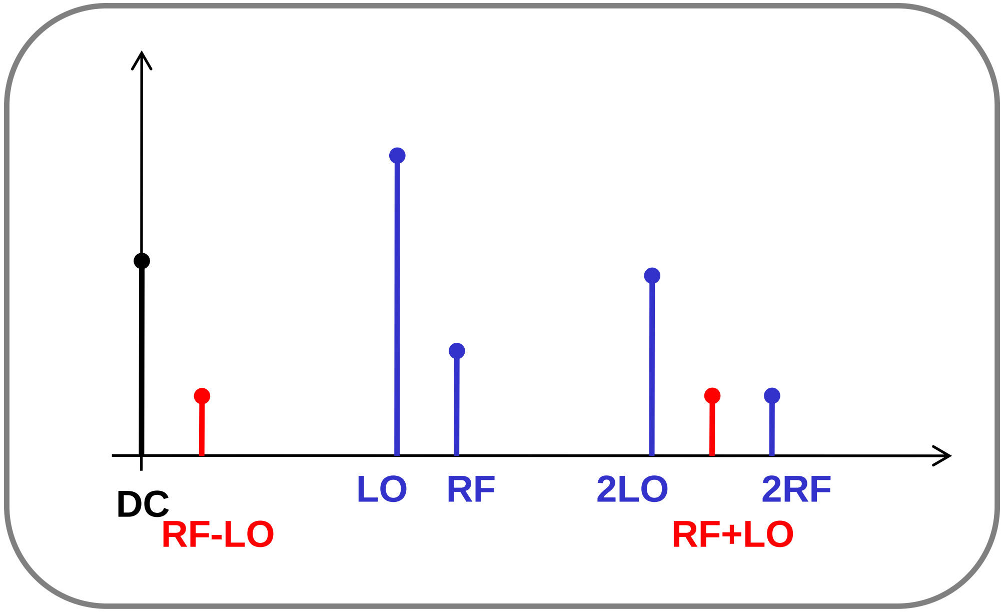
MOSFET drain current with two input signals:

$$I_{DS} = \frac{K_n^{'}W}{2L}\left(V_{GS0} - V_T + v_{RF} + v_{LO}\right)^2$$

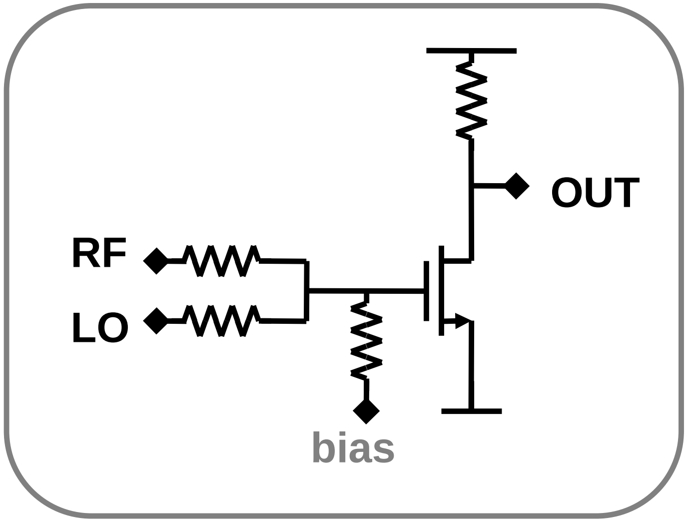
$$= \frac{K_n^{'}W}{2L}\left[\left(V_{GS0} - V_T\right)^2 - 2\left(V_{GS0} - V_T\right)\left(v_{RF} + v_{LO}\right) + v_{RF}^2 + v_{LO}^2 + 2v_{RF}v_{LO}\right]$$

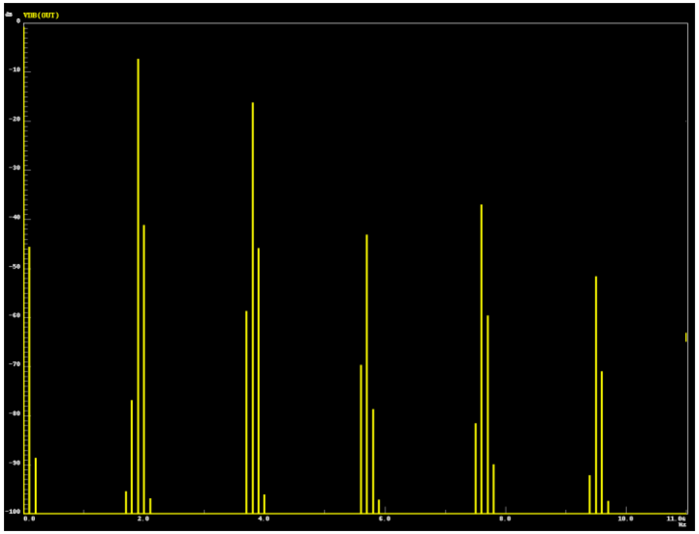
The output includes

- DC component
- Feedtrough components
- Distortion components
- Mixing product components

