Single-stage RF quadrature front-end receivers for ultra low power applications

(Invited Paper)

Antonio Liscidini
Electronic Department, University of Pavia
antonio.liscidini@unipv.it

Abstract— **A very compact and flexible single stage RF front-end for low power receiver is presented. The key feature of the circuit proposed is the large separation of the different functions implemented (RF amplification, mixing, LO and quadrature generation) even while sharing the same bias current and the same devices.**

Two different prototypes are reported. The first one is a RF front-end for GPS applications with a noise figure of 4.8dB, a gain of 36dB, an IIP3 of -19dBm and a power consumption of only 5.4mW. The second design is a ZigBee receiver with a noise figure around 9dB, an IIP3 of -12.5dBm and a power dissipation of 3.6mW (including baseband filter).

I. INTRODUCTION

In low power receiver design (e.g. GPS, ZigBee and wireless sensor network), long battery life and area-saving are the main targets to realize a long-lasting and low cost device. However, while GPS receivers still need a high dynamic range to coexist with cellular handset, sensors and ZigBee transceivers trade off performance with a cheaper design. In this case in fact, since a large number of units present network relaxes the sensitivity of the single receiver, a lower cost solution increases the density of elements and the flexibility of the system.

A classic technique to reduce power consumption is the current reuse across different functional blocks. Since a simple stack of two or more elements demands an higher voltage supply, a more efficient strategy is the combination of several functionality into a single stage, sharing also the active devices and the voltage drop across them. A popular example is cascoding the Gilbert mixer on top of the input stage of the LNA in a receiver front-end, while less frequent is merging VCO and mixer [1][2].

In this paper, starting from the LC tank oscillator topology, LNA Mixer and VCO are combined into a single stage providing a compact and low power solution. The idea takes advantage of the fact that a Gilbert mixer and a differential oscillator resemble very closely each other, since in both cases the differential-pair transistors behave like switches mixing input signals.

The structure, called LMV cell, is successively inserted in two I&Q receiver architectures where the quadrature generation is realized at the local oscillator level or directly on the RF signal path. The first approach offers a more efficient solution in terms of dynamic range and for this reason was used in the design of a GPS RF front end. On the contrary, the second quadrature technique minimizes the number of integrated coil and die-size, limiting performance but leading to a very low cost and compact design oriented to ZigBee and wireless sensor network applications.

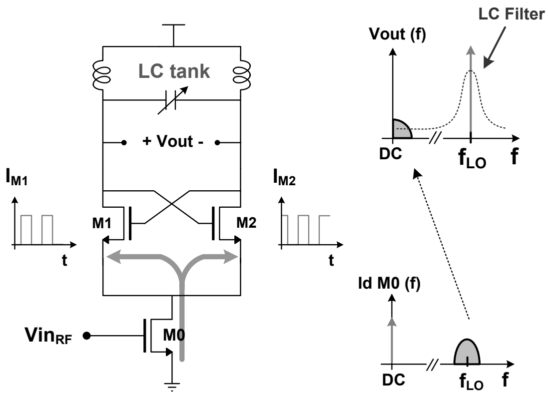

Fig. 1. LC tank oscillator as a mixer.

II. FROM LC TANK OSCILLATOR TO A SINGLE STAGE RF FRONT-END

A traditional LC tank oscillator, as the one shown in Fig.1, intrinsically performs the mixing functionality since any RF signal in the VCO bias current is down-converted by the switching pair M1-M2. This occurs through the same mechanism by which the dc current of M0 is up-converted to the LO frequency. The mixing property of this structure is generally exploited in transmission where the LC tank oscillator is used as up-converter in direct modulation architectures [3]. Nevertheless, when this topology is used as a down-converter, the high-Q LC tank, attenuates the low frequency signal preventing any IF amplification (Fig.1).

