CMOS Quadrature Front Ends in a single-stage: The LMV Cell

Antonio Liscidini

antonio.liscidini@unipv.it

Università degli Studi di Pavia, Italy

Outline

- **The LNA-Mixer-VCO cell**
  - The LC tank Oscillator as a Mixer
  - Single/Double Switching Pair SOM
  - LNA introduction
- **Loss Mechanisms in the SOM**
  - Output parasitic capacitances
  - Common Mode and Differential losses
  - Voltage Mode vs. Current Mode
- **I & Q LMV Cells**
  - Quadrature at the VCO
  - Quadrature at the RF signal path
- **Prototypes**
  - GPS RF Front-End
  - ZigBee Receiver
- **Conclusions**

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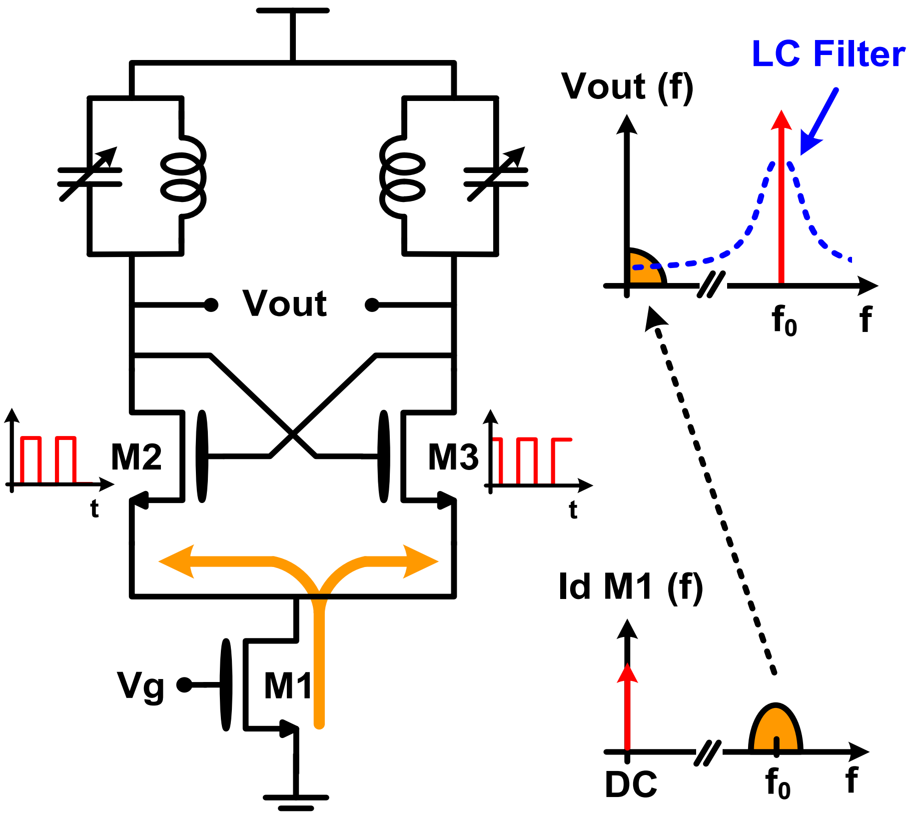
Mixer inside LC Oscillator

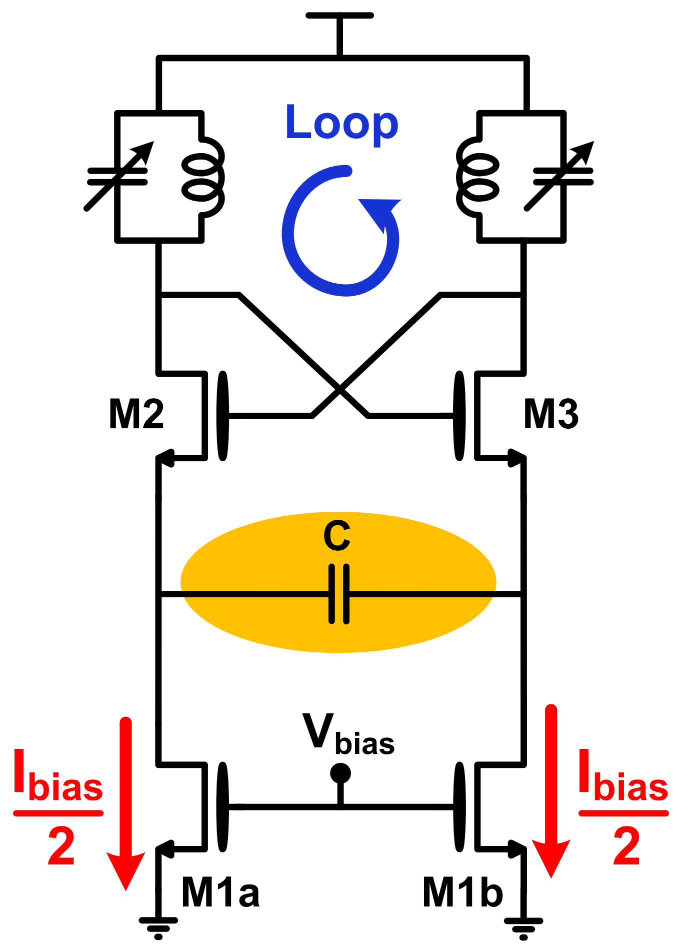


- Any RF signal in the VCO bias current is naturally down-converted at IF

- LC tank attenuates the low frequency components of V_{out}

Problem: how to sense the down-converted current signal preserving oscillation

Basic Idea: Bias Splitting

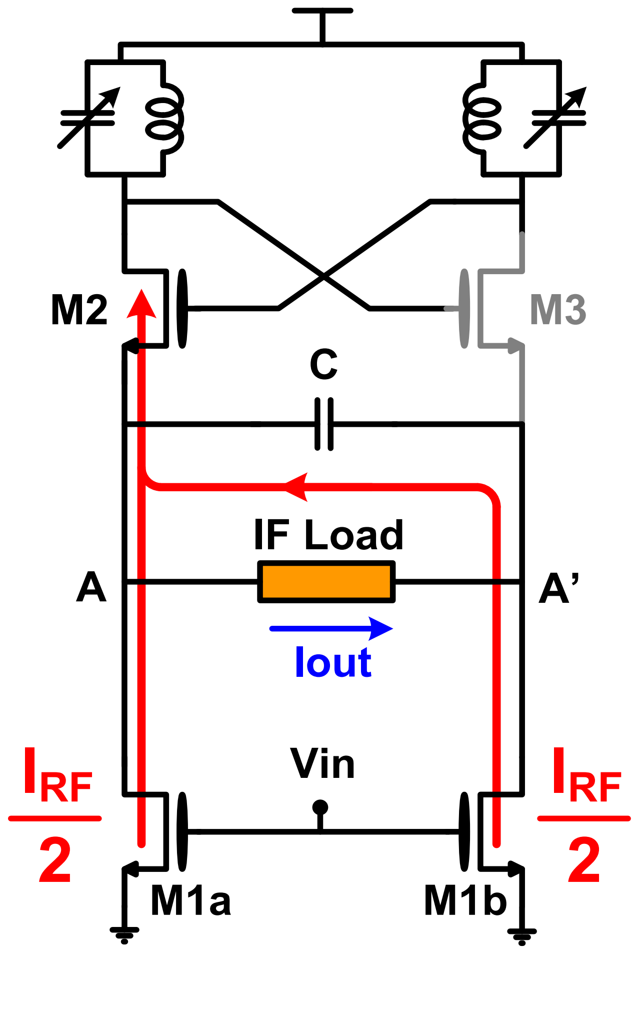


- M1 is spitted in two transistors and a capacitor C is used to close the loop at RF
- C is a degeneration for M2 and M3

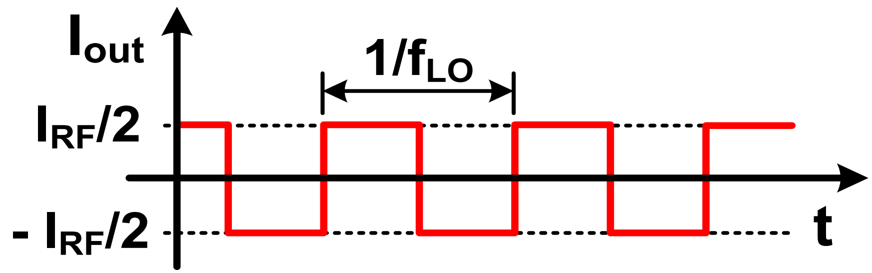
$$\omega_{LO} C >> gm_{2,3}$$

- At low frequency it has an high impedance between M2,M3 sources.

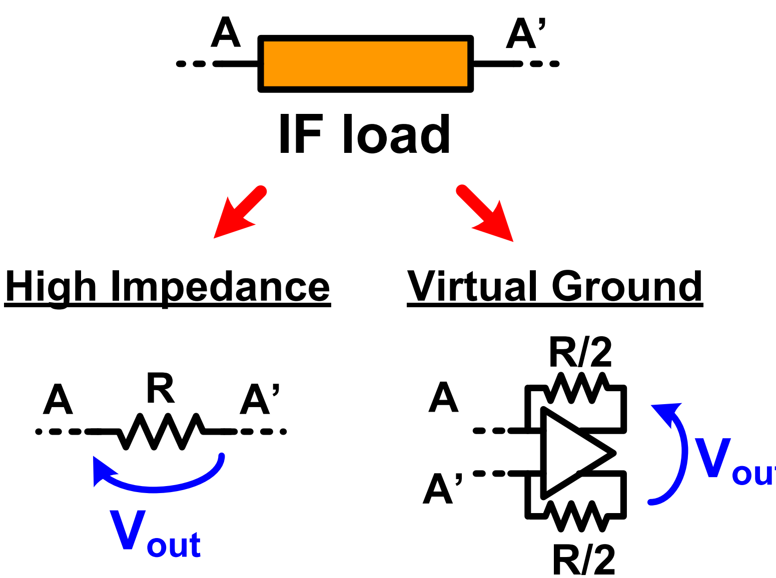
Bias Splitting SOM



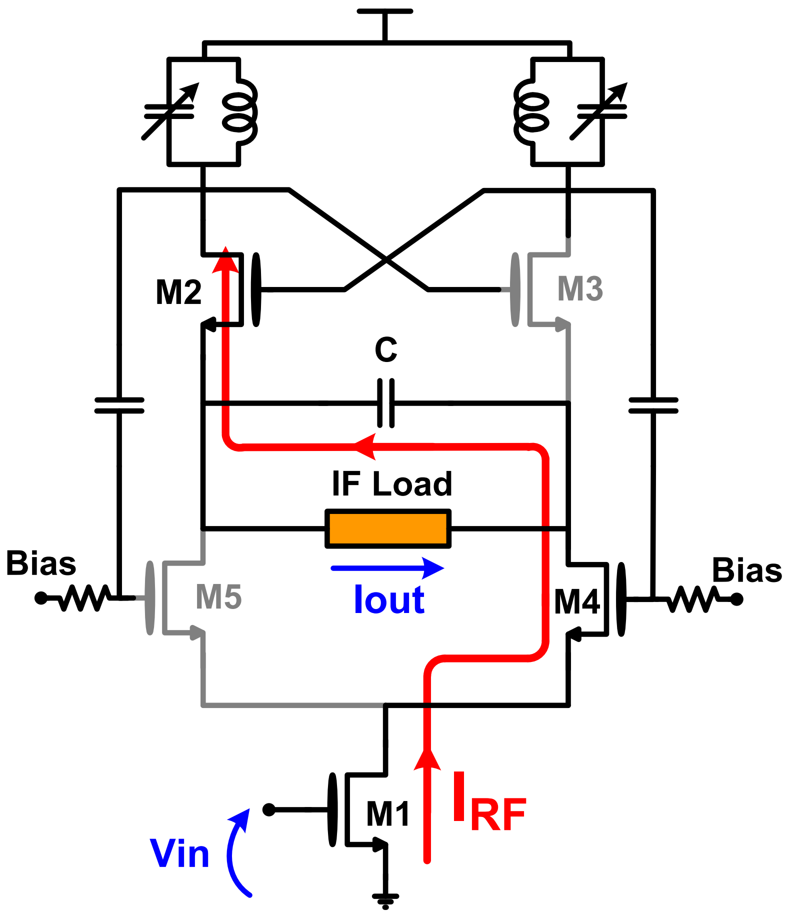
Semi-period with M2 on



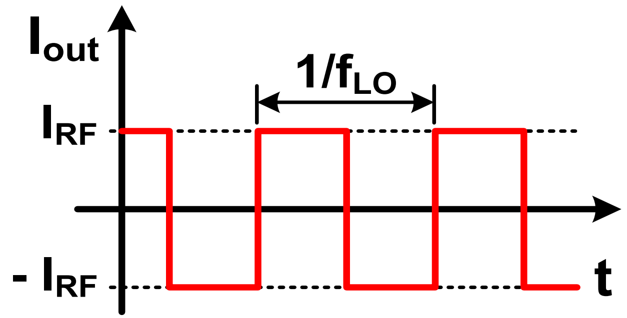
- Only half of the signal current flows through IF load



