Combined LNA and Mixer Circuits for 2.4 GHz ISM Band

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***Abstract*—We present a combined LNA-Mixer circuit with low area and low power, for the 2.4 GHz ISM band. The circuit has two versions: one has an output RC low-pass filter suitable for low IF frequencies; the other has an output LC band-pass filter suitable for medium IF frequencies. Circuits, with IF of 50 MHz and 400 MHz, were designed using UMC 0.13 μm CMOS technology and 1.2 V supply, and dissipate approximately 7.6 mW.**

I. Introduction

Conventional receiver architectures use independent blocks: a single narrowband low noise amplifier (LNA), a mixer, and an oscillator within a PLL [1], [2]. These blocks were originally designed independently because other blocks (mainly filters) were necessary between them. Impedance matching was required at all ports because filters could not be integrated, and non-integrated long connections were required. This leads to signal power waste and to complex circuits. Nowadays, with full system integration, long connections between blocks are unnecessary, and so impedance matching is not required.

In recent fully integrated RF receivers, some attempts have been made to merge blocks in order to minimize area, cost and power consumption: merged LNA-mixer [4], and oscillator-mixer [5], [6]. In this paper we describe a new combined LNA-mixer, which has low area and low power consumption, and uses few inductors. The use of inductors, in different blocks (LNA, mixer, oscillator and others), was minimized because inductors occupy large die areas, and may cause unwanted inter-dependence between these blocks due to parasitic magnetic coupling between the inductors. This effect is not yet suitably modeled [3].

We present two circuits for a 2.4 GHz RF input signal suitable for low IF values for ISM band applications with low power (approximately 6.3 mA from a voltage supply of 1.2 V). One circuit uses few integrated inductors and has low area. The other circuit is suitable for medium IF values. These circuits are described in section II. In section III we present the circuit design, and in section IV we present simulation results to evaluate the circuit performance. Finally, in section V we draw some conclusions.

II. Combined LNA and Mixer Circuits

A. Circuit Description

The LNA-mixer proposed here is based on the narrow-band cascode LNA with inductive degeneration, represented in figure 1.a) [7], and on the single-balanced mixer represented in figure 1.b) [1]. The LNA topology has low noise, while the mixer topology is one of the simplest to design [1], [7].

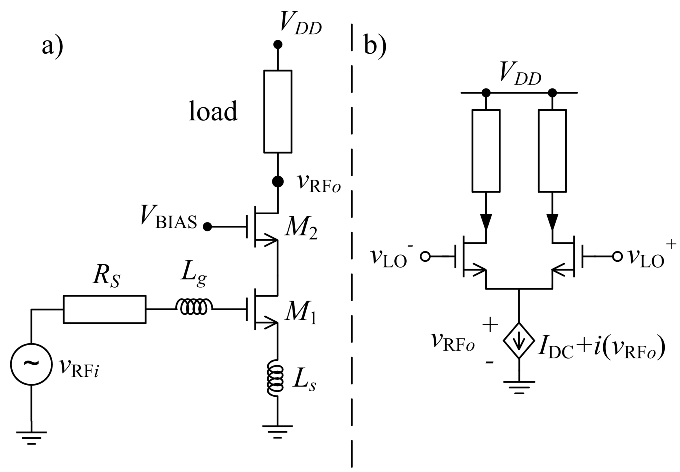

Fig. 1. a) Cascode LNA with inductive degeneration. b) Single-balanced mixer.

When both circuits are integrated in the same receiver, the LNA uses transistor M_1 to convert the input voltage into a current, that is re-converted to a voltage by the output load. This voltage, that feeds the mixer input, is again converted to a current that will be mixed with the local oscillator signal (v_{LO}). The mixer down-converts the RF current by switching the current from one side to the other at the LO frequency. Thus, the use of the two circuits of figure 1 as separate blocks requires two conversions, one from current to voltage at the LNA output, and the other from voltage to current at the mixer input.