A. Mixer and LNA functionalities

Attempting to sense the mixed signal at the output of the VCO unavoidably degrades the oscillator phase noise therefore the idea is to read the down-converted signal at the sources of M1 and M2 where the oscillator loop can be opened at low frequency, without perturbing the RF oscillation. This can be done as drawn in Fig.2 where the the short circuit between the sources of M1 and M2 is substituted by a capacitance C1 that closes the loop at RF while presenting a high impedance at IF [4]. Notice that the

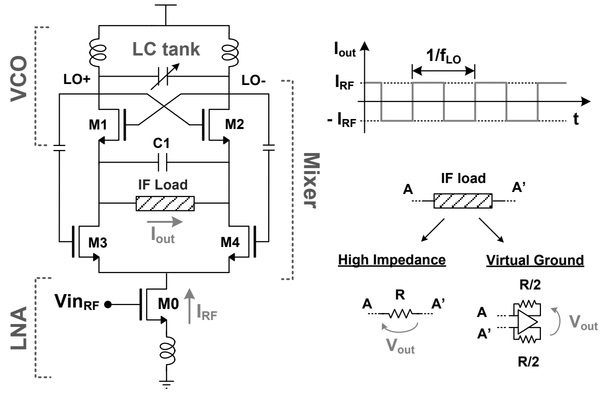

Fig. 2. The LNA-Mixer-VCO cell (bias not shown)

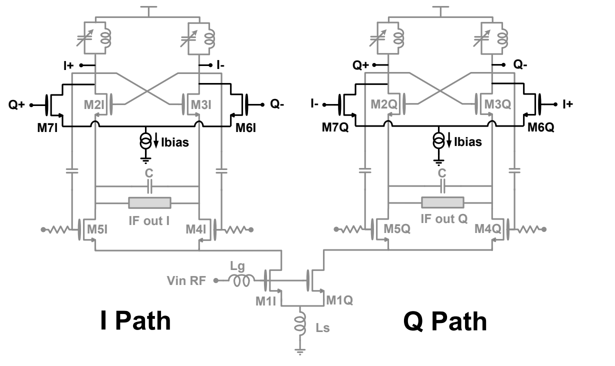

Fig. 3. LO Quadrature generation: Cross Coupled LMV scheme.

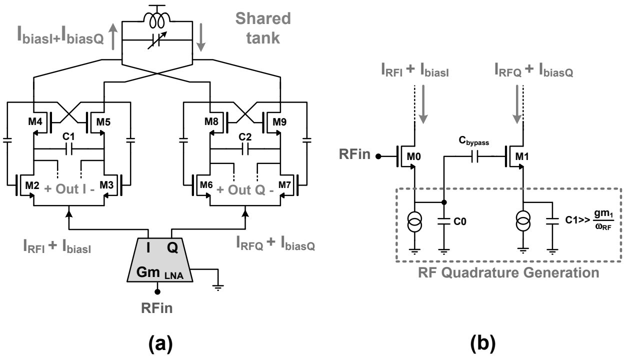

Fig. 4. Quadrature generation on the RF signal path: (a) single coil quadrature LMV cell, (b) stacked quadrature LNA.

capacitance C1 represents a degeneration for M1 and M2 and thus its value must be enough high to guarantee a loop gain greater than one to sustain the oscillations. An additional switching pair M3-M4 has been inserted to get a complete down conversion of the RF signal that in this way is multiplied by +1 and -1 flowing alternatively through M4-M1 and M3-M2.

To perform the LNA functionality, any additional active device is needed since a low noise input termination can be obtained inductively degenerating the oscillator current generator M0. As a result, the structure in Fig.2 includes all the main blocks of RF front-end sharing bias current and active devices, leading to a compact and very low power architecture.

B. Sensing down-converted signal

As reported in Fig.2, the signal at the output of the cell can be sensed as a voltage across a low IF high impedance or as a current flowing into a virtual ground. Although this last approach is not mandatory for the LMV to perform the down-conversion, the use of a virtual ground at the mixer outputs reduces the sensitivity to parasitic capacitances between mixer outputs and ground, enabling a more robust control of the conversion gain. Further, moving the whole voltage gain out of the LMV stack reduces the minimum supply voltage required for proper operations. On the other hand, it must be appreciated that the lack of voltage gain in front of the base-band buffers tends to increase the contribution of these stages to the overall noise figure.

III. QUADRATURE GENERATION

Typically all the RF front-ends adopt a quadrature down-conversion architecture to eliminate one signal sideband folded during the mixing to IF frequency (image rejection). For this reason, inserting the LMV cell in a quadrature receiver is mandatory for an effective use in most of applications.

The quadrature operation of the cell can be straightforwardly achieved acting at the level of the local oscillator (LO) or directly on the RF signal path. Although this last approach can appear disadvantageous in terms of signal-to-noise ratio in ultra low power applications such as ZigBee is generally preferred because less onerous in terms of power consumption and die area [5]. In this section it will be shown that both solutions are compatible with the LMV cell confirming the versatility of the structure.