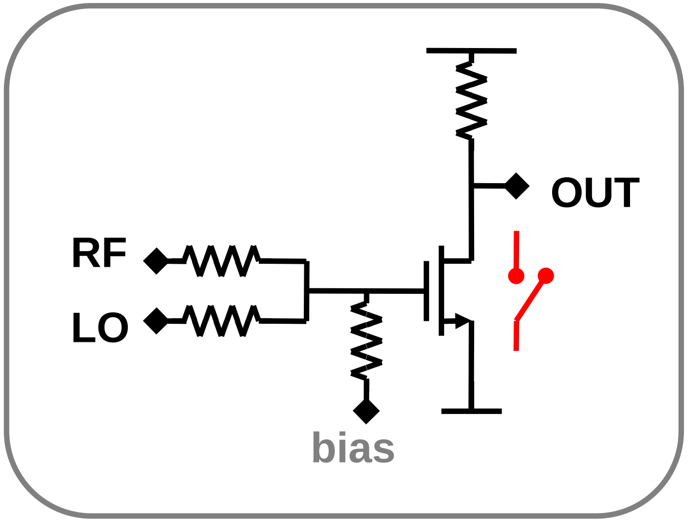


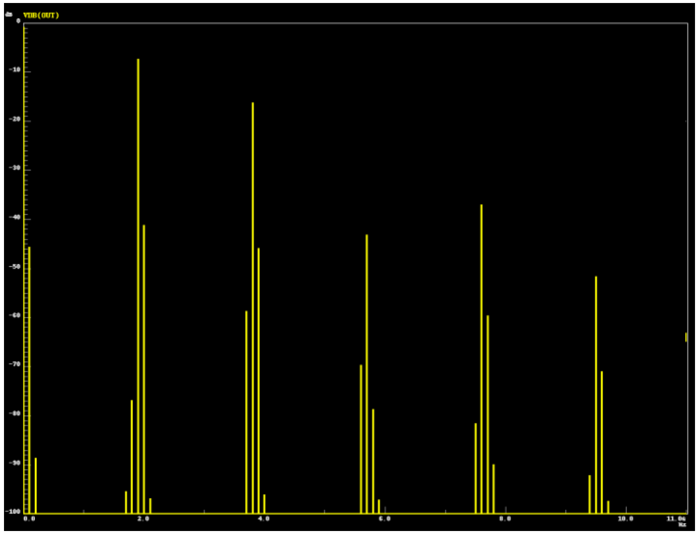
Example: MOSFET Drain Current





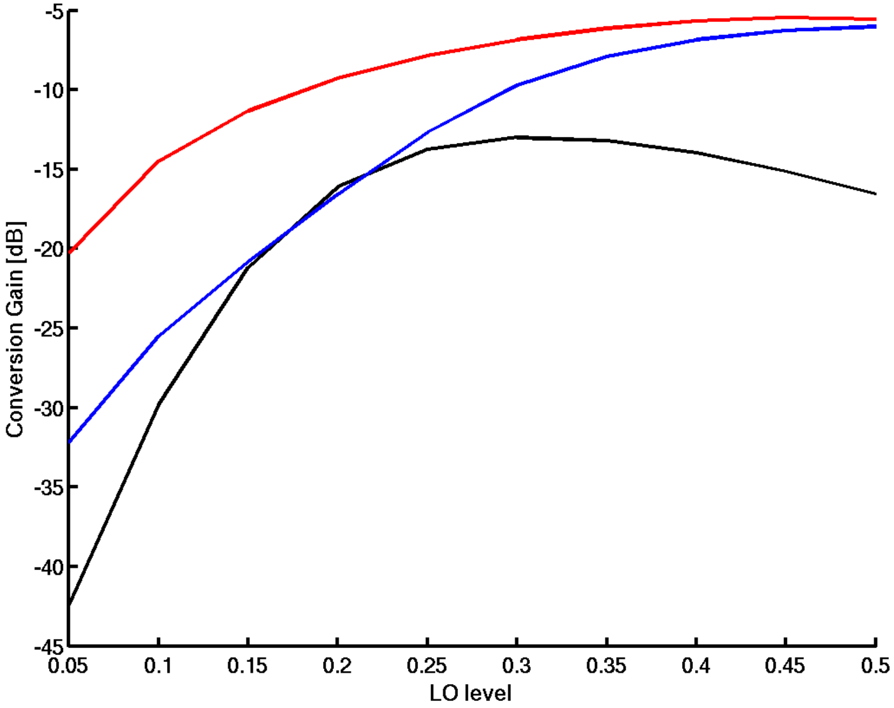
Example: MOSFET Drain Current

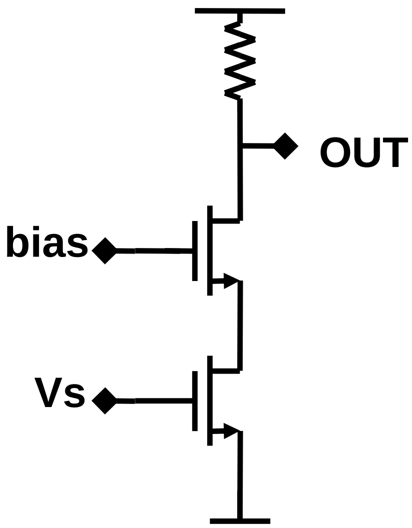




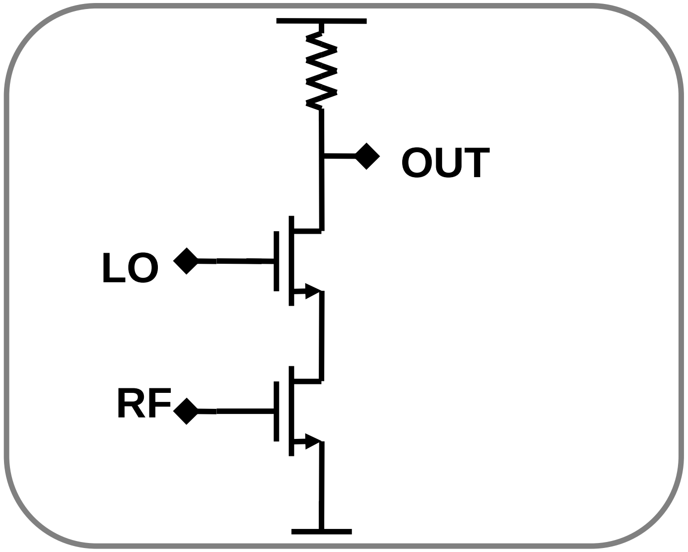
Three ”modes”

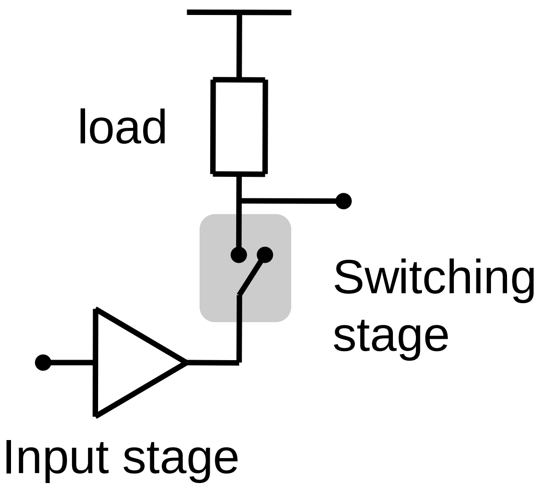
- Good amplifier, bias=0.6V
- Switch,”class-C”, bias=0.4V
- Resistive mixer, bias=0.8V




OUT
bias
Vs

Cascode Amplifier → Mixer





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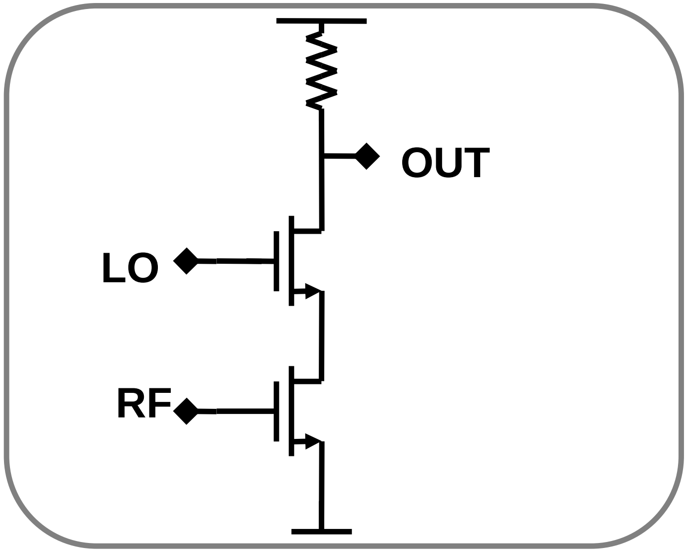
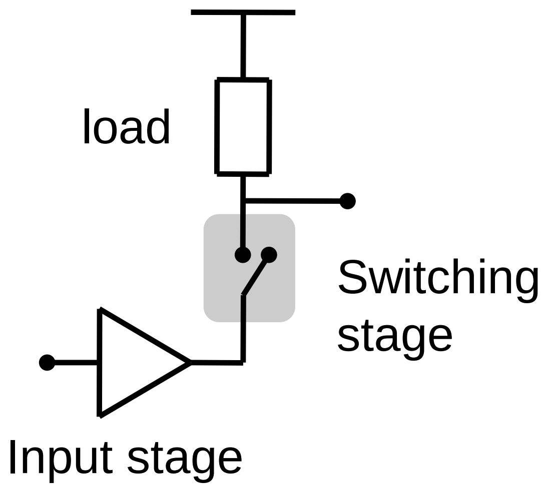
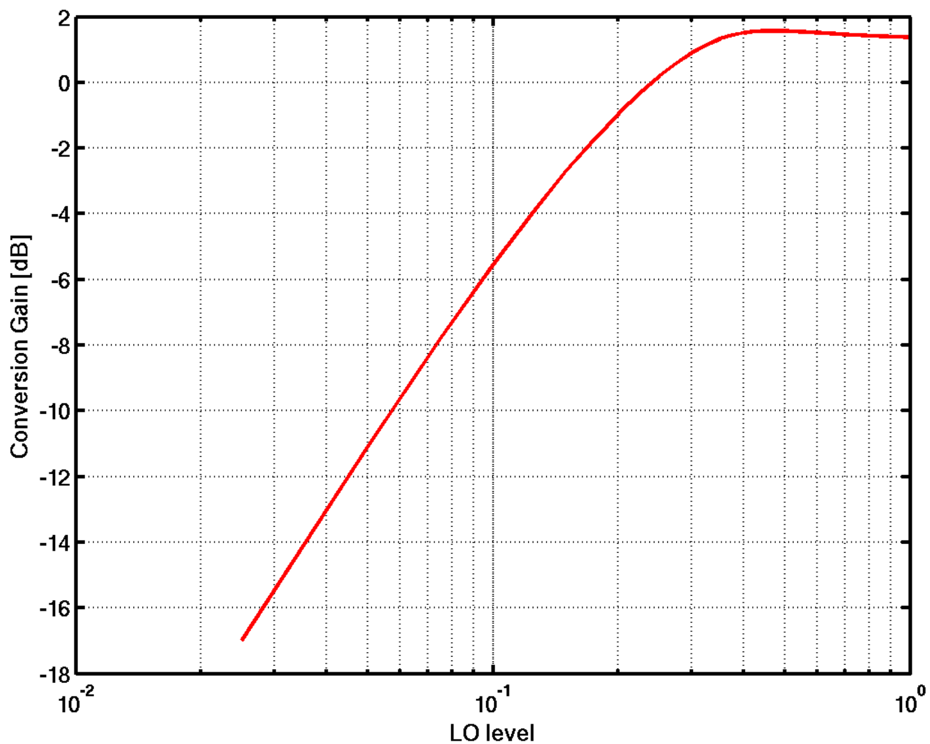
Cascode Amplifier → Mixer

