Combined LNA and Mixer Circuits for 2.4 GHz ISM Band

Miguel A. Martins(1), Luis B. Oliveira(2) and Jorge R. Fernandes(1)
(1) INESC-ID/TU Lisbon; Rua Alves Redol, 9; Lisboa, Portugal; {miguel.martins; jorge.fernandes;}@inesc-id.pt
(2) INESC-ID/Universidade Nova de Lisboa; Monte da Caparica; Caparica, Portugal; luis.b.oliveira@inesc-id.pt

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 $\mu$m 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.](image)

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 $\Omega$ 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.

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.

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 $M_1$.

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

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, $V_M$:

$$V_{D1_{min}} = V_{DS1sat} + V_M$$

The DC voltage at node $A$ should be approximately its minimum voltage, $V_{D1_{min}}$, plus the voltage swing, $V_{SA}$:

$$V_A = V_{D1_{min}} + V_{SA}$$

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

$$V_B = V_A + V_{DS2sat} + V_{SB} + V_M$$

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.
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>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Figure</td>
<td>$NF$</td>
<td>16.5 dB @ 50 MHz</td>
</tr>
<tr>
<td>Compression Point at 1 dB</td>
<td>$P_{1dB}$</td>
<td>-18.6 dBm</td>
</tr>
<tr>
<td>Intermodulation Intercept Point</td>
<td>$IIP_3$</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td>Conversion Gain</td>
<td>$CV$</td>
<td>-3.3 dB</td>
</tr>
<tr>
<td>LNA Noise Figure</td>
<td>$NFLNA$</td>
<td>1.4 dB @ 2.4 GHz</td>
</tr>
<tr>
<td>Input Impedance Matching</td>
<td>$S_{11}$</td>
<td>-27.7 dB @ 2.4 GHz</td>
</tr>
<tr>
<td>Current Consumption</td>
<td>$I_{DD}$</td>
<td>(6.3 mA @ 1.2 V)</td>
</tr>
<tr>
<td>Estimated Area</td>
<td>-</td>
<td>$≈ 0.06 \text{mm}^2$</td>
</tr>
</tbody>
</table>
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 × 120 μm, while capacitor $C_{IF}$ has an area of 100 μm × 100 μm. Thus, we expect that the total area of the LNA-mixer with resistive load is approximately 300 μm × 200 μm (excluding pads). Inductor $L_{IF}$ has an area of 150 μm × 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 × 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.

REFERENCES