A High Dynamic Range Multi-Standard CMOS Mixer for GSM, UMTS and IEEE802.11b-g-a Applications

Mohammad B. Vahidfar, Omid Shoaei*, Francesco Svelto
Università di Pavia, 27100 Pavia, Italy
* University of Tehran, Tehran, Iran

Abstract — Software defined radios are a topic of intense research and constitute one key industry need for future generation wireless products. In this paper, we investigate the down-conversion mixer, a particularly challenging block, due to the stringent dynamic range requirements set by cell-phone applications and the wide operation bandwidth. The proposed mixer is based on a Gilbert cell and operates between 900MHz and 6GHz. The parasitic capacitor of the switching pair, main responsible for the limited dynamic range, is tuned out by means of a spiral inductor at 900MHz, a transformer based programmable inductor between 1.7GHz and 2.4GHz, and a small spiral in the 5GHz-6GHz range. Prototypes have been integrated in a 65nm CMOS technology and are operated from a 1.2V supply. Minimum IIP2 and maximum average noise are 65dBm and 5.4nV/sqrt(Hz) in DCS. The mixer current consumption is 7.5mA.

Index Terms— Software defined radio, mixer, CMOS, multi-standard, dynamic range, reconfigurable passive components, highly integrated devices

I. INTRODUCTION

An effort toward the realization of universal radios, i.e. radios able to tune to carrier frequency over a wide RF range and supporting high data rate modulations is underway [1-3]. Hardware sharing between different applications and programmability are key to save silicon costs. Direct conversion and low-IF architectures lend themselves to a compact solution, with minimum number of external components and a simpler reconfigurable base-band. On the other hand, the dynamic range requirements set by cell-phones in particular make the RF radio front-end extremely challenging. In fact techniques lowering noise and second order inter-modulation distortion leverage the narrow-band nature of the signal in radios addressing single or few applications [4-7]. On the contrary, a compact implementation for the universal radio is motivating research and study of wide band topologies, LNA using noise cancelling techniques and passive mixers in particular [1-2].

In this paper, we focus the attention on the down-conversion mixer, the major responsible for the limited dynamic range in the RF front-end, investigating a reconfigurable narrow-band Gilbert type solution. The mixer operates in the 900MHz – 6GHz range, and takes advantage of the different requirements set by the different standards, minimizing the number of passive components. In particular, the circuit employs a programmable inductor to address DCS/PCS/UMTS, IEEE802.11b-g, a single stand-alone spiral for GSM, and a small tuning inductor (100um x 100um) for IEEE802.11a, where both 1/f noise and IIP2 are relatively relaxed. Prototypes, realized in 65nm CMOS, show the mixer meets the requirements set by each standard [3]. With respect to a passive mixer, the proposed solution consumes more area, but performance degradation with respect to multiple narrow-band mixers is almost negligible.

The paper is organized as follows. Section IIA introduces the transformer based programmable inductor, section IIB presents the design of the multi-standard active mixer, based on the Gilbert cell, section III presents the experimental results while section IV draws conclusions.

II. HIGH DYNAMIC RANGE MULTI-STANDARD ACTIVE MIXER

A conventional Gilbert cell shows a limited dynamic range when direct down-converting an RF signal to DC or close to DC. The major reason is the limited bandwidth of the switching core. In particular, the parasitic capacitor, loading the pair source, is charged and discharged during each LO period. Noise components and low frequency inter-modulation tones modulate the charging and discharging capacitor current, being finally down-converted around DC at mixer output. Detailed analysis of these mechanisms is found in the literature [4-5]. A very effective counter-measure consists in tuning out the parasitic capacitor by means of an inductor. The node impedance raises by Q, the inductor quality factor, and by the same amount increases the IIP2 of the switching core.
A significant improvement both in $1/f$ and white noise comes along.