A. Quadrature at the local oscillator

The LMV quadrature scheme is shown in detail in Fig.3. Since the top of the cell acts exactly like a traditional LC tank oscillator, the LO quadrature generation can be obtained via the standard cross-coupling of the two VCOs through the additional differential pairs M6I-M7I and M6Q-M7Q [4]. This does not interfere with the rest of the LMV and is yet another proof of the robustness of the cell.

Notice that the additional pairs do not significantly affect the total current consumption while guaranteeing an adequate image rejection in most of applications. However, since the LMV cell has been duplicated, the area and the power required by the front-end is doubled.

B. Quadrature on the RF signal path

When the quadrature is realized on the RF signal path, the tanks of the two LMV cell can shared as shown in Fig.4.a. In this way only a differential coils is required minimizing the active area. Furthermore, since the bias current of I and Q path flow in the same LC load, the total current necessary to sustain the oscillation can be reduce leading to more efficient structure in terms of power dissipation [6].

To share the bias current with the low noise amplifier, the signals quadrature can be realized as shown in Fig. 4.b. The quadrature is obtained degenerating transistor M0 with capacitor C0 and sensing the Q signal at the source of M0 by an identical stage but operating in common source mode

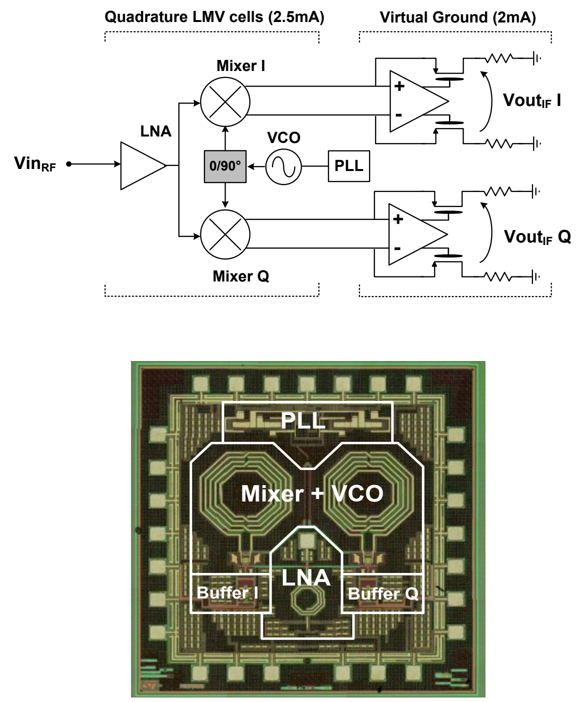

Fig. 5 GPS prototype circuits and chip micrograph.

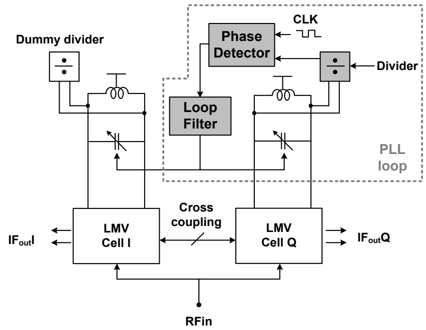

Fig. 6 GPS Measurements and state of art comparison

TABLE I
GPS MEASURES AND STATE OF ART COMPARISON

	[7]	[8]	[1]	**LMV cell**
Gain [dB]	25	33	50	36
NF [dB]	4	8.5	4	4.8
IIP3 [dBm]	n.a.	n.a.	-15	-19
PN @ 1MHz [dBc/Hz]	-95	-109	-107	-104
LO leak. at input[dBm]	-66	n.a.	n.a.	-55
Technology	0.18μm	0.18μm	0.35μm	0.13μm
Total Power[mW]	**35**	**19**	**27**	**11***

***PLL power consumption included (5.6mW)**

thanks to the large value of the capacitor C1. While the 90° phase shift is guaranteed in a wide frequency range, the amplitude match is obtained only around the working frequency ω_{RF} setting C0=gm/ω_{RF}.

Notice that the quadrature generation on the RF signal path introduces a 3dB loss that degrades the noise figure of the full receiver, nonetheless the use of a single coil reduced significantly the active area.