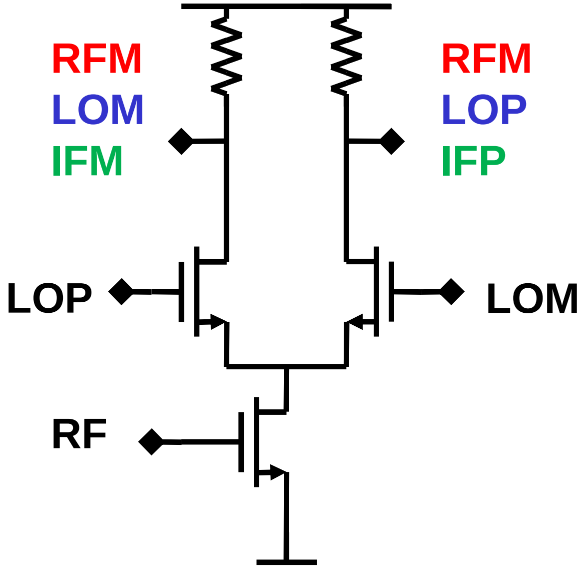


- Active mixer = conversion gain >0
- Poor port-to-port isolation
  → *What to do ?*





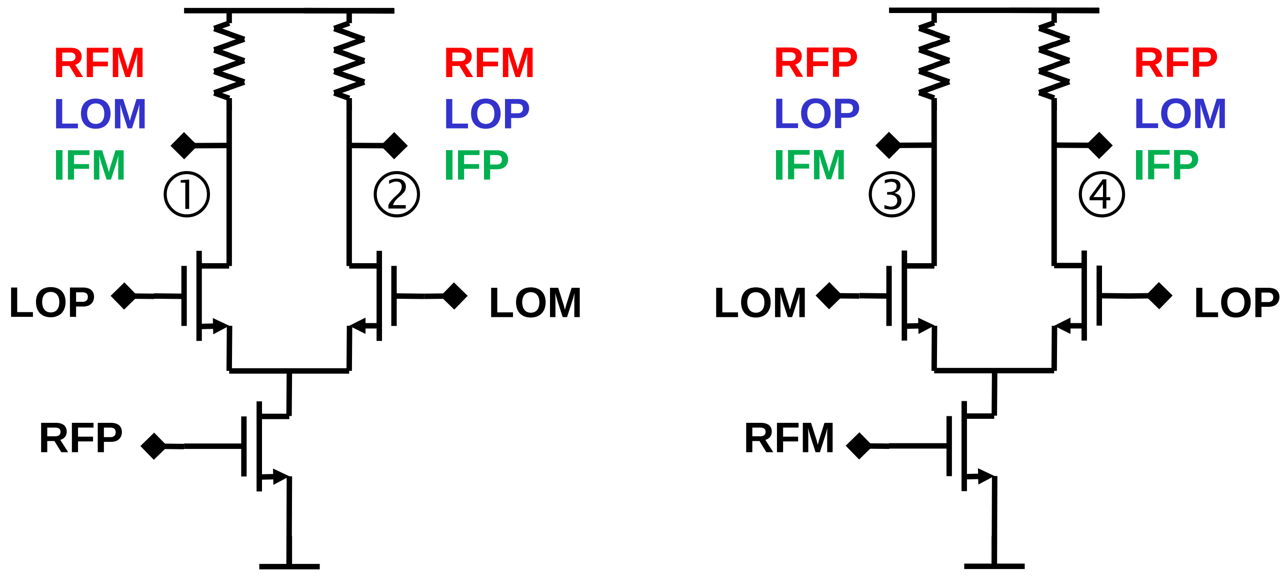
Single-Balanced Mixer



- Differential LO signal → differential output w/o RF
- Rest of performance essentially same as previously

- Differential LO cancels out RF; how to cancel LO leakage ?

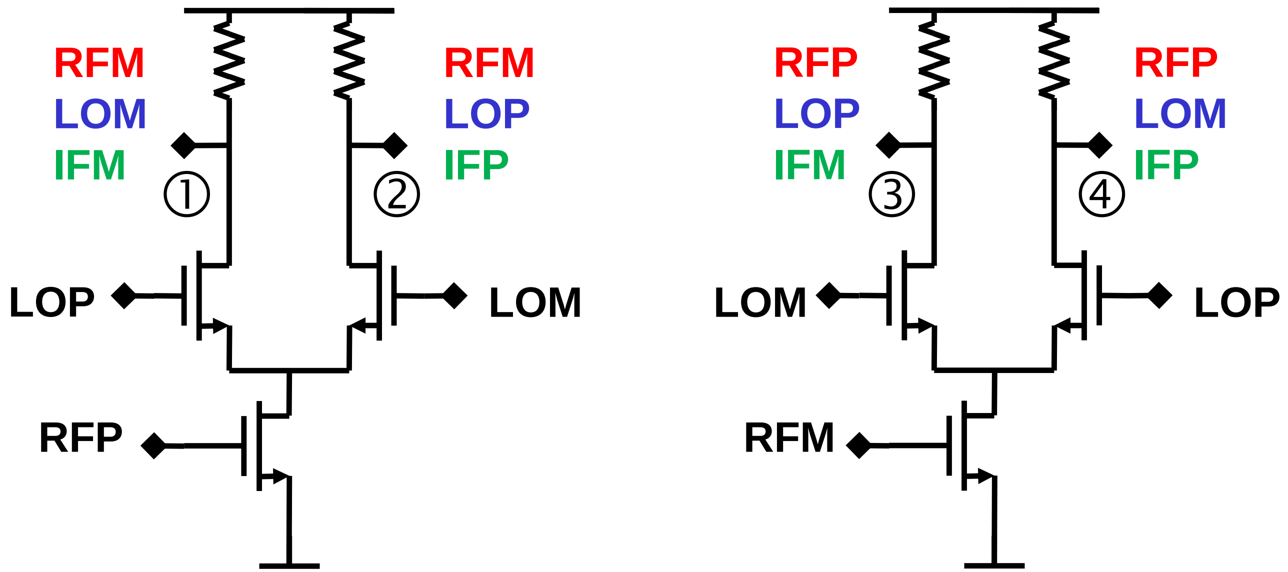
Double-Balanced Mixer (derivation)



- Differential LO signal → differential output w/o RF
- Differential RFsignal → differential output w/o LO

How to combine ① ② ③ ④ ?

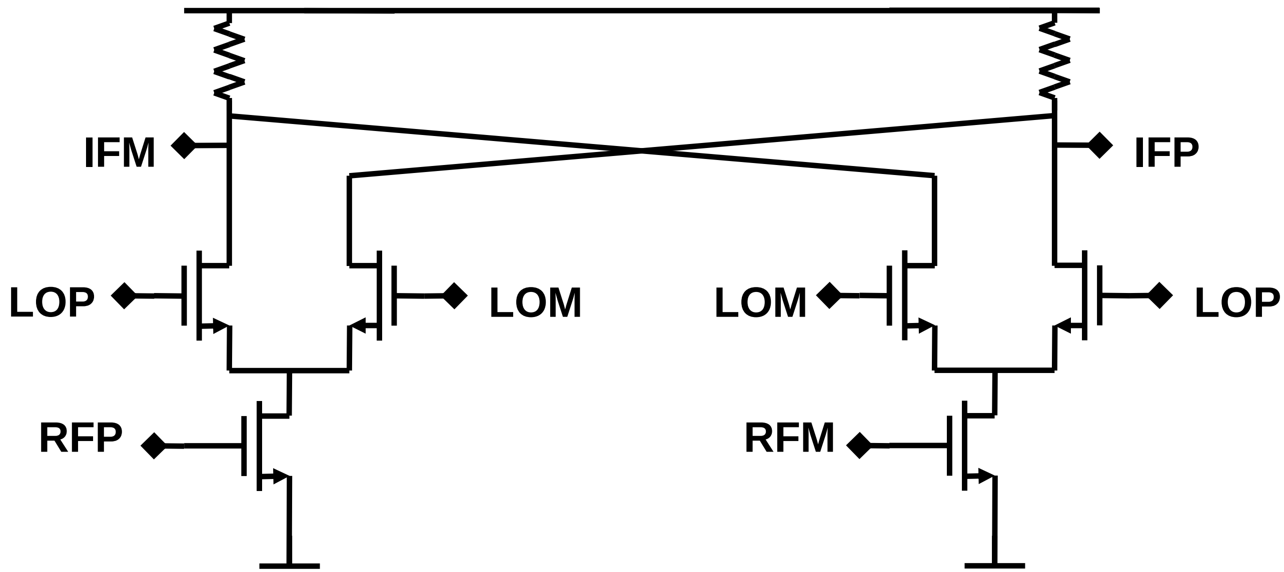
Double-Balanced Mixer (derivation)