Double Switching Pairs



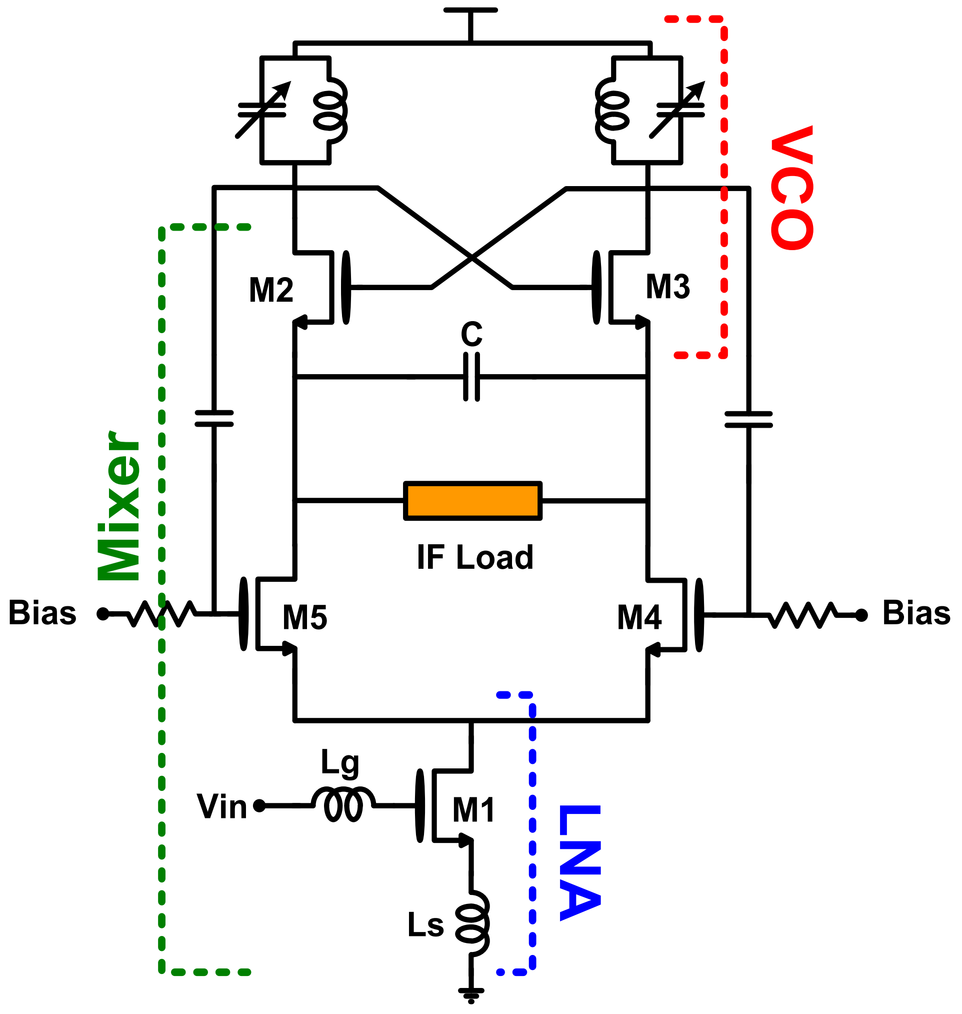
Semi-period with M2 and M4 on



- All RF signal current is down converted leading:

$$\frac{Iout}{Vin} = \frac{2}{\pi} gm_1$$

LNA-Mixer-VCO (LMV) Cell



- LNA is implemented re-using M1 in a inductive degenerated topology.
- Three transistor stacked but minimum V_{DD} is 1 V_{TH} plus 3 V_{OV}

LNA, Mixer and VCO share bias and devices

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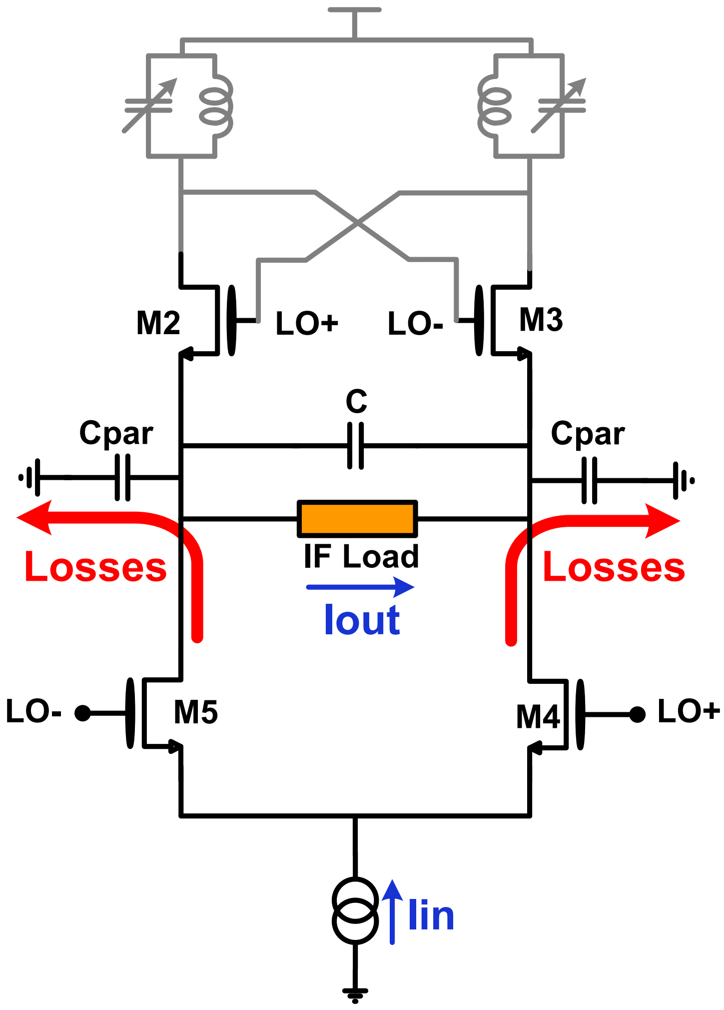
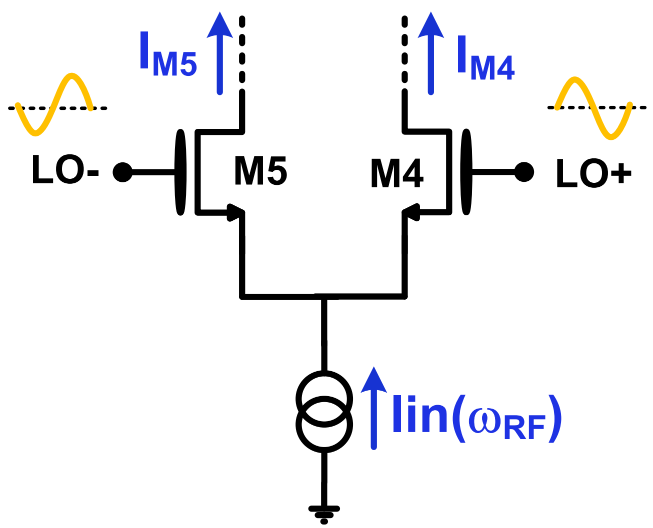
Loss Mechanisms



- **Parasitic capacitors** at the output of LMV cell limit the conversion gain.
- The **analytical derivation** of the LMV transfer function is difficult since the structure is **time-variant**

The losses depend on the IF load impedance

Differential and Common Mode Components (1)



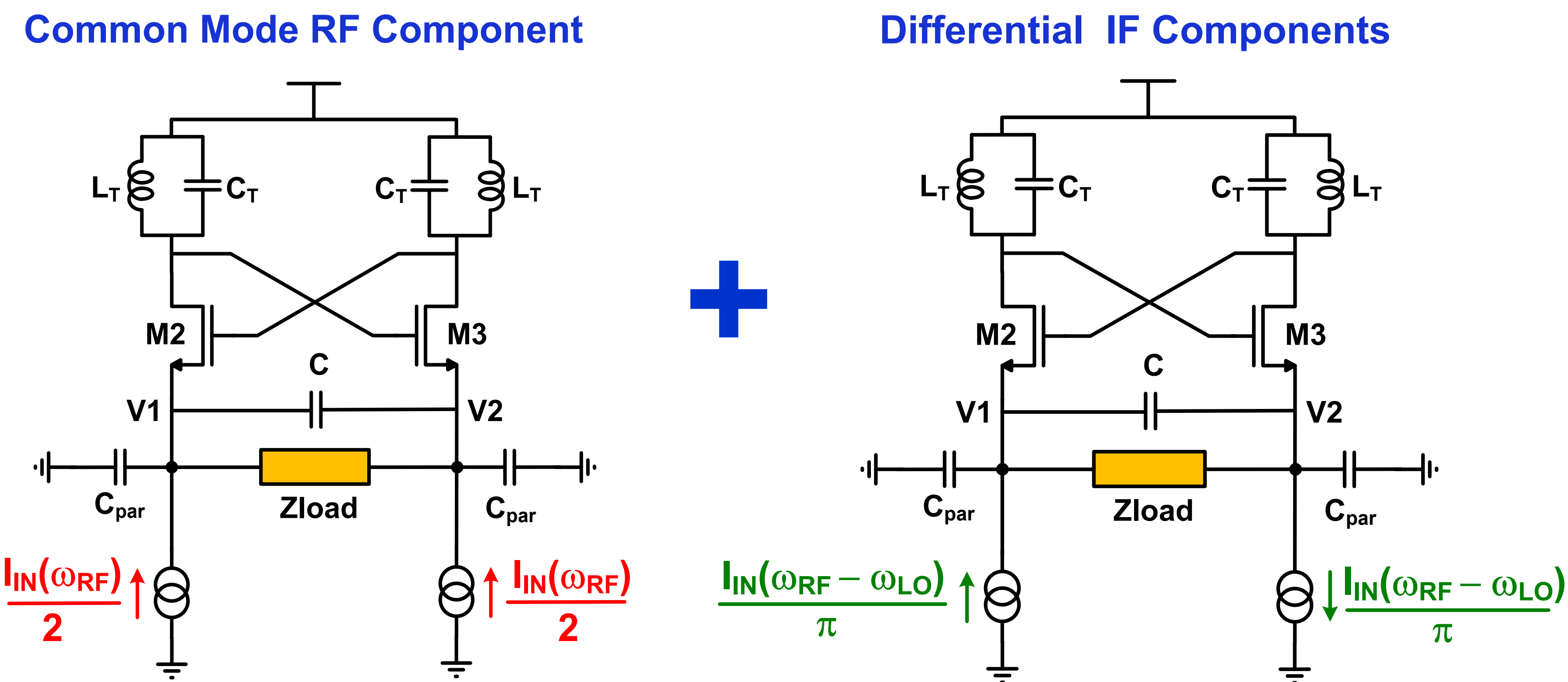
- The current injected by the first switching pair has two components:
  - A **Common Mode** not down converted
  - A **Differential** mixed at ω_{RF}-ω_{LO}