IV. PROTOTYPES

The two LMV cell quadrature architectures were implemented in a GPS RF front-end and in ZigBee receiver. In the case of GPS the LMV cross-coupled approach was preferred due to the challenging spec in the term of sensitivity required by the standard. In the ZigBee prototype, thanks to the more relaxed specs in terms of noise figure and linearity, the quadrature topology of Fig. 4 was preferred minimizing the number of integrated coils to get a very compact and low cost solution.

A. GPS RF front-end

The GPS front-end, fabricated in a 0.13µm CMOS process is reported in Fig.5. The down-converted signal is sensed as a current flowing into a couple of low-frequency virtual ground, realized with a super-cascode structure and it is finally collected as a voltage at the output of the buffers. The active die area of the RF front end is 1.5mm^2 thanks to the used of only 3 integrated inductors (one for the source degeneration in the LNA and two for the cross coupled LMV cells). To improve reliability, thick gate MOS transistors have been used in both VCO and mixer, although this is not strictly necessary when the minimum supply voltage (1.2V) is used in the RF part. With standard gate oxide devices, the supply voltage can be lowered to 1.0V.

To lock the LO frequency, the quadrature LMV cell is inserted in a phase locked loop as shown in Fig.6. Once again, since the top of the LMV cell operates exactly like an LC tank oscillator the LO signal can be sensed across the tank, duplicating the input of the divider to load symmetrically I and Q oscillators. The phase locked loop is finally closed on traditional MOS varactors at the VCOs outputs.

A summary of the most relevant measurements results, with a comparison with the state of art of GPS front-ends, are reported in Table I. Notice that all the data are referred only to the RF front end including the PLL. In particular the solution proposed represents the less onerous in terms of power consumption even considering the PLL circuit not optimized for this application. It can be noticed how the closer power dissipation can be reached by decreasing the receiver performance [8] or through a partial current reuse [1].

B. ZigBee receiver

The ZigBee receiver has been fabricated in a 90nm CMOS process. Fig. 7 shows the full scheme of the receiver and the chip micrograph. Since the quadrature signal has been realized on the RF signal path, the VCO tank sharing allowed the use of only one integrated inductor, resulting in an active die area of only 0.35mm^2 including the baseband filter.

The input-matching is realized through an internal resistor and a L-match network formed by the pad capacitance the bond-wire and an external inductor. Although a resistive termination tends to increase the noise figure of the receiver, this solution is fully compatible with

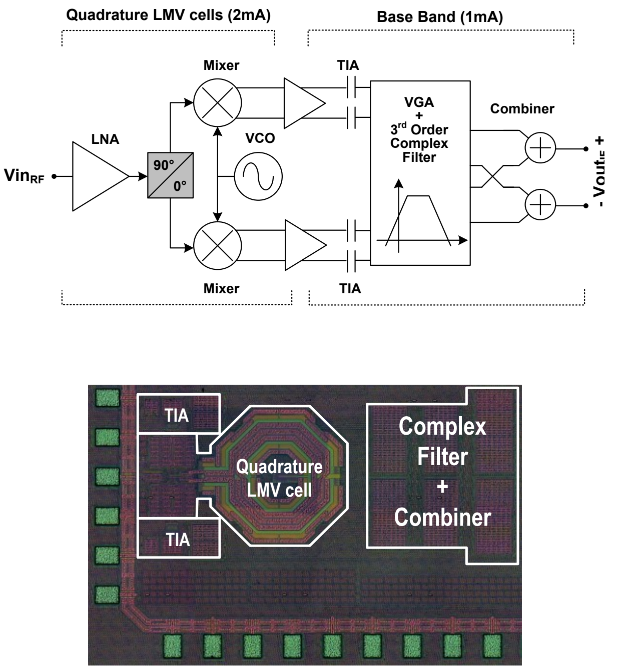

Fig. 7 ZigBee receiver scheme and chip micrograph

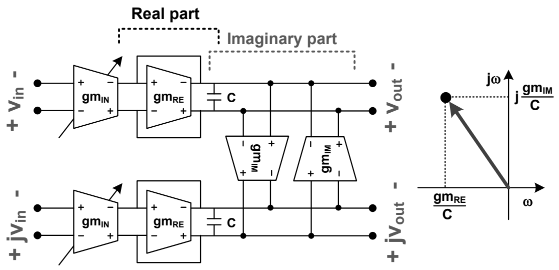

Fig. 8 Gm-C complex pole synthesis

TABLE II

ZIGBEE MEASURES AND STATE OF ART COMPARISON

	[5]	[9]	LMV cell
SFDR [dB]	55.3	50.3	55.5
NF [dB]	5.7	24.7	9
IIP3 [dBm]	-16	-4.5	-12.5
Number of Integrated Coils	4	6	1
Area [mm^2]	0.8	2.1	0.35
Technology	0.18μm	0.18μm	0.09μm
Total Power[mW]	**17**	**15**	**3.6**

the quadrature architecture reported in Fig.4.b and does not required any additional integrated inductors, minimizing the active area.