- Differential LO signal → differential output w/o RF
- Differential RFsignal → differential output w/o LO

How to combine ① ② ③ ④ ? ➡ (①+③) – (②+④)

Double-balanced Mixer (derivation 2)



- Independent RF transistors have poor matching

→ Differential pair helps

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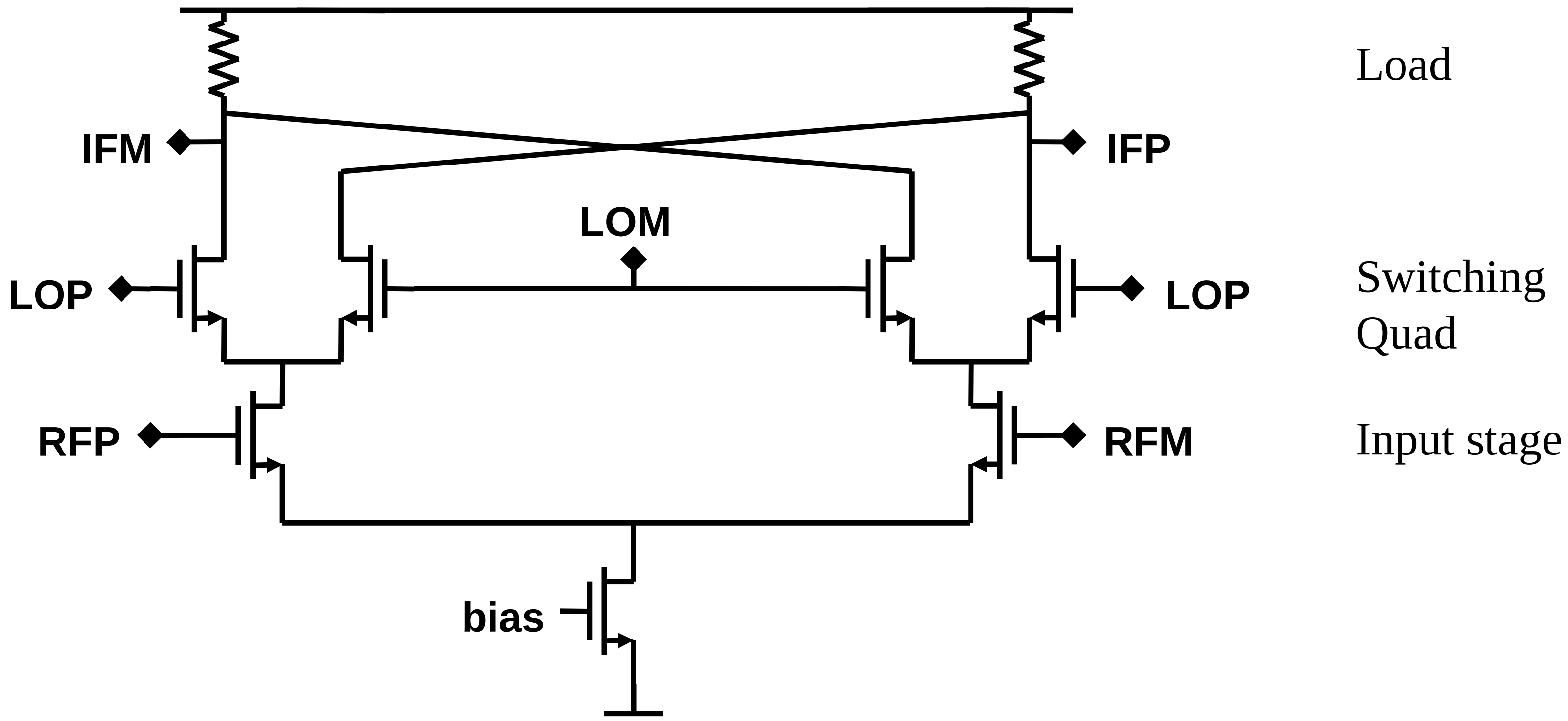
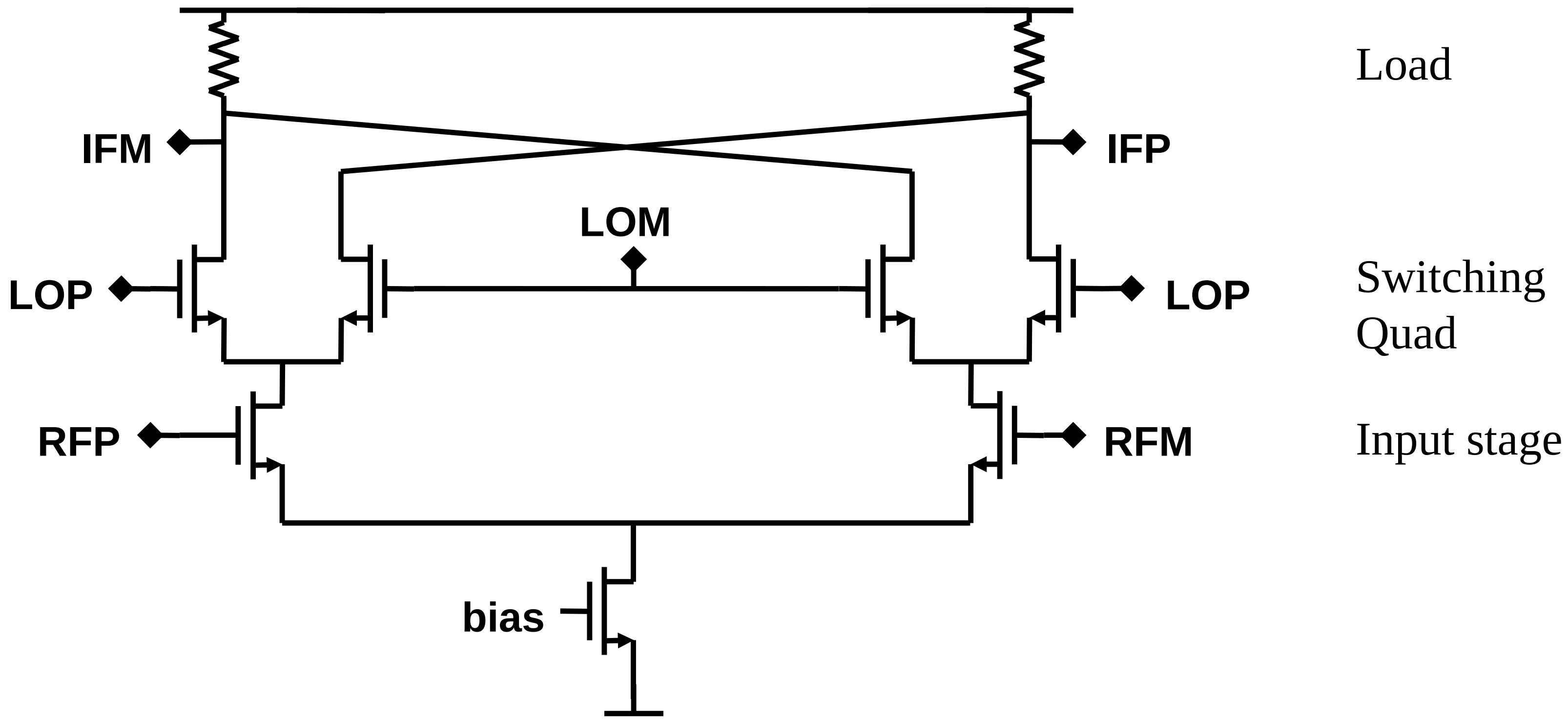
Gilbert Cell Mixer



Gilbert cell mixer was the work horse of RF IC transceivers.
It dominated until some problems appeared …