Common Mode | **Differential Part**

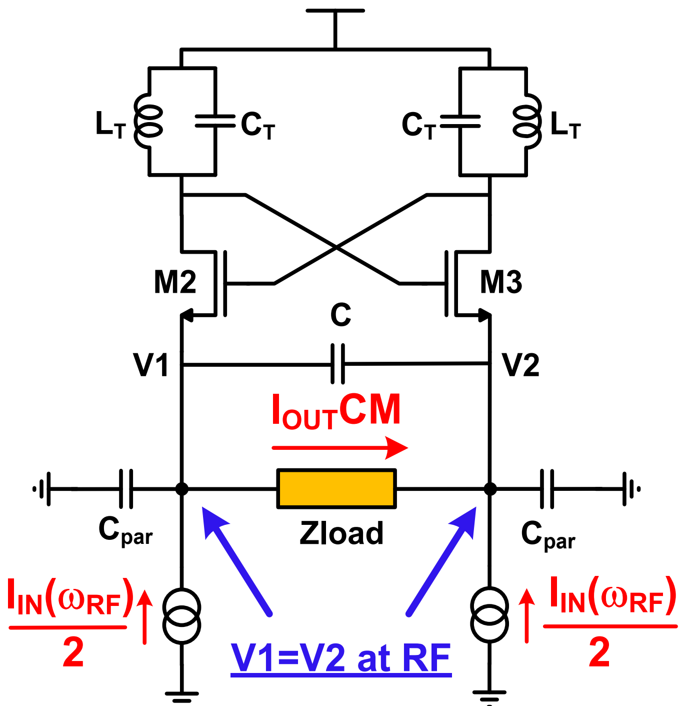
$$\begin{cases} I_{M4} = \dfrac{Iin}{2}(1+\mathrm{sign}[\cos(\omega_{LO}t)]) = \dfrac{Iin(\omega_{RF})}{2} + \dfrac{Iin(\omega_{RF}-\omega_{LO})}{\pi} + \ldots \\ I_{M5} = \dfrac{Iin}{2}(1-\mathrm{sign}[\cos(\omega_{LO}t)]) = \dfrac{Iin(\omega_{RF})}{2} - \dfrac{Iin(\omega_{RF}-\omega_{LO})}{\pi} + \ldots \end{cases}$$

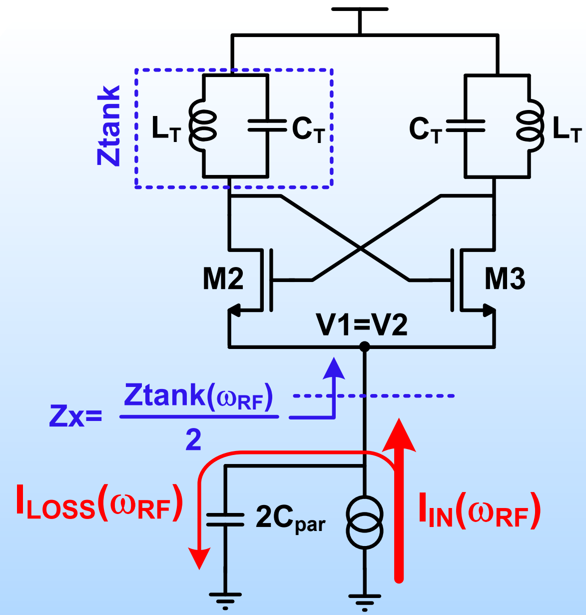
Differential and Common Mode Components (2)

The *double switching pair SOM* can be transform in “the sum” of two *bias splitting SOM*



Losses at RF Frequency (Common Mode Components)





The loss is due to an **RF current partition between** C_{par} and Zx

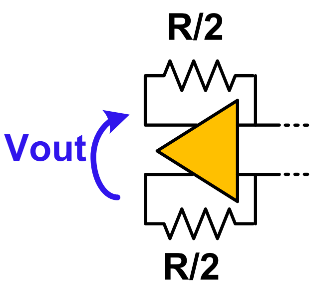
Current and Voltage Mode LMV has the same **Common Mode conversion gain**

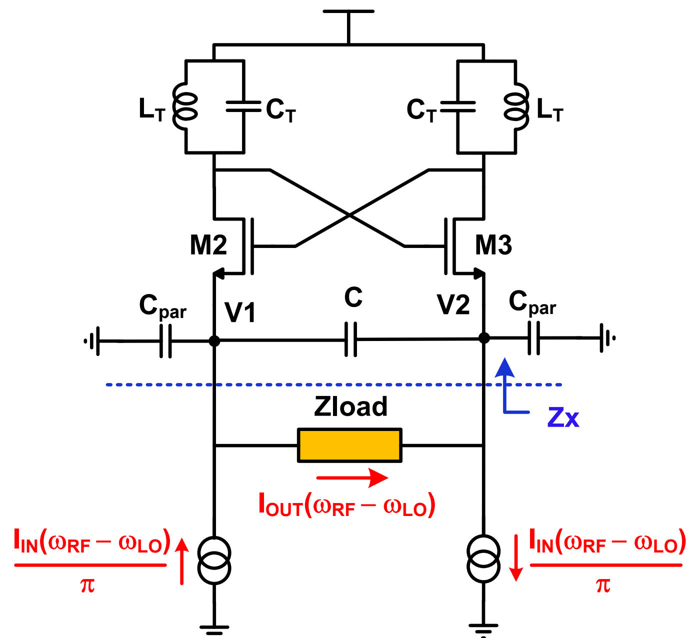
$$I_{OUT}CM(\omega_{RF}-\omega_{LO}) = \frac{1}{\pi}\frac{1}{1+j\omega_{RF}C_{par}\cdot Z_{tank}(\omega_{RF})}I_{IN}(\omega_{RF})$$

Losses at IF Frequency (Differential Components)

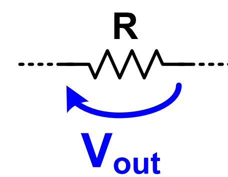
The IF losses depend on a current partition between IF load and Zx

Current Mode





Voltage Mode



- Zload ≈ 0 → No losses

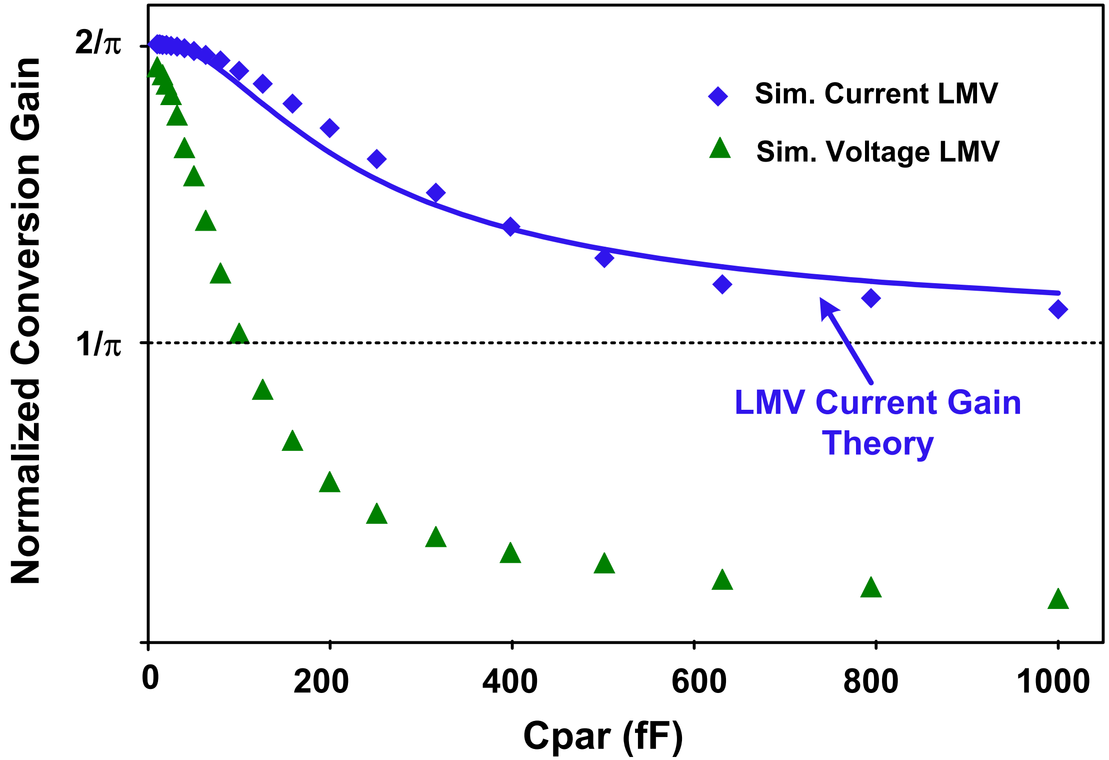
$$I_{OUT}DIFF(\omega_{RF}-\omega_{LO}) = \frac{1}{\pi} I_{IN}(\omega_{RF})$$

- Non linear, time variant current partition with Zx

Current Mode has no losses for the differential components

Voltage Mode vs. Current Mode

The total down-converted signal is given by $\mathbf{I_{OUT}CM + I_{OUT}DIFF}$



<u>Current mode Gain</u>

$$I_{OUT}(\omega_{RF}-\omega_{LO}) = \frac{1}{\pi}\frac{2+j\omega_{RF}C_{par}\cdot Z_{tank}(\omega_{RF})}{1+j\omega_{RF}C_{par}\cdot Z_{tank}(\omega_{RF})} I_{IN}(\omega_{RF})$$

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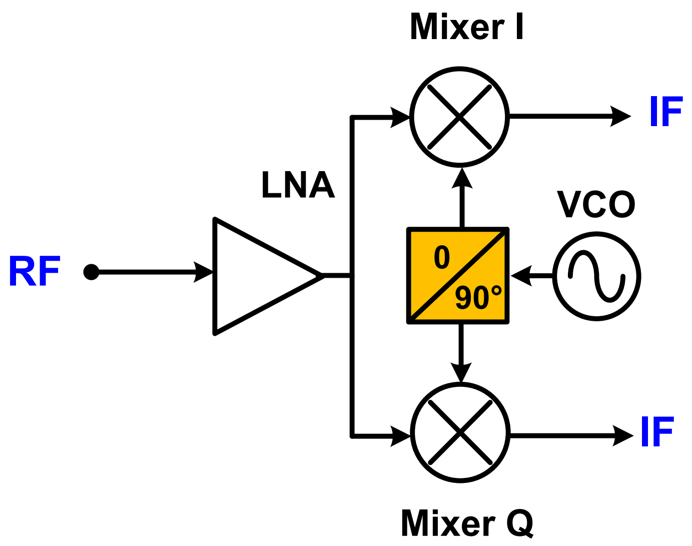
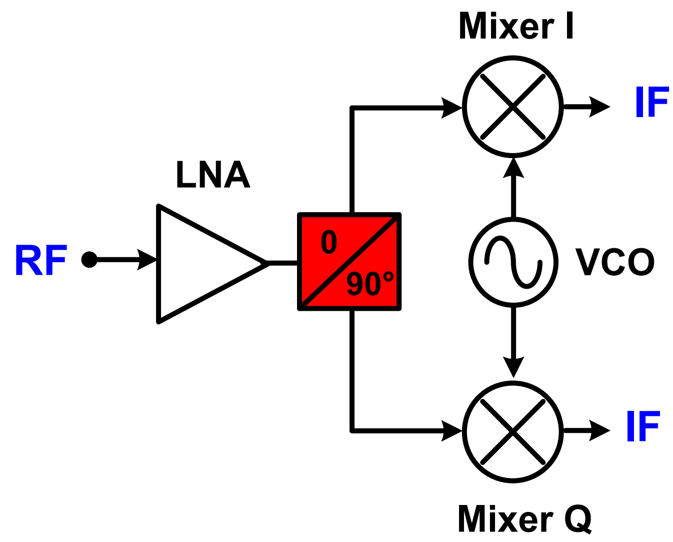
Quadrature Receivers