The channel selection is performed by a fully differential three-stage variable gain complex gm-C filter, AC coupled at the output of the TIA to suppress DC offset and low frequency noise. The complex poles are synthesized as shown in Fig.8. In each stage, two gm-C filters with a real transfer function are joint into a complex one by adding an imaginary term realized cross-connecting the transconductances gm_{IM} between the I and Q paths. The two paths are finally combined to provide the image rejection required for the signal demodulation (Fig.7).

In Table II the prototype is compared to the complete ZigBee receivers present in literature. The noise figure averaged over the band from 1MHz to 3MHz is around 9dB while the IIP3 is -12.5dBm. This results in a spurious free dynamic range of 55.5dB with 20% of power consumption and an active area less than half compared to the state of art.

V. CONCLUSIONS

A self-oscillating mixer architecture based on the LC tank topology, has been presented. Starting from this structure, two different single stage RF quadrature front-end were developed, implementing two different strategies of quadrature generation (i.e. quadrature at the LO or on the RF signal path).

Several apparently contrasting tasks have been successfully merged: current reuse, multiple functionality without spurious interactions, device count reduction, and compatibility with a low supply voltage. The flexibility of the cell has been demonstrated with two different prototypes achieving in both case a power consumption and an active area significantly improved compared with the state of art.

ACKNOWLEDGEMENTS

This project has been supported by the Italian National Research Program FIRB (Contract Nr. RBAP06L4S5).

REFERENCES

[1] F. Behbahani et al., "A 27-mW GPS Radio in 0.35μm CMOS," in IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers, pp. 398–399, Feb. 2002.

[2] J. van der Tang, D. Kasperkovitz. "A 0.9-2.2GHz Monolithic Quadrature Mixer Oscillator for Direct-Conversion Satellite Receivers", in Dig. Tech. Papers 1997 *IEEE ISSCC Tech. Papers*, pp. 88-89, Feb. 1997

[3] E. Hegazi, A.Abidi "A 17mW Transmitter an Frequency Synthesizer for 900-MHz GSM Fully Integrated in 0.35-μm CMOS" *IEEE Journal of Solid-State Circuits*, vol. 38, pp. 782–792,May. 2003.

[4] A. Liscidini, et al., "Single-Stage Low-Power Quadrature RF Receiver Front-End: The LMV Cell," *IEEE J. Solid-State Circuits*, vol. 41, no. 12, pp. 2832-2841, Dec. 2006.

[5] W. Kluge , F. Poegel , H. Roller , M. Lange , T. Ferchland , L. Dathe and D. Eggert "A fully integrated 2.4GHz IEEE 802.15.4 compliant transceiver for ZigBee applications," *IEEE ISSCC Dig. Tech. Papers*, Feb. 2006, p. 1470.

[6] A. Liscidini, M. Tedeschi, R. Castello," A 2.4 GHz 3.6mW 0.35mm2 Quadrature Front-End RX for ZigBee and WPAN Applications" *IEEE ISSCC Dig. Tech. Papers*, Feb. 2008, pp.370-371.

[7] G. Montagna et al., "A 35mW 3.6-mm fully integrated 0.18-μmCMOS GPS radio", IEEE Journal of Solid-State Circuits, vol. 38, pp.1163–1171, July 2003.

[8] J. Ko, et al., "A 19-mW 2.6-mm2 L1/L2 Dual-Band CMOS GPS Receiver", IEEE Journal of Solid-State Circuits, vol. 40, pp. 1414–1425, July 2005.

[9] T.K. Nguyen, at al., "A Low-Power RF Direct-Conversion Receiver/Transmitter for 2.4-GHz-Band IEEE 802.15.4 Standard in 0.18-um CMOS Technology", *IEEE Trans. on Microwave Theory and Techniques*, vol. 54, No. 12, Dec 2006, pp. 4062-4071.