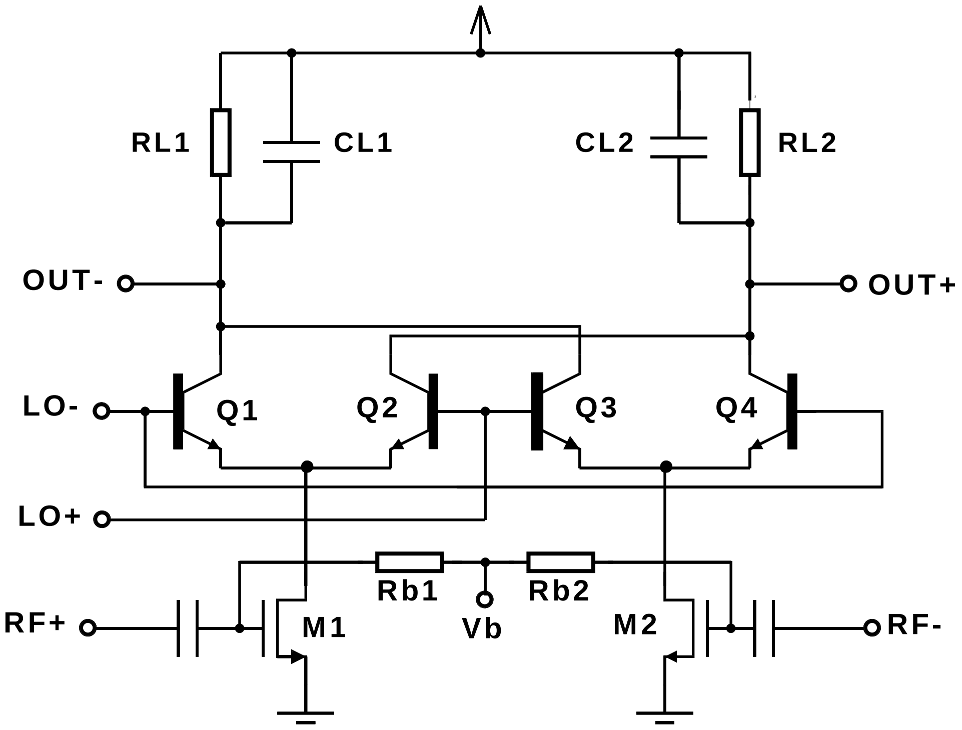
Gilbert Cell Mixer



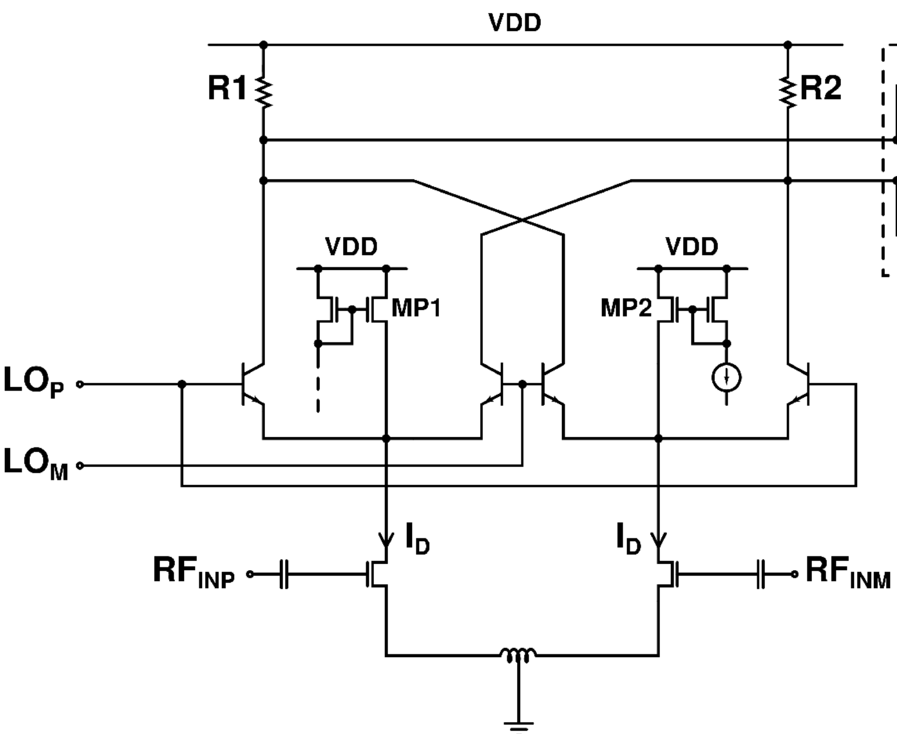
Gilbert cell mixer was the work horse of RF IC transceivers.
It dominated until some problems appeared …

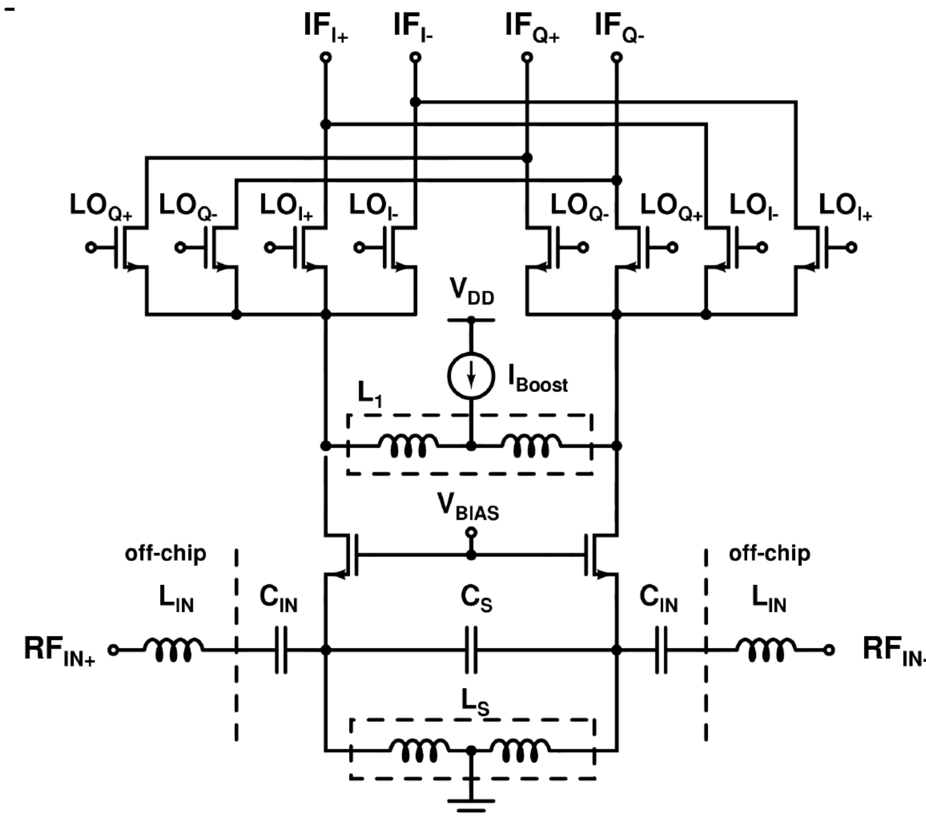
This circuit needs a high supply voltage.
Low-voltage versions have poor characteristics.