Quadrature at LO



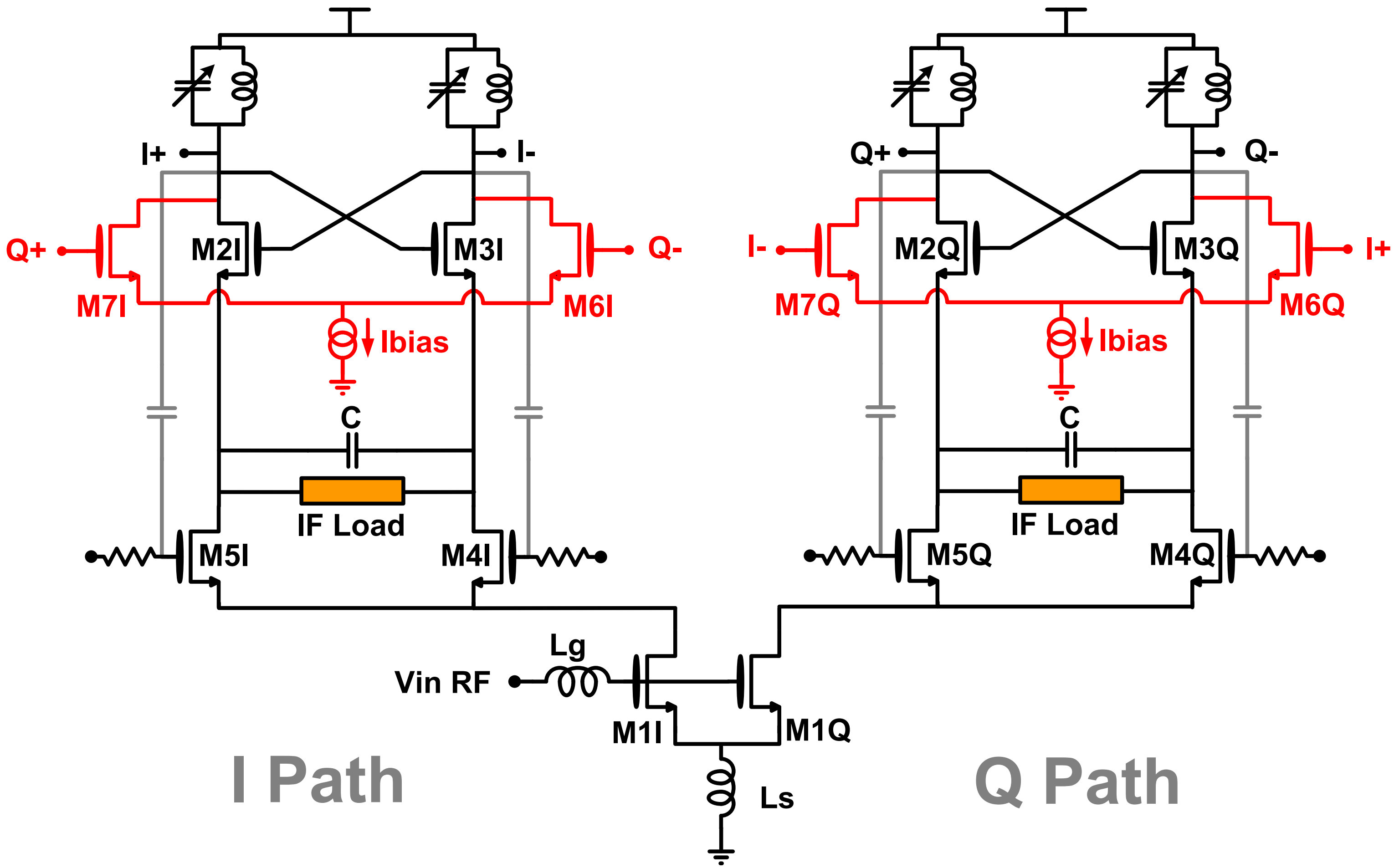
Quadrature on RF signal path



- Good quadrature accuracy
- Several architectures available:
  (Quadrature VCOs, Divider, Polyphase Filter)

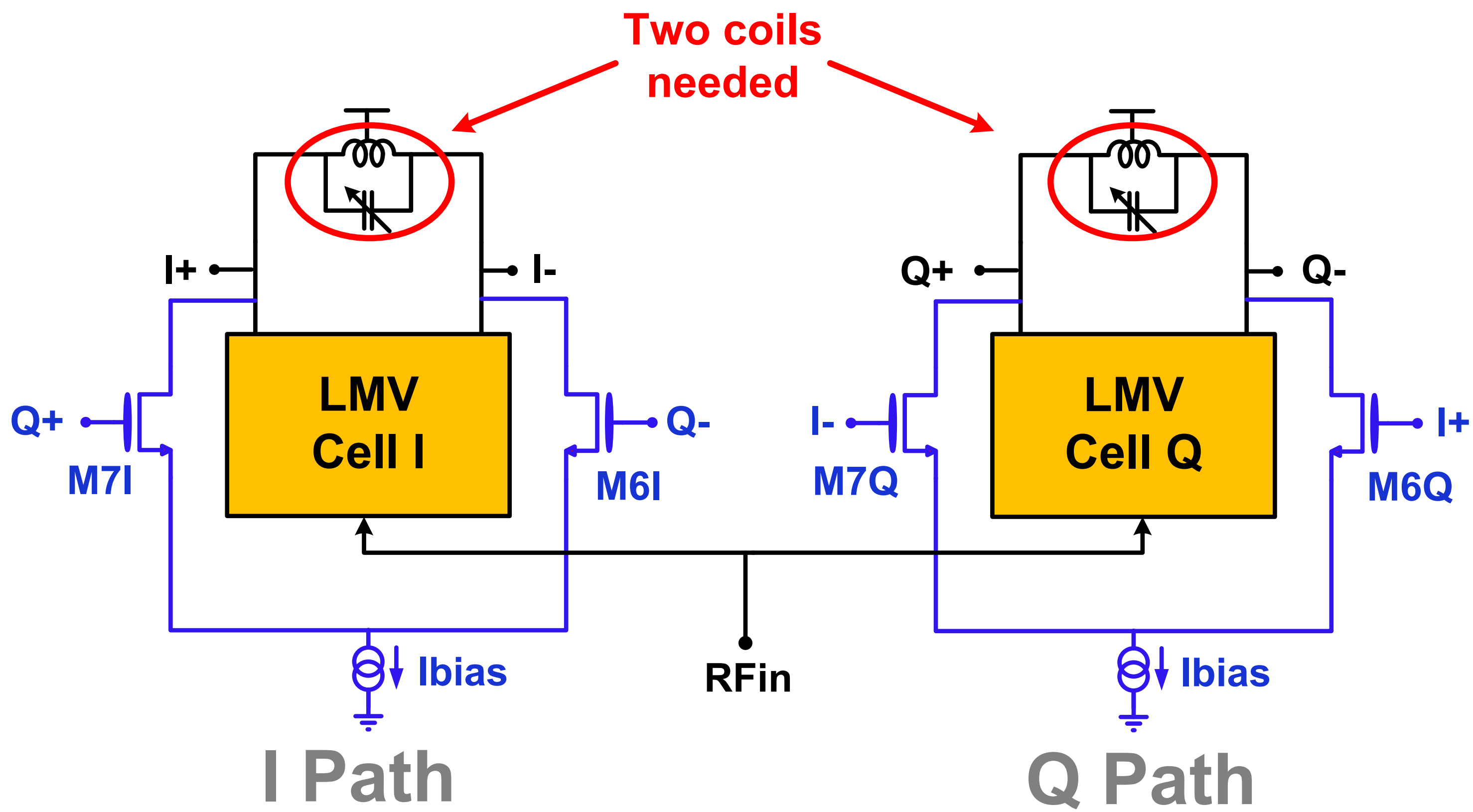
- Only two phase for LO signal
- Losses on RF path

Cross Coupled LMV Quadrature (1)



Traditional cross-coupling topology for quadrature generation

Cross Coupled LMV Quadrature (2)



- Good quadrature accuracy
- **Two LMV Cells** (Double area and power)

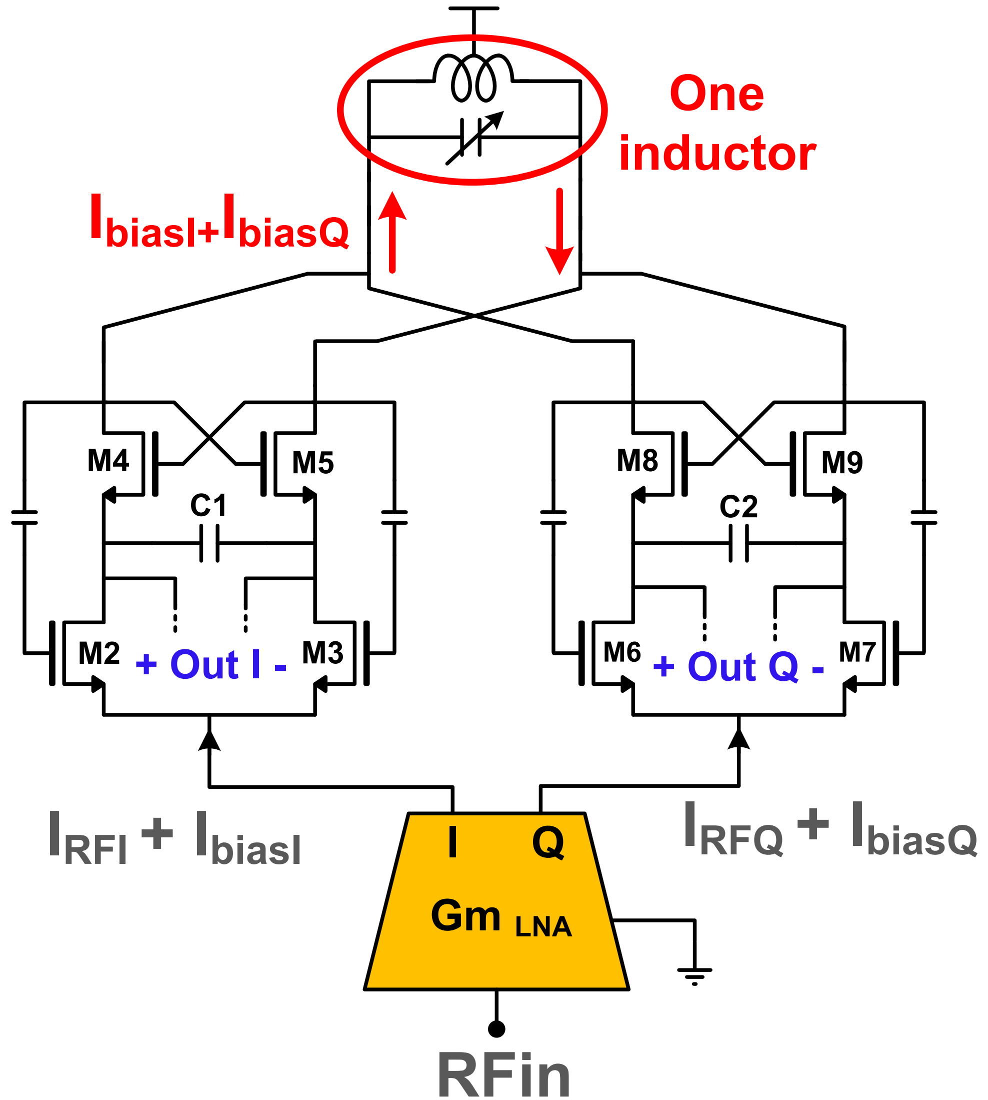
How to reduce number of inductors?