The proposed circuit, presented in figure 2, consists of a common-source transistor, M_1, with inductive degeneration, as in figure 1.a). L_S is used to obtain the 50 Ω input impedance, and, since the resulting inductance does not resonate with C_{gs} at the desired frequency [7], inductor L_G

and capacitor C_x are added to tune the LNA input to the desired frequency and, additionally, to improve the noise performance of the circuit [8]. To prevent the conversions mentioned above, the LNA load and the cascode transistor in figure 1.a) are removed and the remaining circuit is connected directly to the mixer of figure 1.b). This concept is not new [1], [4], but it is used in a different circuit configuration, as shown in figure 2.

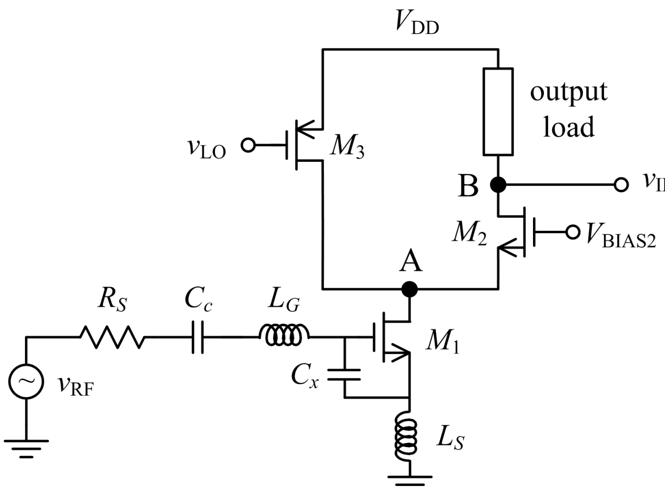

Fig. 2. Merged LNA-mixer (biasing of M_1 not represented).

This new circuit of figure 2, the mixing is performed by NMOS transistor M_2, PMOS transistor M_3, and the load. The use of a PMOS transistor enables the mixing in current, since the PMOS drain current of M_3 depends on the voltage v_{SG} which is controlled by the LO. Consequently, the LNA current from M_1 and the current from transistor M_3 are subtracted. Transistor M_3 also works as a buffer for the oscillator output, isolating the oscillator from the rest of the circuit. This solution is simpler than others in the literature. At the output node B several mixing products are present, but the output load selects the wanted frequency components. The output load can be a low-pass filter or a band-pass filter, according to the value of IF. Both cases are analyzed in the following.

B. LNA-Mixer with RC Load

If the IF frequency is low, it is possible to use a low-pass filter. The simplest circuit consists of a capacitor C_{IF} and a resistor R_{IF}, as represented in figure 3. Only the low frequency mixing product is selected and the remaining mixing products and the two fundamental tones, LO and RF are strongly attenuated [4].

The main advantage of this circuit is its low area, due to the low number of elements and the use of the RC output. The circuit has only two inductors: L_S has typically a low value (few nH) and can be implemented using a bond-wire [7], [9]; L_G has a higher value, requiring an integrated inductor, but its value is usually not very high and its area can be small [10]. Thus, this circuit only uses one integrated inductor. This solution is only suitable for low IF frequencies, otherwise some unwanted mixing products would not be suppressed.

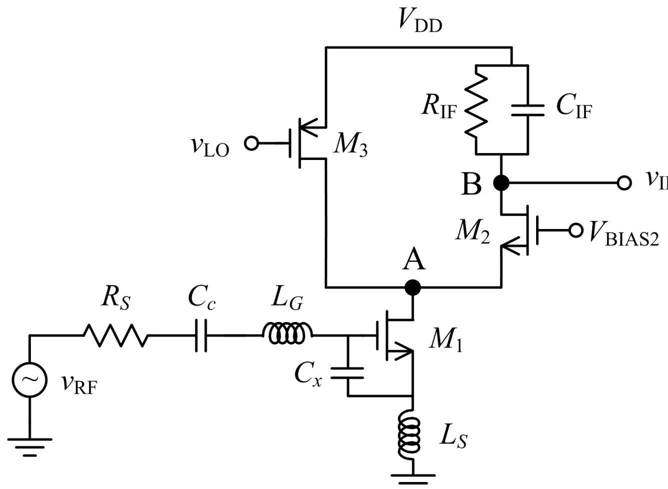

Fig. 3. Merged LNA-mixer with RC filter (biasing of M_1 not represented).