Gilbert Mixer, Examples



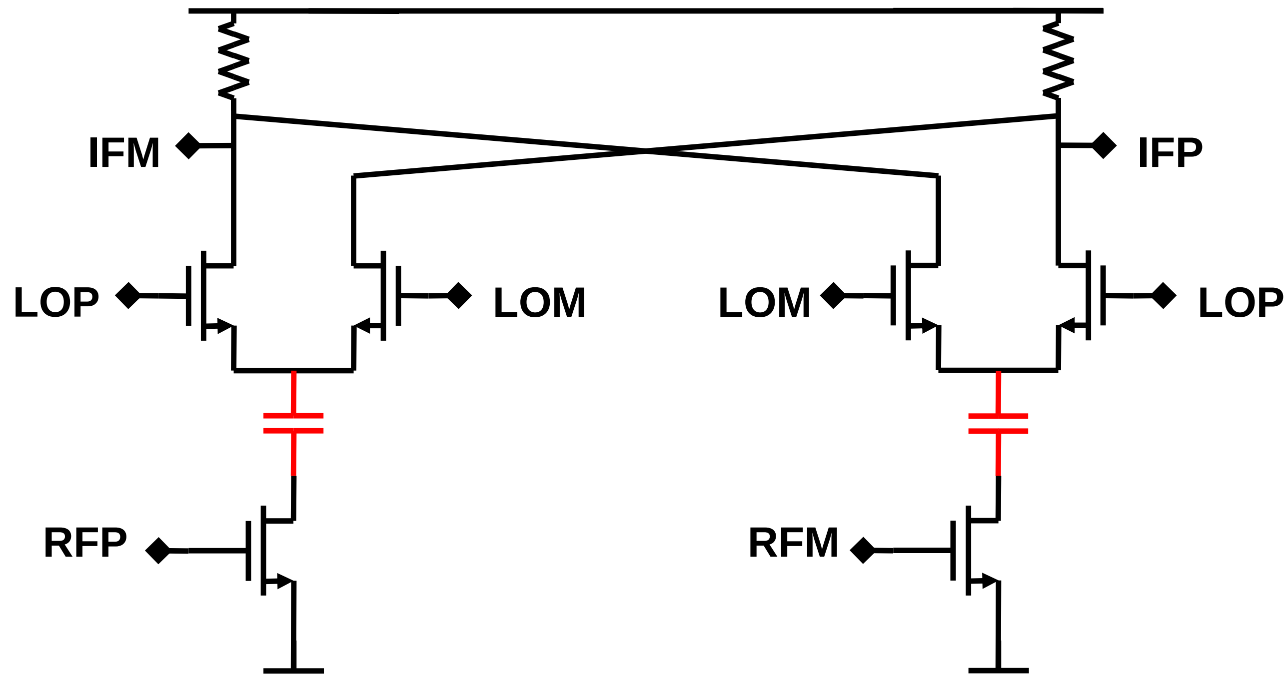
Gilbert Mixer, Examples





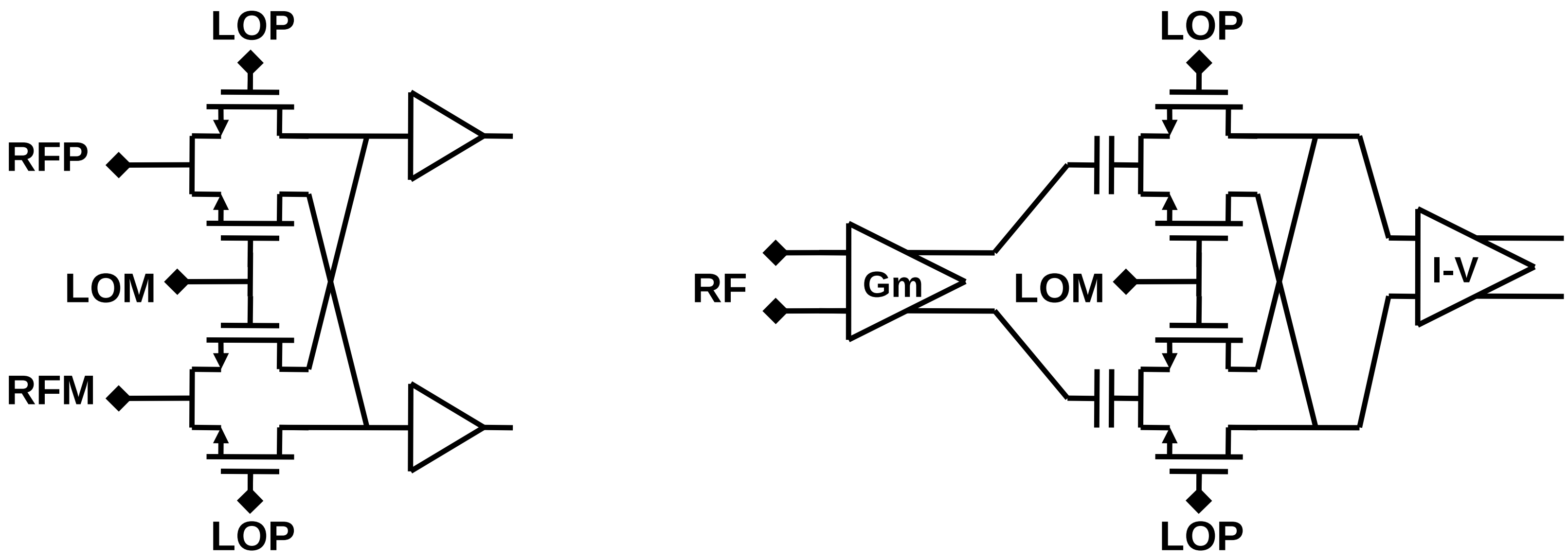
Passive Mixers

WHY ? Demand for **low supply voltage** and high linearity
→ Gilbert cell and its variants do not work well



If we ignore DC bias matters, would this work ?

Voltage-Mode / Current-Mode Passive Mixer

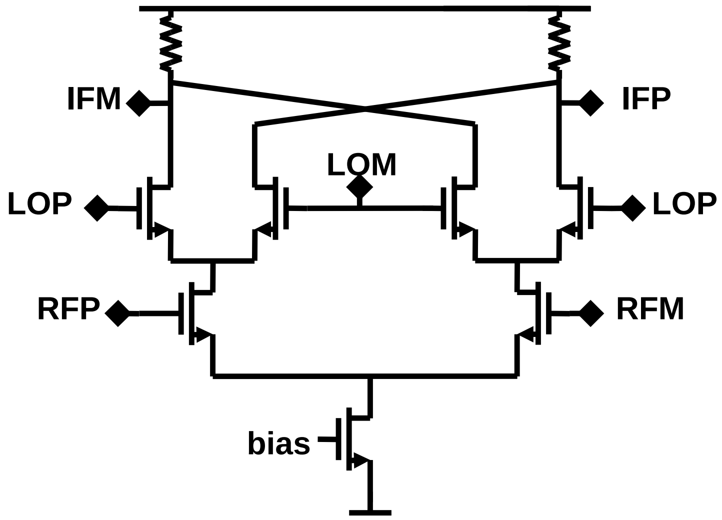


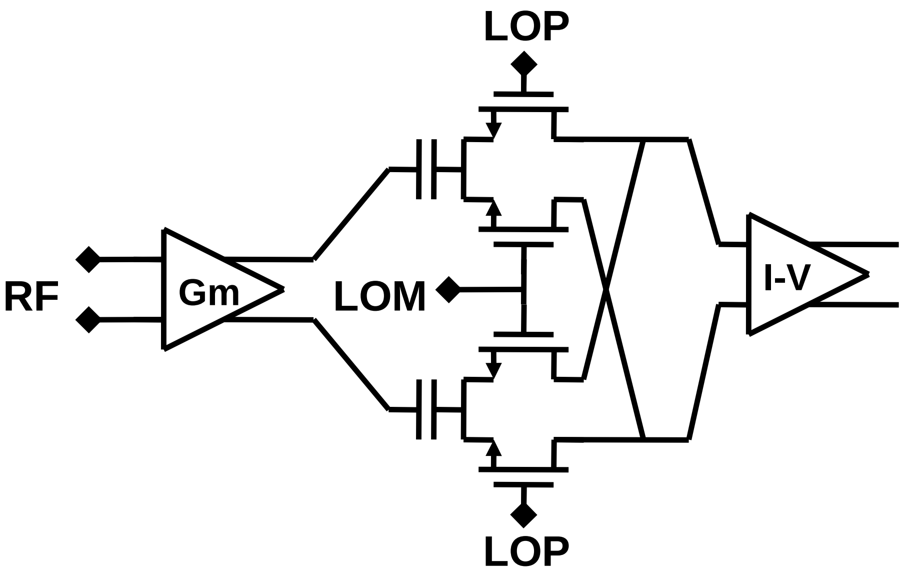
- Input V_{in} → output V_{out}
- R_{DS}(ON) << Zin
  → high imp output buffer

- Input I_{in} → output I_{out}
- Requires I-V converter (TIA)
  → low imp output buffer

Identification of voltage or current-mode mixer may be difficult and even unnecessary; Main feature is that **no DC current flows** in the mixing FETs

Active / Passive Mixer





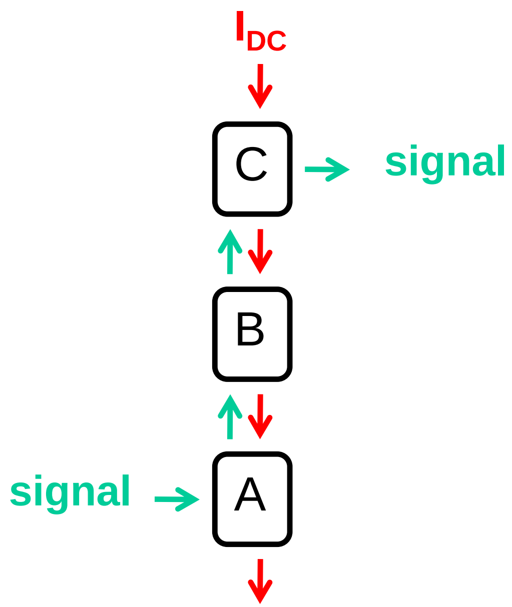
Passive mixer is just a ”folded” version of active mixer