Because this technique is intrinsically narrow-band, it does not directly lend itself to address a universal radio, where the number of area hungry inductors would equal the number of standards to be tuned. The idea, proposed here, is to exploit the properties of a transformer in order to realize a programmable inductor. Covering a band as wide as 900MHz to 6GHz would require an inductance change by ~16, which is not feasible. The strategy is then employing the programmable inductor in the 1.7GHz to 2.4GHz, the spectrum portion most crowded of wireless standards, while using dedicated inductors at 900MHz and between 5GHz to 6GHz for wireless LANs.

A. Programmable inductor

The secondary winding of the transformer, shown in Fig. 1, is loaded by a capacitor to realize the programmable inductor. In fact, capacitor $C_2$ forces $V_2$ and $i_2$ to be orthogonal and, as a consequence, $i_1$ and $i_2$ in-phase [8].

By inspection of the circuit, the impedance seen at the input terminal is inductive and the effective inductance ($L_e$) is given by:

$$L_e(\omega) = L_1 + \frac{i_2}{i_1}M = L_1 + \frac{L_2C_2\omega^2}{1 - L_2C_2\omega^2}k^2L_1$$

(4)

$L_1$, $L_2$ and $M$ are the inductances of the primary winding, secondary winding and the mutual inductance, respectively. $k$ is the magnetic coupling coefficient

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}}$$

(5)

Equation (4) holds provided $\omega$ is lower than the secondary self-resonance frequency.

Fig. 1. Simplified model of the programmable inductor.

Varying capacitance $C_2$ varies the ratio $i_2 / i_1$ and ultimately the effective inductance.

Fig. 2 plots, as an example, $L_e$ versus $C_2$ for $L_1=4.3nH$, $L_2=2.1nH$ and $\omega=2GHz$. The inductance variation can be rather large because of the steep increase around $L_2C_2$ resonance frequency. But, once we take account of ohmic losses associated with the windings, e.g. series resistors for a first order model, we conclude as shown in the graph that the equivalent quality factor $Q_e$ degrades with increasing $C_2$, setting an upper value.

Fig. 2. Equivalent inductance ($L_e$) and quality factor ($Q_e$), seen at the transformer primary, versus capacitance $C_2$.

The programmable inductor is intended to tune out switch pair parasitic capacitors in order to increase the pair loading impedance with benefit to low-frequency noise and second order inter-modulation distortion. The actual inductance useful range is thus limited by parasitics and, foremost, by the quality factor of the transformer in the band. To gain insight we have simulated the differential transformer of Fig. 1, including accurate spiral inductors model, assuming a 0.6pF switching pair capacitance to be tuned out. Fig. 3 shows the impedance of the programmable inductor versus frequency.

Fig. 3. Impedance of the LC network tuning out switch pair capacitance: a) the programmable inductor implements $L$, b) a spiral fixed inductor implements $L$.

As an alternative, a standard inductor might be considered to tune out the parasitic in the same band. For the sake of comparison, the impedance of the standard LC, tuning out the same capacitance at 2.1GHz, has been simulated and plotted in the same figure. As it is expected the latter impedance quickly falls over frequency (roughly 12dB at $f=1.8GHz$).
B. Proposed implementation

The core of the resonant network, employed to tune out switched pair parasitics, is reported in the dashed box of Fig. 4, where the complete mixer is detailed. Inductors L1 and L3 are used in GSM and IEEE 802.11a bands, respectively. L3 is a compact, small inductor with relatively low Q, used primarily to reduce switch white noise and minimize gain reduction. L1 is series connected to the transformer primary and its Q is of primary concern. Moreover switch Sw2 is critical because its on resistance degrades the programmable inductor Q. The switches are sized as 160µm/60nm, the best compromise between low on-resistance and off-paracitic capacitance.

A nMOS varactor, with minimum and maximum capacitance of 0.2pF and 1.1pF respectively, is employed to control the programmable inductance. The programmable inductor, optimized by means of the Electromagnetic simulator ADS-Momentum, is made of a differential transformer with \( L_{21} = 2 \times 4.3\text{nH} \), \( L_{22} = 2 \times 2.1\text{nH} \) and \( k = 0.75 \). Inductors L1 and L3 are 16nH and 1nH, respectively.