This circuit can have low voltage, and in this case the dimensioning requires special attention. Neglecting the inductor L_S parasitic resistance, the critical path for the voltage swing distribution is the cascade consisting of resistor R_{IF} and transistors M_2 and M_1.

$$V_{DD} \cong V_{R_{IF}} + V_{DS2} + V_{DS1} \tag{1}$$

The circuit must have a bias point that accounts for the maximum voltage swings at each node. The DC voltage at the source of M_1 is approximately zero and this node has a small voltage swing, that will be neglected. The drain of M_1 has a minimum voltage V_{DS1sat} plus a small margin, V_M:

$$V_{D1\min} = V_{DS1sat} + V_M \tag{2}$$

The DC voltage at node A should be approximately its minimum voltage, $V_{D1\min}$, plus the voltage swing, $V_{S\text{A}}$:

$$V_{\text{A}} = V_{D1,\min} + V_{S\text{A}} \tag{3}$$

The drain voltage of M_2 (node B) is V_{A} plus V_{DS2sat} and the voltage swing at that node, $V_{S\text{B}}$, with a margin V_M added,

$$V_{\text{B}} = V_{\text{A}} + V_{DS2sat} + V_{S\text{B}} + V_M \tag{4}$$

Figure 4 illustrates the description above. The low-pass filter (R_{IF}, C_{IF}) reduces the large interferes, which decreases the voltage swing at that node. This voltage swing together with the expected DC current through R_{IF} determines the resistor value.

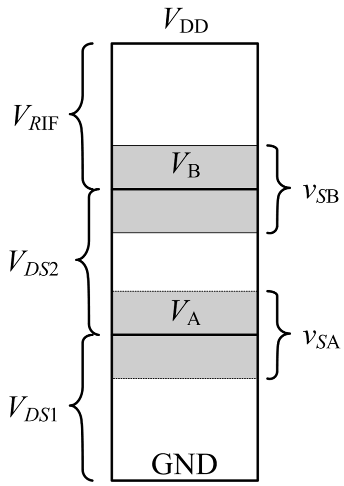

Fig. 4. DC voltage distributions throughout the critical voltage path.

C. LNA-Mixer Circuit with LC Load

If the IF value is high, and mixing products fall at lower frequencies than IF, and it is necessary to use a band-pass filter. The RC filter is replaced by an LC filter, as shown in figure 5.

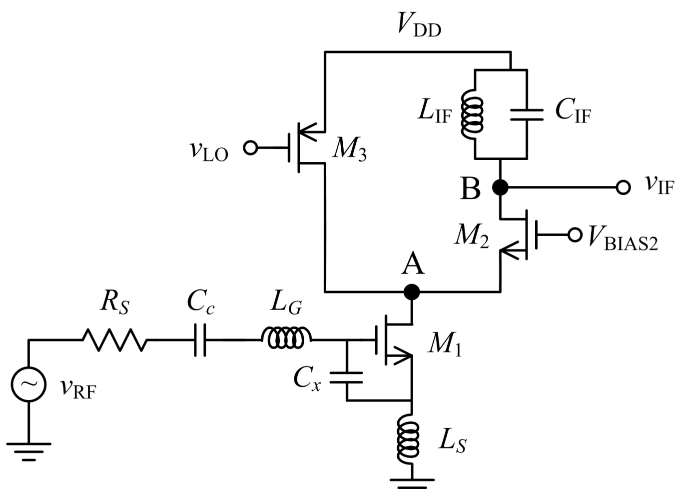

Fig. 5. Merged LNA-mixer with LC filter (biasing of M_1 not represented).