Quadrature LMV Tank Sharing

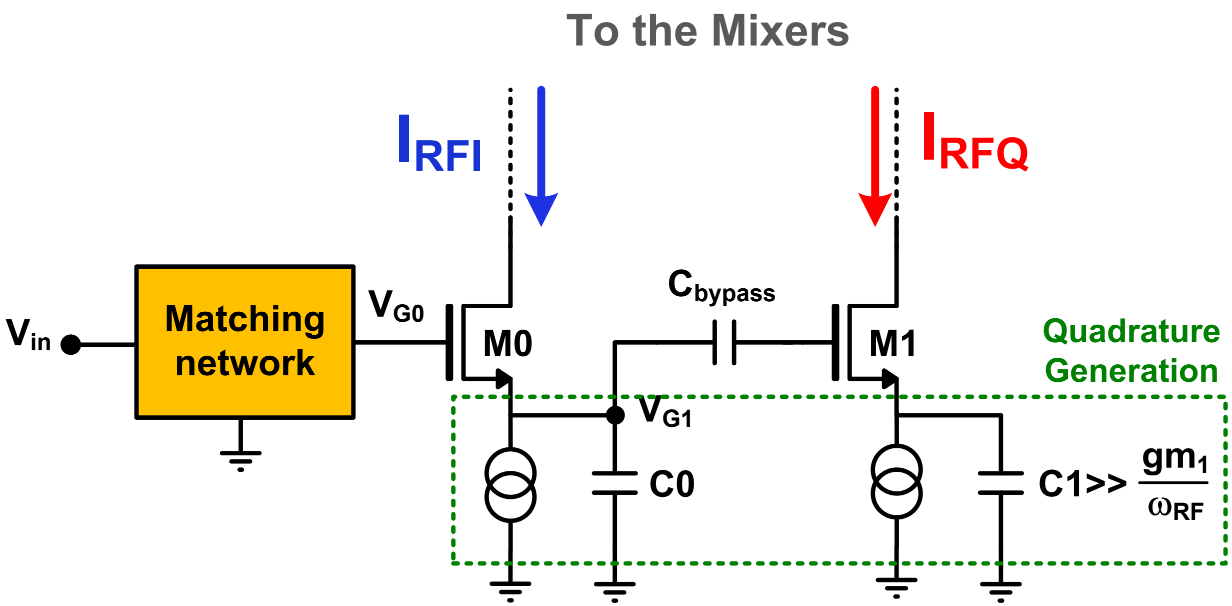
- **Share the tank** between the two LMV and provide **quadrature on RF path**

I & Q bias in the same tank:
dissipation and area reduced

How to realize a quadrature LNA?

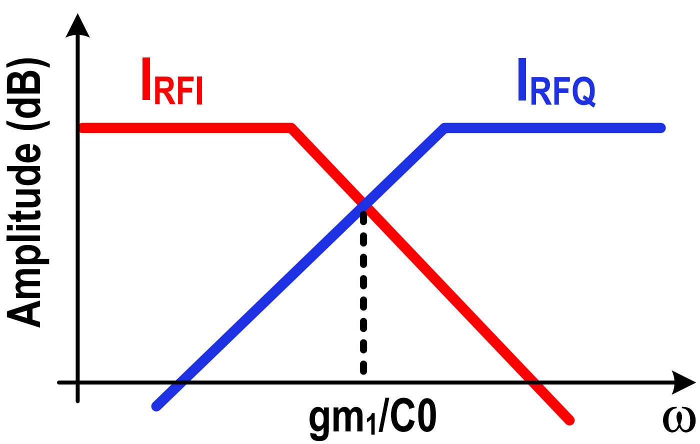


LNA Quadrature Generation



$$I_{RFI} = \frac{j\omega C0}{1 + j\omega C0/gm_0} V_{in}$$

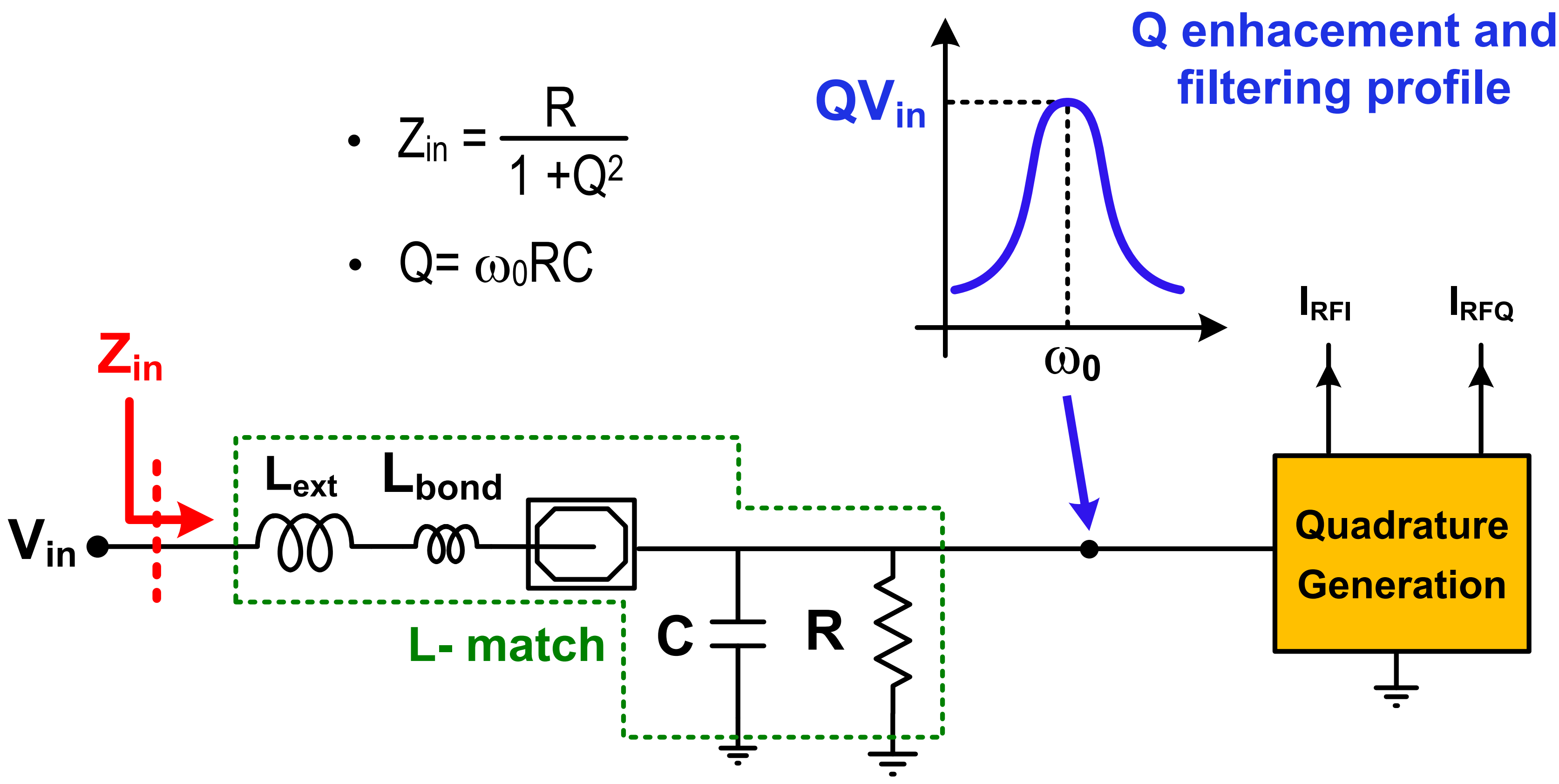
$$I_{RFQ} = \frac{gm_1}{j\omega C0} I_{RFI}$$



- Signal **quadrature** guaranteed on a **wide range**
- **Amplitude match** obtained only **close to $gm_1/C0$**

LNA matching network

- $Z_{in} = \dfrac{R}{1 + Q^2}$
- $Q = \omega_0 RC$



The **L-match network** provides **a filtering action** for out of band blockers and a **gain boost** to reduce noise