- In an active mixer DC current flows through the switching quad

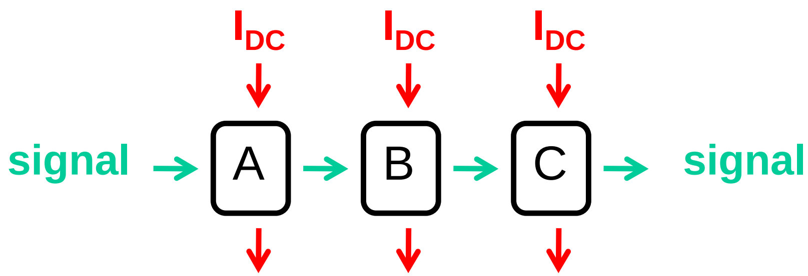
→ CG FETs provide gain but also contribute to noise

Principles

”current re-use”



”low voltage”



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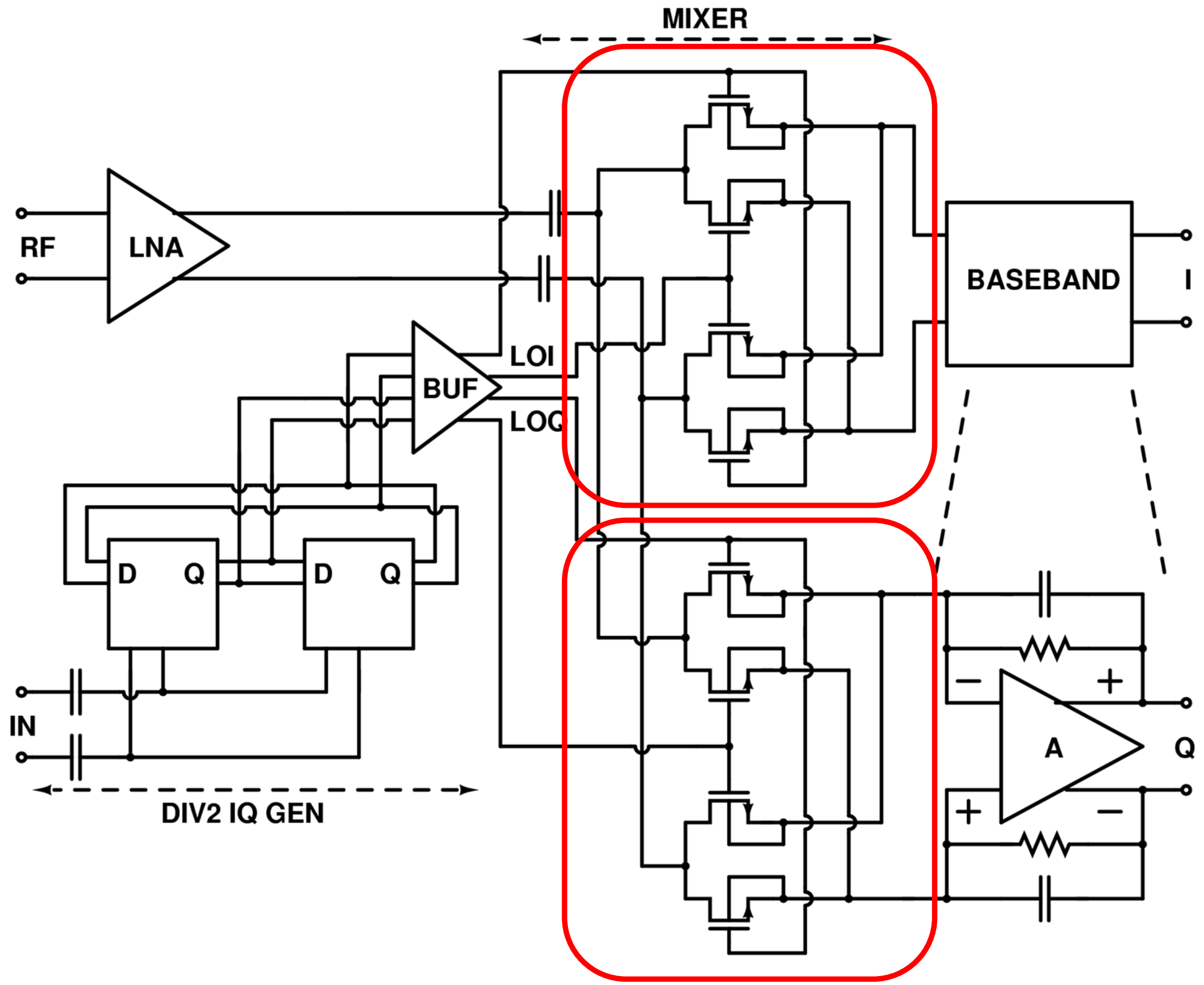
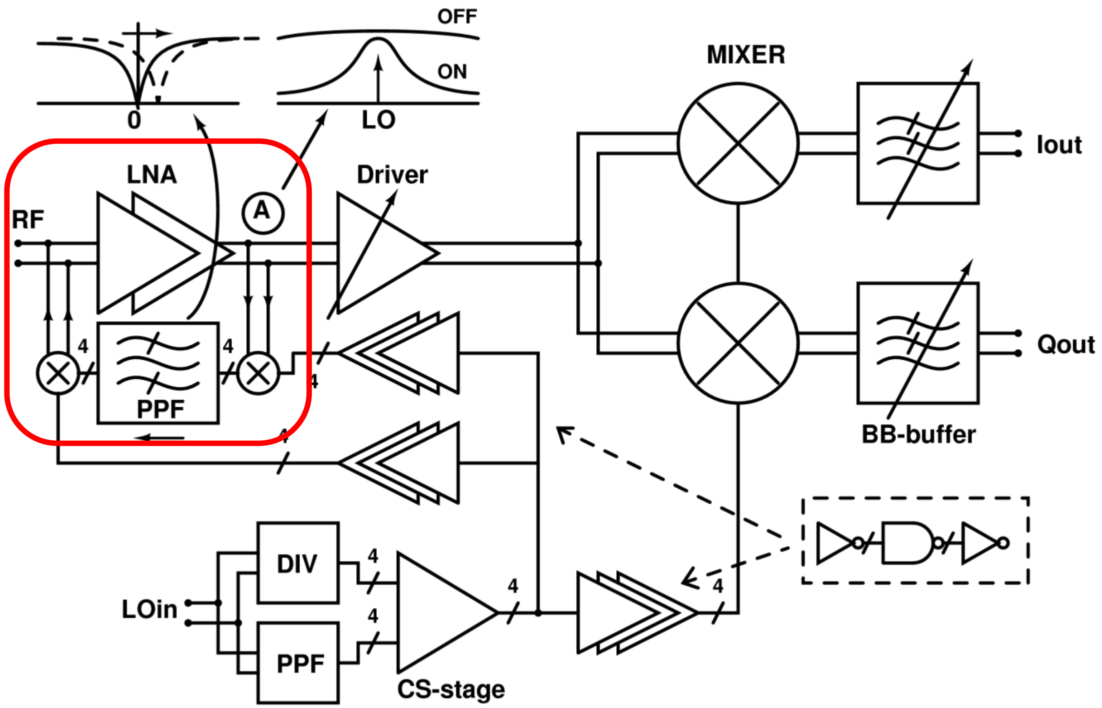
Passive Mixer, Use Case 1