In comparison with the circuit of figure 3, the circuit in figure 5 has the advantage of a wider voltage swing, since the LC tank allows the voltage at the output node to go above V_{DD}. However, there is the disadvantage that the area is higher due to the use of an additional integrated inductor; in addition to the area occupied by L_{IF}, there is also the need to guarantee a suitable distance to the other inductors to ensure negligible magnetic coupling.

III. Circuit Design

To demonstrate the functionality of the proposed circuits, prototypes were designed in UMC 0.13 μm CMOS technology, for a voltage supply of 1.2 V.

A. LNA-Mixer with RC Load

The RC load circuit was dimensioned for an IF frequency of 50 MHz. The RF frequency is 2.4 GHz and the LO frequency is 2.35 GHz.

The R_{IF} value should be high enough to increase the mixer conversion gain, and the resistor feasibility. On the other hand, it should be low to minimize the voltage drop. A value of 100 Ω and a voltage drop of 500 mV are a good compromise (this means 5 mA of current through the resistor). The voltage drop remaining for transistors M_1 and M_2 is approximately 700 mV. Since M_2 has a larger voltage swing than M_1, it must have a larger V_{DS}. Finally, the DC current at the PMOS transistor should be higher than the AC current amplitude, to keep M_3 in saturation; a DC current of approximately 1 mA was used.

For an RC filter cut-off frequency of about 300 MHz, the capacitor should have about 5 pF. This value is feasible in most integrated technologies, and leads to a reasonable footprint area. The circuit was simulated with an RF signal amplitude of -35 dBm and an LO signal amplitude of 300 mV.

B. LNA-Mixer with LC Load

The LNA-Mixer with LC load was designed for the same specifications of the RC circuit, but the LO frequency is 2.0 GHz, which means that the IF frequency is now 400 MHz. A inductor of 16 nH and a capacitor of 5 pF are required. The sizing philosophy for the rest of the circuit is the same as above, but the V_{DS} values of M_1 and M_2 are more relaxed.

IV. Simulation Results

Figure 6 shows the power spectral density of the LNA-mixer with RC load. The IF frequency is clearly visible at 50 MHz. In table I some performance values are listed.

TABLE I
Performance of the LNA-mixer with RC load.

Parameter	Symbol	Value
Noise Figure	NF	16.5 dB @ 50 MHz
Compression Point at 1 dB	$P_{-1\ \mathrm{dB}}$	-18.6 dBm
Intermodulation Intercept Point	IIP_3	-10.3 dBm
Conversion Gain	CV	-3.3 dB
LNA Noise Figure	NF_{LNA}	1.4 dB @ 2.4 GHz
Input Impedance Matching	S_{11}	-27.7 dB @ 2.4 GHz
Current Consumption	I_{DD}	(6.3 mA @ 1.2 V)
Estimated Area	-	$\approx$ 0.06 mm^2

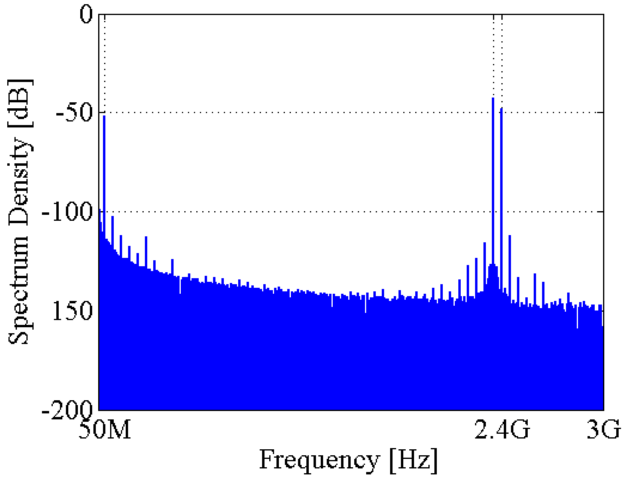

Fig. 6. Power spectral density of the LNA-mixer with RC load.