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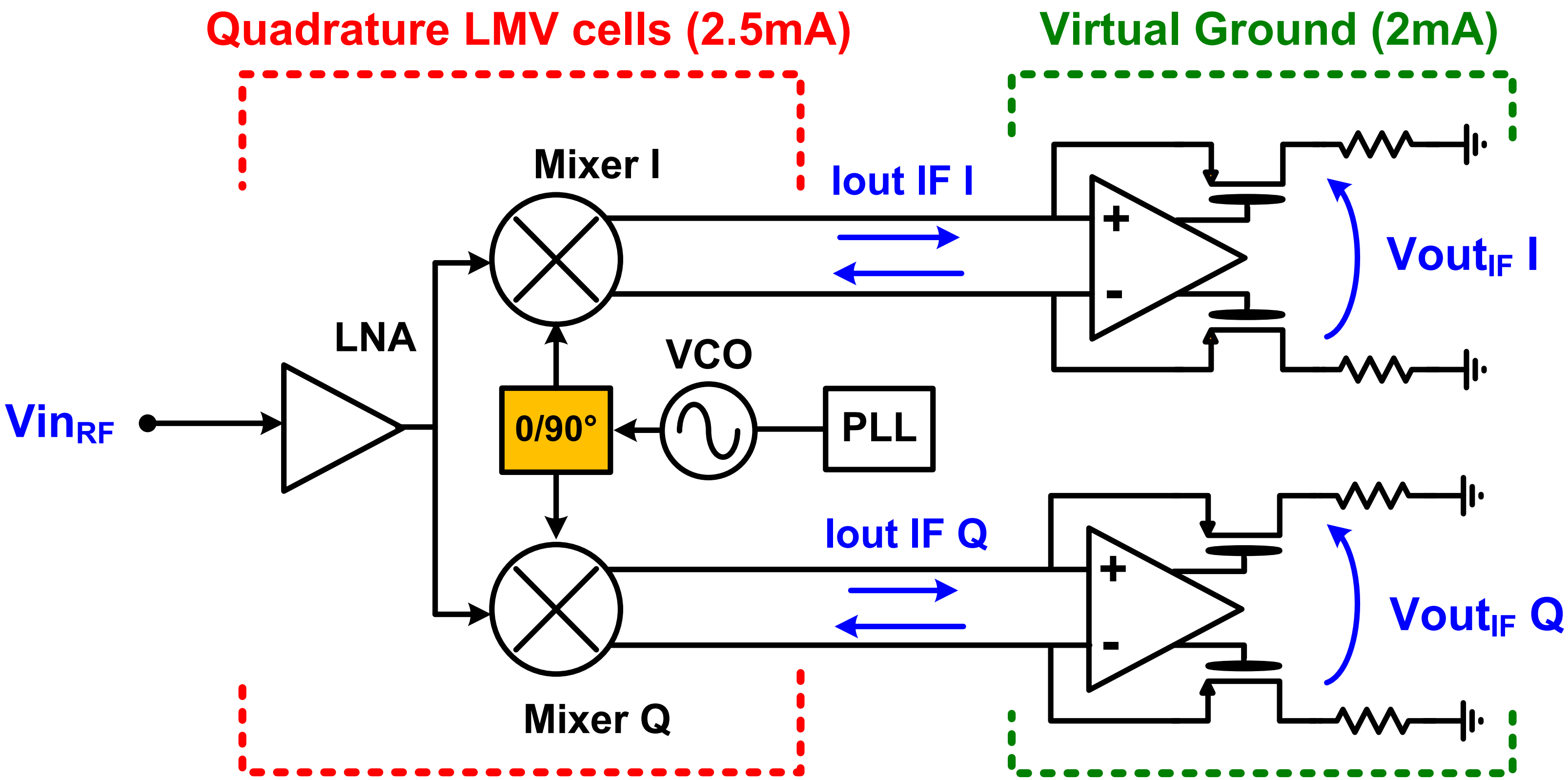
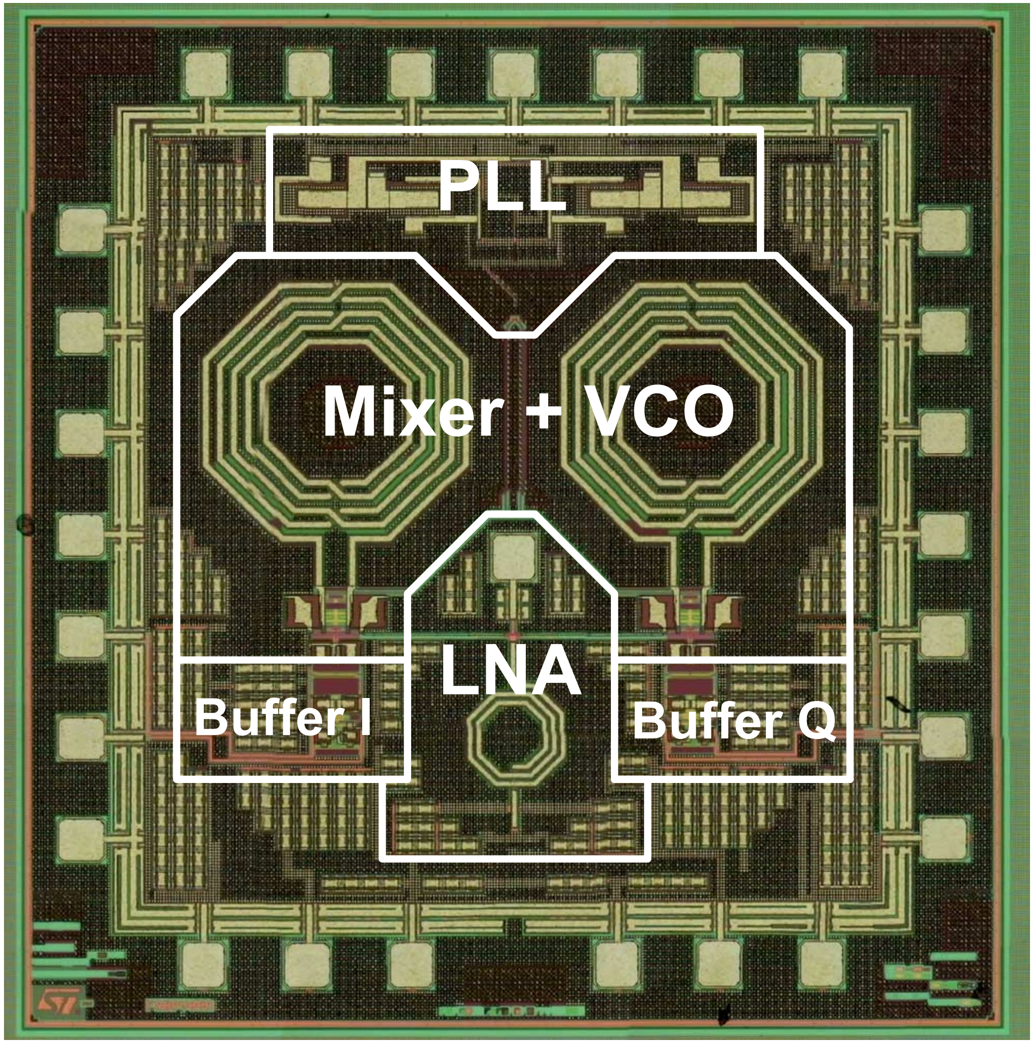
Low IF Receiver with Quadrature @ LO



GPS quadrature Front-End: Low IF architecture at 4MHz

[*Liscidini et al.* ISSCC'06]

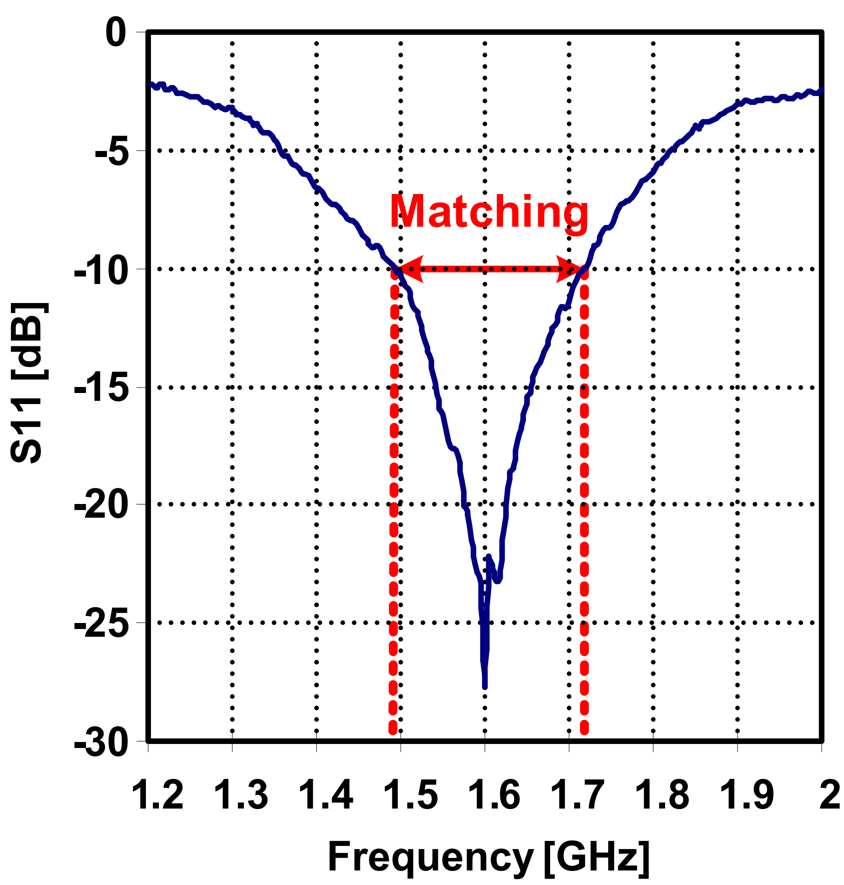
Chip Micrograph



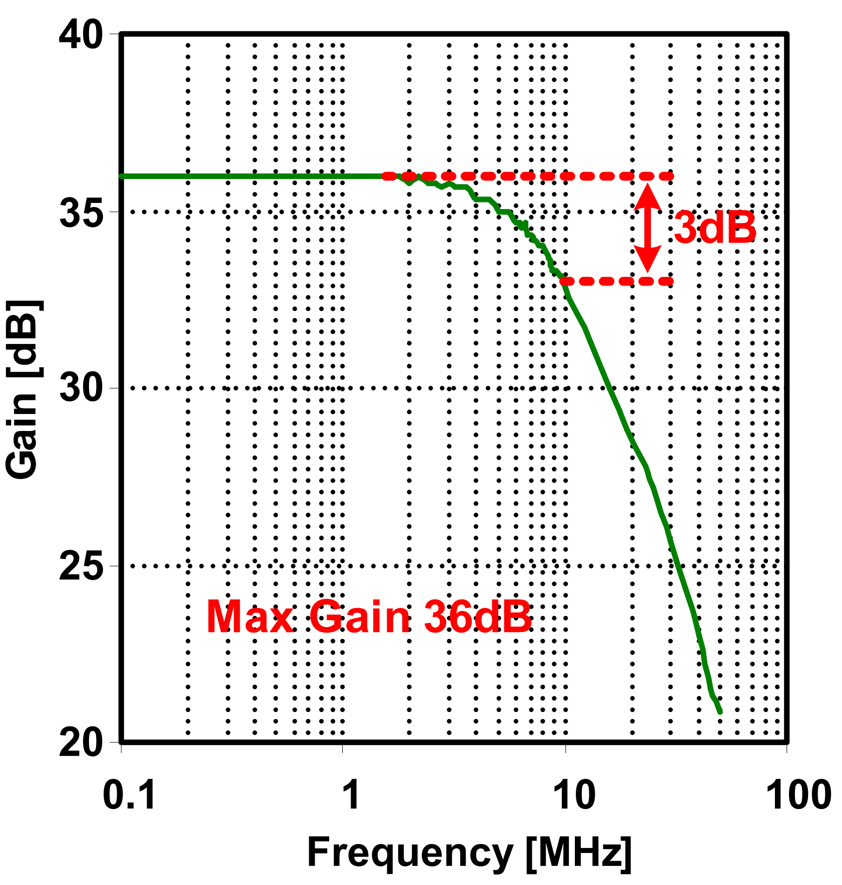
- Active area only 1.5 mm^2
- Differential inductors for VCO tanks
- PAD ESD protected
- Technology CMOS 0.13 μm