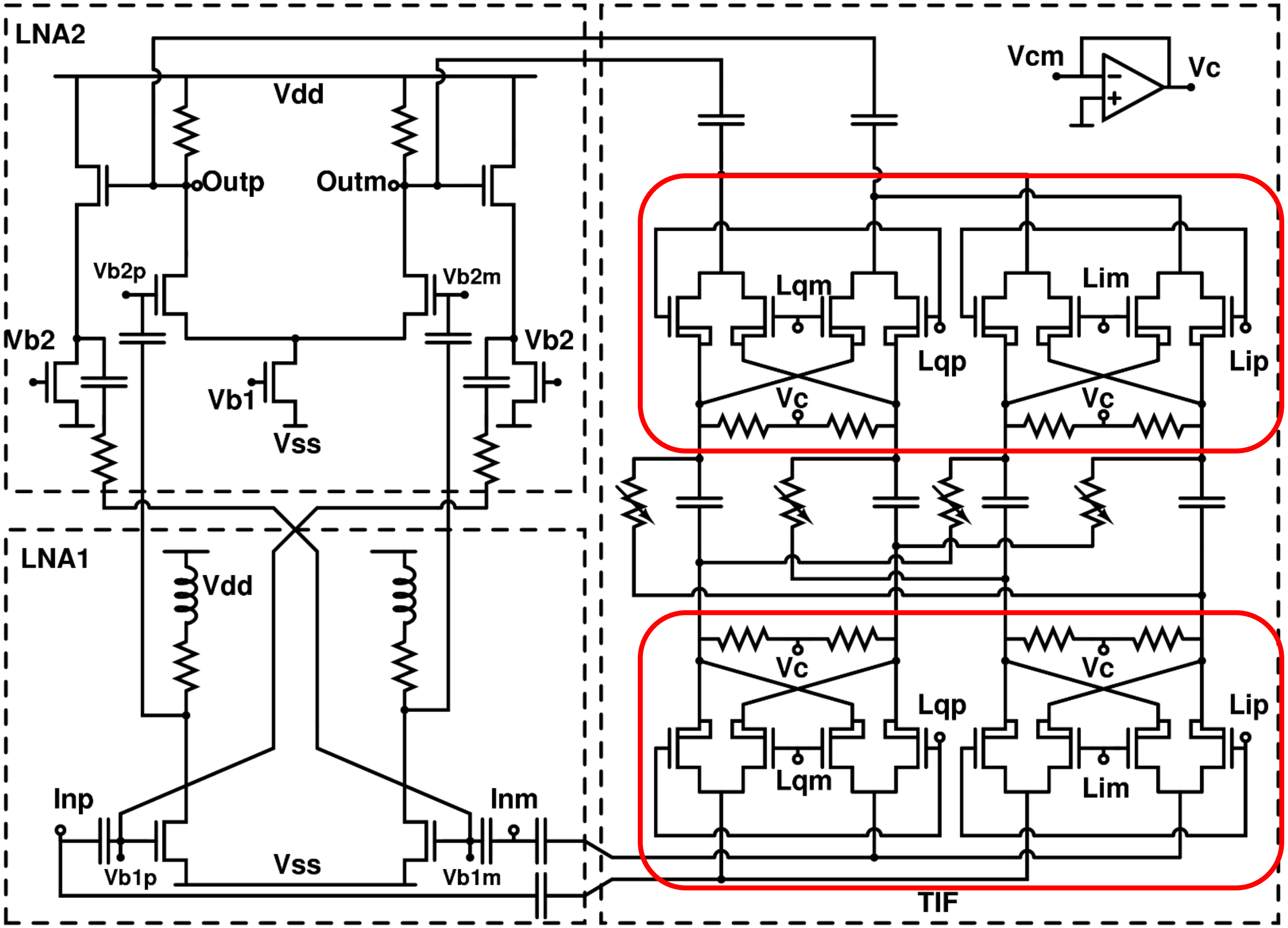


Passive Mixer, Use Case 2

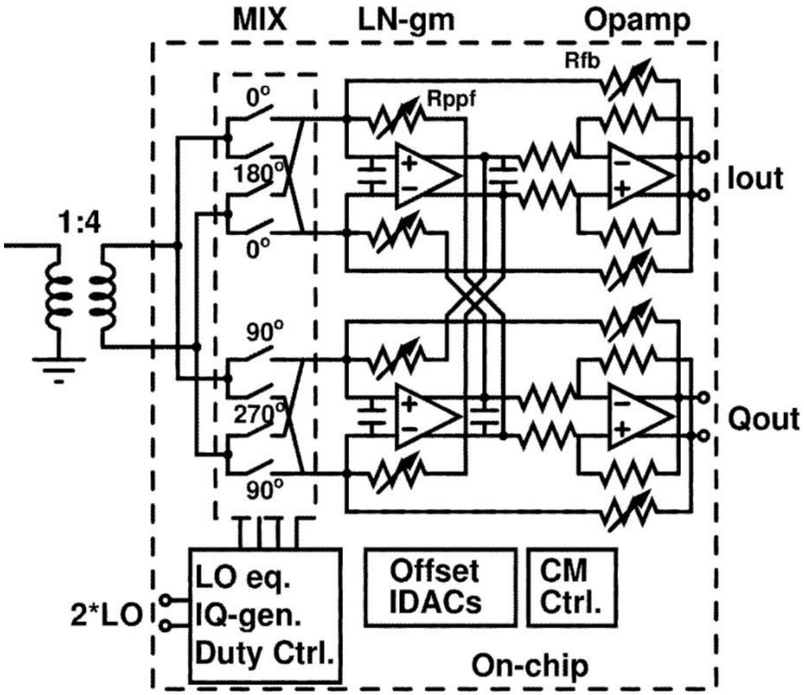


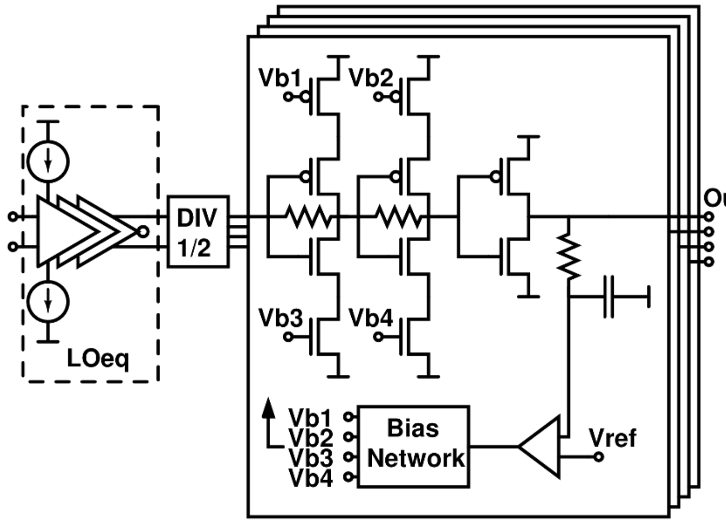
	TIF OFF/ON	TIF OFF/ON	TIF OFF/ON
LO Freq (GHz)	2.4	4.0	5.3
Gain (dB)	42/40	43/41	42/40
IIP3 (dBm)	-11/-5	-13/-5	-11/-7
Blocker ICP (dBm)	-20/-15	-23/-16	-23/-18
NF (dB)	4.3/5.8	3.2/5.7	3.9/5.9
S11< -10dB (GHz)	2.5-5.5		
LO leak (dBm)	-85/-63	-56/-54	-58/-56
Idc (mA)	45/53	44/56	46/58
Gain Adjustment (dB)	15		
BB bandwidth (MHz)	5-50		
Active area (mm^2)	0.25		
Technology	1.2V 65nm CMOS		

Passive Mixer, Use Case 2

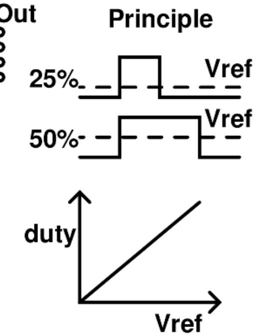


Passive Mixer, Case 3

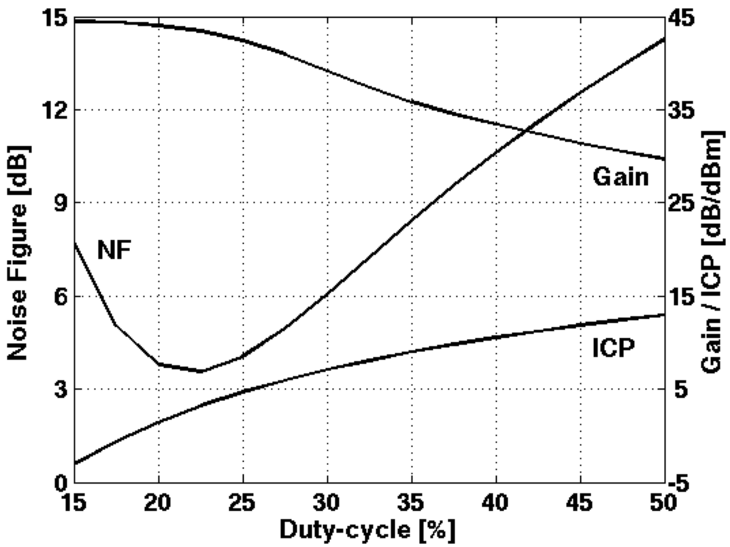




15-53% duty



Measured results



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Self-Learning Assignment 4

Objective is to familiarize yourself with passive mixers.

Read three journal papers and write a reference essay.

You can find the assignment from

MyCourses / Assignments - SLA / Self-learning assignment 4

Return your answer as a pdf-file to Return Box in the same page

Next Meeting Tuesday 3.5.

Synthesizers

Topics will be

- concepts related to LO / CLK generation
- Synthesis methods
- Oscillators
- Frequency dividers
- IQ generation