Figure 7 shows the power spectral density of the LNA-mixer with LC load, and in table II some performance values are listed.

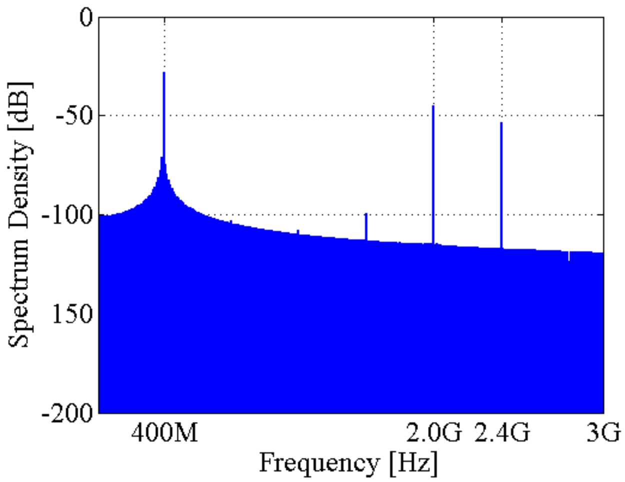

Fig. 7. Power spectral density of the LNA-mixer with LC load.

TABLE II
PERFORMANCE OF THE LNA-MIXER WITH LC LOAD.

Parameter	Symbol	Value
Noise Figure	NF	11.5 dB @ 400 MHz
Compression Point at 1 dB	$P_{-1\text{ dB}}$	-23.6 dBm
Intermodulation Intercept Point	IIP_3	-16.5 dBm
Conversion Gain	CV	-2.5 dB
LNA Noise Figure	NF_{LNA}	1.4 dB @ 2.4 GHz
Input Impedance Matching	S_{11}	-27.7 dB @ 2.4 GHz
Current Consumption	I_{DD}	(6.3 mA @ 1.2 V)
Estimated Area	-	≈ 0.16 mm^2

Even without the layouts, a reasonable estimate of the die areas can be made. The elements that occupy more area are the inductors and capacitors. Using the UMC 0.13 μm CMOS technology, inductor L_G has an area of 120 μm $\times$ 120 μm, while capacitor C_{IF} has an area of 100 μm $\times$ 100 μm. Thus, we expect that the total area of the LNA-mixer with resistive load is approximately 300 μm $\times$ 200 μm (excluding pads). Inductor L_{IF} has an area of 150 μm $\times$ 150 μm (this is a large inductor due to the IF frequency value), and extra space between inductors is required to avoid magnetic coupling; thus the estimated total area of the LNA-mixer with LC load is of 400 μm $\times$ 400 μm (excluding pads).

The results in tables I and II are comparable to those obtainable with the conventional approach using separate LNA and mixer, but there is an advantage of the proposed circuits in terms of power consumption. Comparing both circuits, we note that the great advantage of the LNA-mixer with resistive load is its low area. The counterpart is a degradation in the cascade noise figure due to the load resistor. The remaining parameters are not significantly different.

V. CONCLUSION

In this paper two versions of a combined LNA-mixer for ISM band are presented, for different IF values. The first circuit uses a low-pass filter at the mixer output and is suitable for low IF frequencies, and has low die area. The second circuit for medium IF frequency, uses an LC band pass filter; the die area is higher, but the cascade noise figure is improved. Both circuits are competitive, mainly in power consumption, when compared with the conventional approach using separate LNA and mixer. One possible drawback is an LO leakage to the RF input due to the short path between the LO and RF nodes.

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