Input Matching and Gain

Input Matching

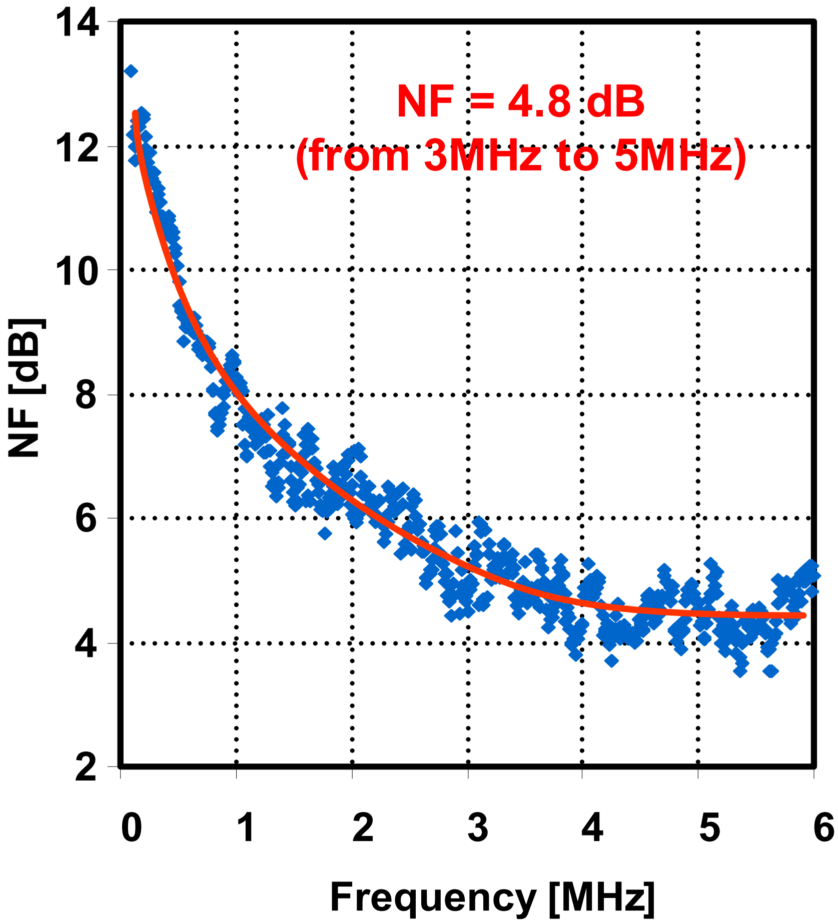


Output Gain

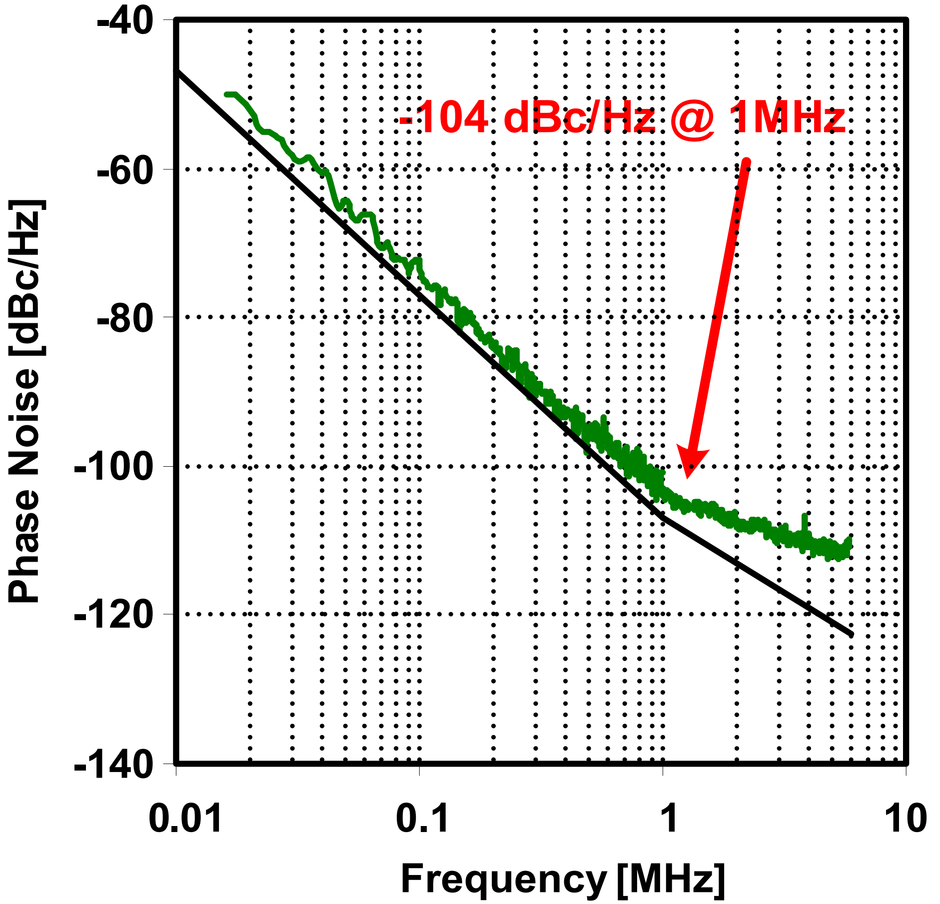


NF and VCO Phase Noise

Noise Figure



Phase Noise



The State of Art

	[1]	[2]	[3]	**This Work**
Gain	(25)+60 dB	(50)+80 dB	(33)+60 dB	36dB
NF	4dB	4dB	8.5dB	4.8dB
IIP3	n.a.	-15dBm	n.a.	-19dBm
1dB Comp. Point	-28dBm	n.a.	n.a.	-31dBm
PN @ 1MHz	-95dBc/Hz	-107dBc/Hz	-109dBc/Hz	-104dBc/Hz
LO leak. at input	-66dBm	n.a.	n.a.	-55dBm
Total Power	**35mW**	**27mW**	**19 mW**	**11mW***

[1] G. Montagna *et al.* JSSC, July 2003 (CMOS 018 μm)
[2] F. Behbahani *et al.* JSSC, Dec. 2002 (CMOS 0.35 μm)
[3] J. Ko *et al*. JSSC, July 2005 (CMOS 0.18 μm)

*** Included PLL (4.6 mW)**

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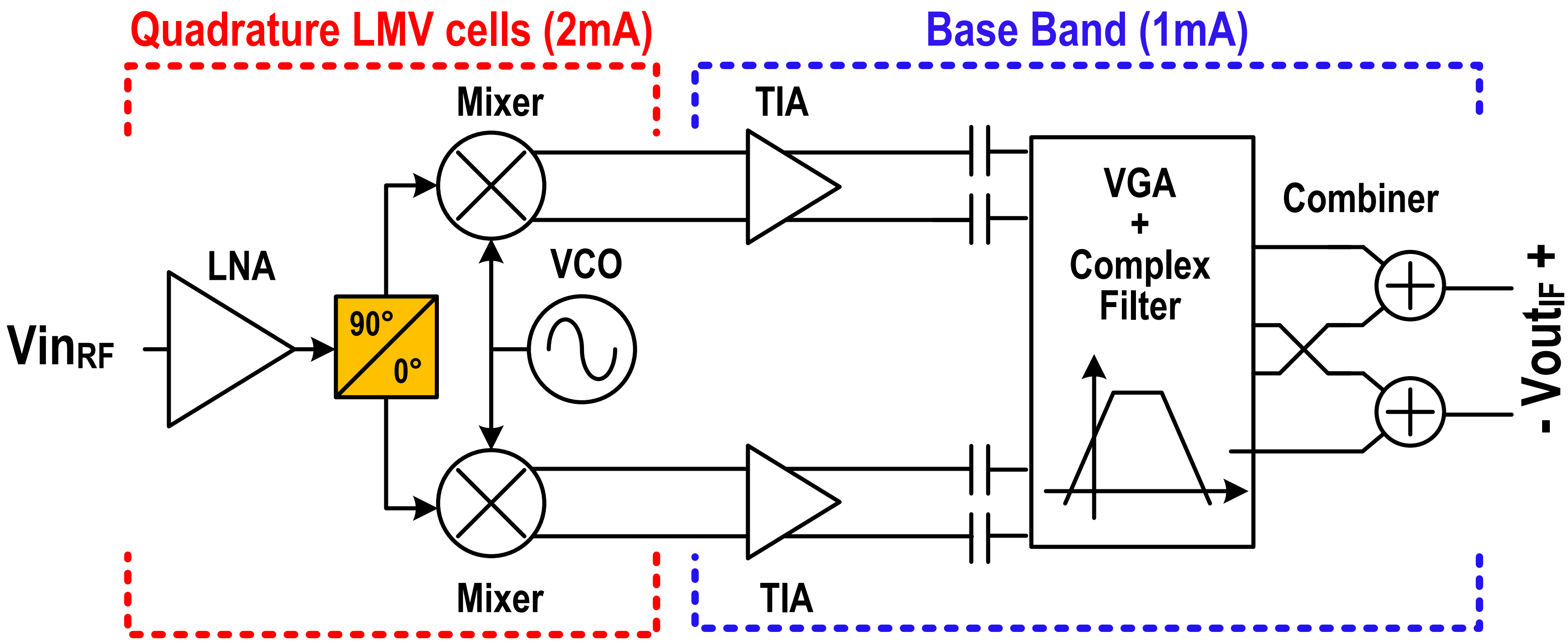
Low IF Receiver with Quadrature on RF path

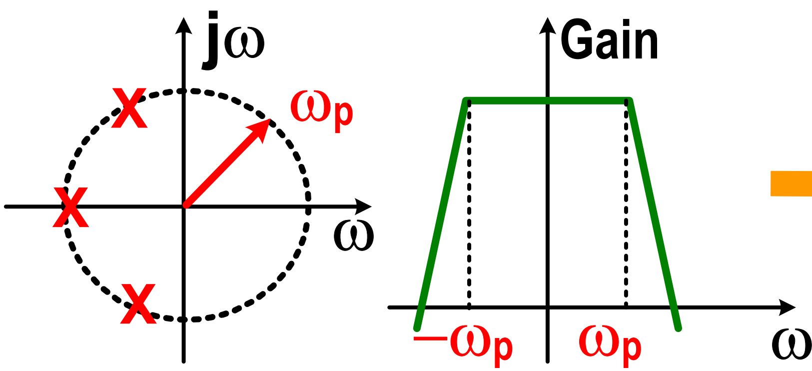


ZigBee Quadrature Receiver: Low IF architecture at 2MHz

[*Liscidini et al.* ISSCC'08]

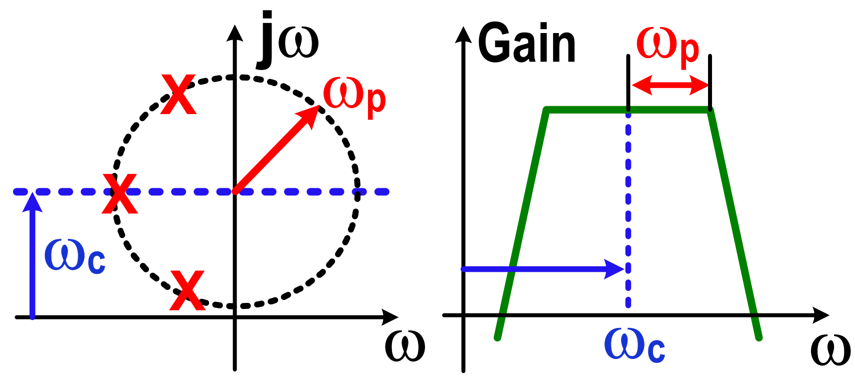
gmC Complex Filter

3^{rd} Order Real Butterworth



Real Pole=ω_p

3^{rd} Order Complex Butterworth



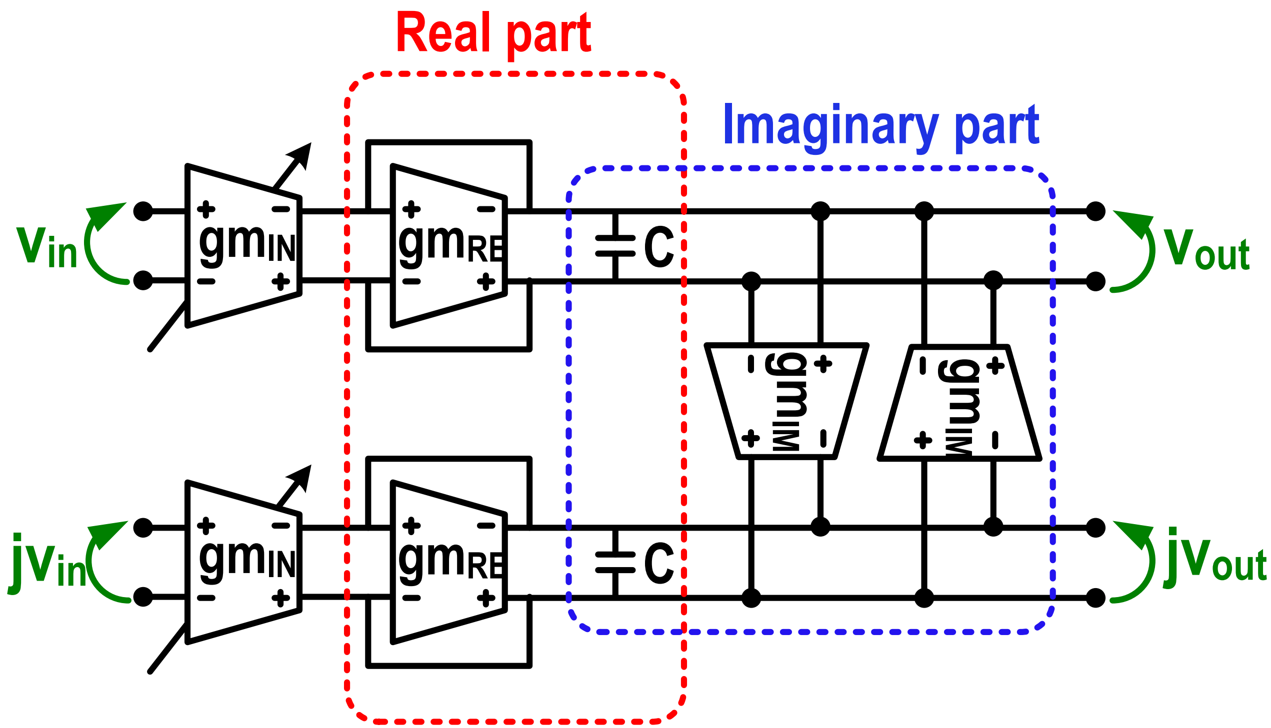
Complex Pole=ω_p+jω_C

From a real to a complex filter there is a **shift of frequencies**:

$$j\omega \rightarrow j(\omega-\omega_C)$$

The f_c shift is the center frequency of the new band-pass

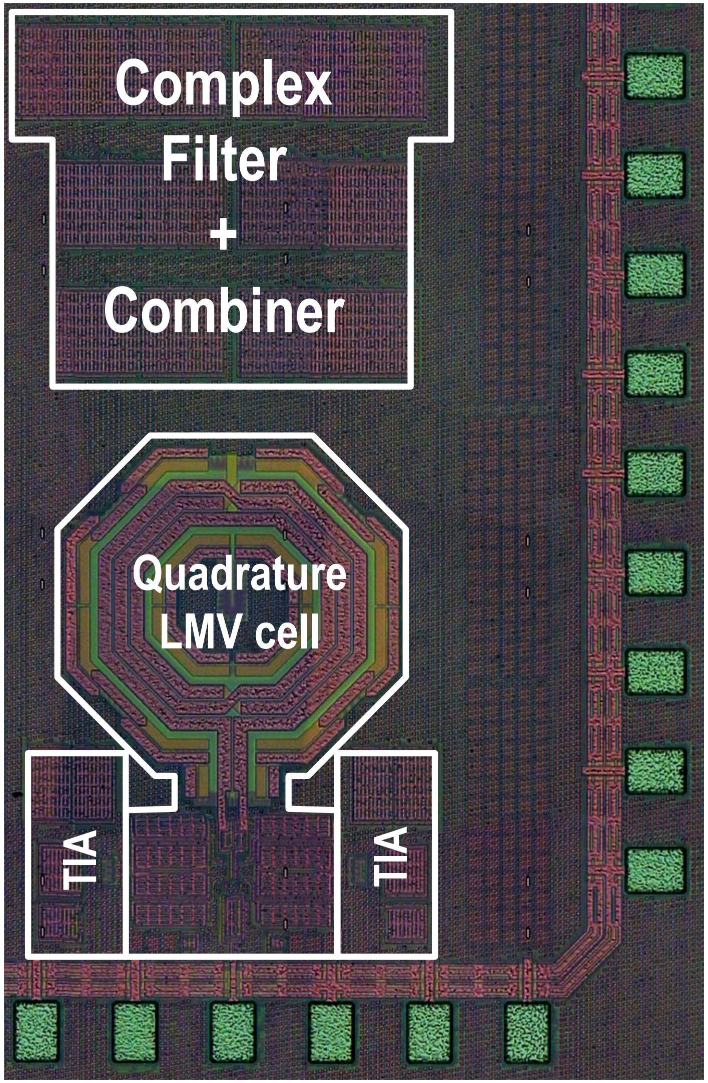
gmC Complex pole Synthesis



Complex pole realized as $\omega_{comp} = \frac{gm_{RE}}{2C} + j\frac{gm_{IM}}{2C}$

Gain stage and pole frequency controlled by gm

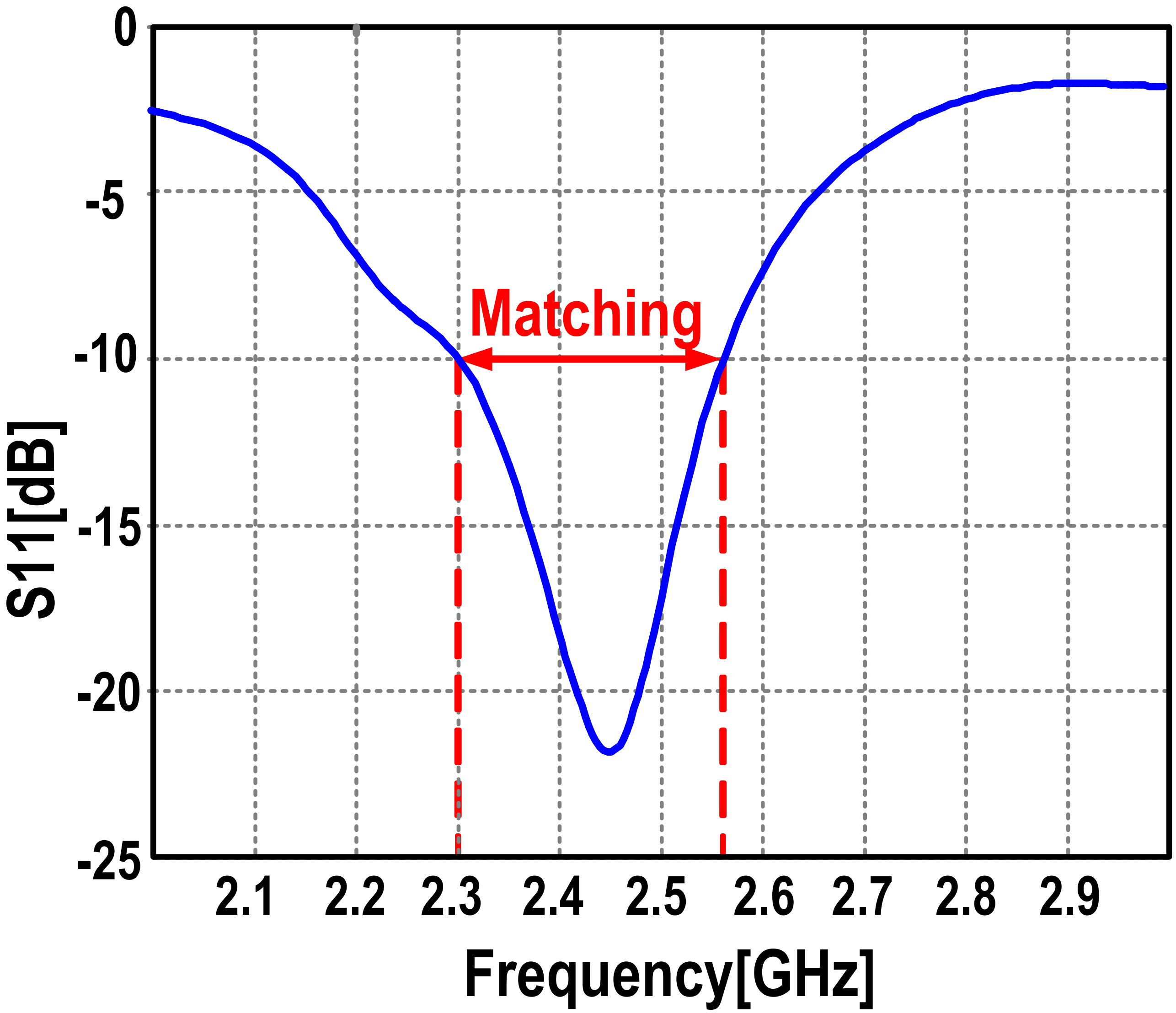
Chip Micrograph



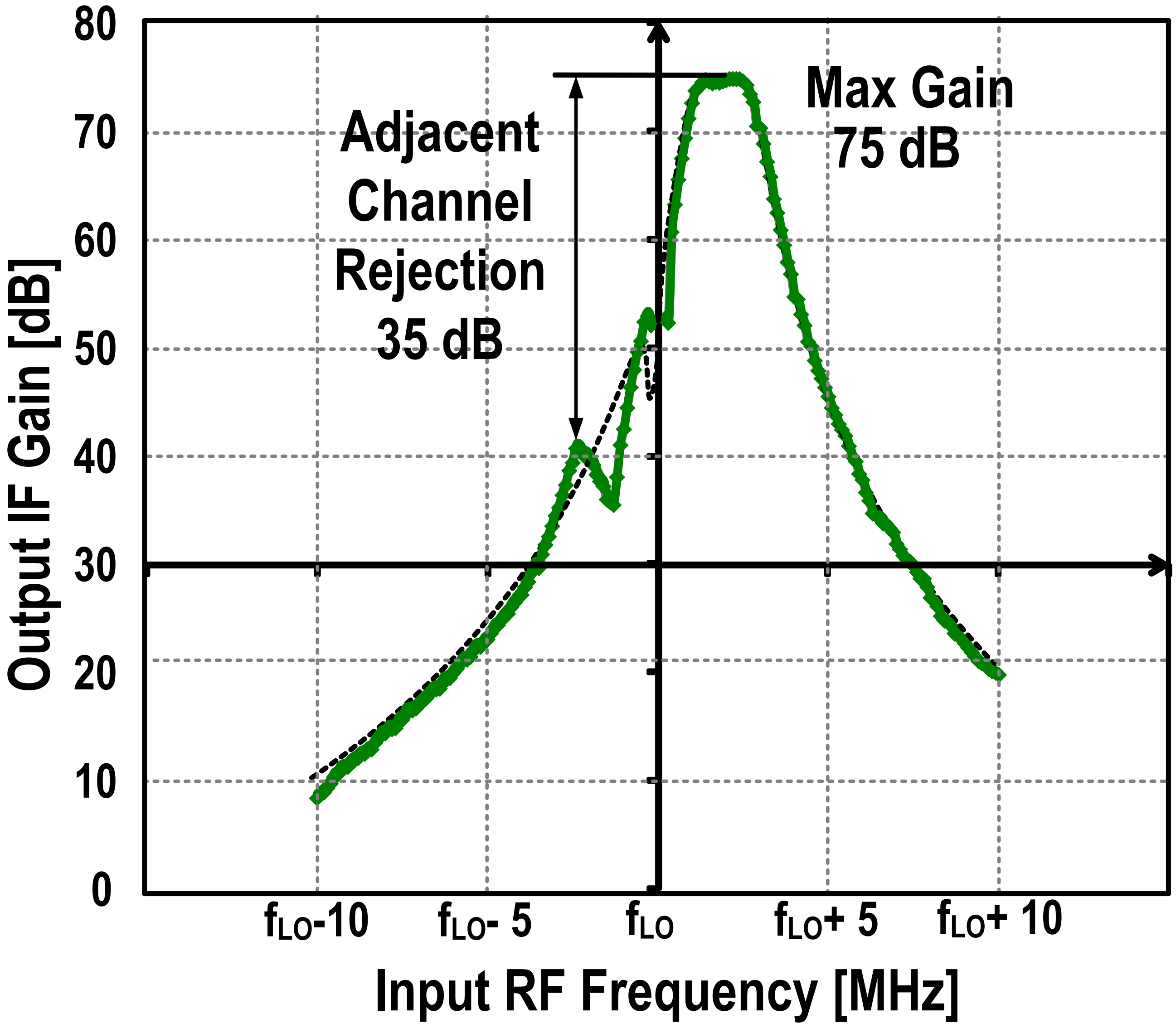
- Technology CMOS 90 nm
- Only one integrated inductor
- Active area only 0.35 mm^2

  (RF section area similar to BB section area)

Input Matching



IF Gain Profile



Specs and State of Art

	[1]	[2]	This work
NF (dB)	24.7	5.7	9
Sensitivity (dBm)	-82	-101	-94.7
IIP3(dBm)	-4,5	-16	-12,5
SFDR (dB)	50.3	55.3	55.5
Image Rejection (dB)	---	36	35
PN(3.5MHz) (dBc/Hz)	--	--	-116
Vdd (V)	1.8	1.8	1.2
Power dissipation (mW)	15	17	3.6
Number of inductors	6	4	1
Area (mm^2)	2.1	0.8	0.35
Technology (μm)	0.18	0.18	0.09

[1] *P. Choi, et al.,* JSSC, Dec 2003 (802.15.4)

[2] W*. Kluge, et al.,*JSSC, Dec. 2006 (ZigBee)

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Conclusions

- The functionalities of RF amplification, mixing and LO generator were successfully merged in a single stage.

- The LMV cell represents a competitive solution to reduce power consumption and area ,compatible with low voltage supply.

- The LMV cell was advantageously used in a very low power GPS quadrature front-end and a ZigBee receiver

Acknowledgements

Thanks to:

Andrea Mazzanti, Marika Tedeschi, Riccardo Tonietto, Luca Vandi,

Piero Andreani, and Rinaldo Castello