The input transconductor, made of pMOS devices to allow a folded topology stacked within 1.2V, uses an RC degenerated stage to reduce common mode second order components [6,9].

The load is made of pMOS transistors (MD) with long channels, shunted by resistors RL, in order to maximize mixer gain for given voltage room.

Considering the different requirements set by different standards, e.g. higher gain in UMTS, lower flicker noise in GSM, different output bandwidths, several features tailored to the specific application have been implemented. The mixer is biased by transistor MB1, connected to the centre tap of the differential inductors L3 and L1 and is bypassed by Cb capacitor, at RF. Notice that MB1 does not contribute to mixer NF because its thermal and flicker noises are common mode noise and consequently rejected at differential output.

III. EXPERIMENTAL RESULTS

The proposed mixer has been integrated in a standard 65 nm CMOS technology from STMicroelectronics. The chip is encapsulated in a TQFP48 plastic package and soldered on a dedicated double-sided RF board with \( \tan \delta = 0.027 \) and \( \varepsilon_r = 3.38 \).

External 180° hybrid couplers (BD0810 for GSM, 3W525 for 1.8-2.4GHz band and BD4859 for IEEE802.11a mode, all from Anaren) were used both at the RF and LO ports to implement the single-ended-to-differential conversion. 50 ohms strip lines, optimized by means of EM simulations, carry the differential signals from the SMD connectors to the package inputs. The mixer draws 7.5mA from a 1.2V supply.

Fig. 4. Schematic of the proposed multi-standard mixer

The IIP2 performance was evaluated, injecting a double side-band with suppressed carrier tone according to standard specifications, i.e. at 6MHz from all GSM versions, 130MHz for UMTS, and 20MHz for 802.11. The tones spacing is chosen in a way that the second order intermodulation components stay in-band.

Due to the narrow channel spacing, low frequency noise is particularly critical in GSM. The 1/f noise corner is 110kHz and 140kHz in 900MHz and 1800MHz frequencies, respectively. The input referred noise of
GSM900 is 5nV/sqrt(Hz) when integrated from 100kHz to 200kHz.

Measurement results are summarized in Table I. The die photo is presented in Fig. 5 and the total area including pads is 2.5mm².

Table I. Measurements summary

<table>
<thead>
<tr>
<th>Specification</th>
<th>GSM</th>
<th>DCS/PCS</th>
<th>UMTS</th>
<th>IEEE 802.11b-g</th>
<th>IEEE 802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>STM 65nm CMOS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply (V)</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current consumption (mA)</td>
<td></td>
<td></td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>0.9</td>
<td>1.8,1.9</td>
<td>2.1</td>
<td>2.4</td>
<td>5.15-5.35</td>
</tr>
<tr>
<td>Conversion gain (dB)</td>
<td>12</td>
<td></td>
<td>14</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>IIP2 (dBm)</td>
<td>71</td>
<td>65</td>
<td>65</td>
<td>60</td>
<td>54</td>
</tr>
<tr>
<td>Input ref. noise (nV/sqrt(Hz))</td>
<td>5</td>
<td>5.4</td>
<td>3.8</td>
<td>3.6</td>
<td>4</td>
</tr>
<tr>
<td>IIP3 (dBm)</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

A high dynamic range mixer has been realized in a 65 nm CMOS process to support GSM, DCS, PCS, UMTS and IEEE802.11b-g-a applications. A programmable inductor to tune out switch pair capacitance, thus improving linearity and reducing noise, has been employed in the 1.7GHz to 2.4GHz band. This allows minimizing the number of spirals dedicated to each single standard, while still meeting specifications. The proposed implementation goes in the direction of fully integrated zero/low-IF architectures for wireless universal radios.

ACKNOWLEDGEMENT

This work has been partially supported by “Studio di Microelettronica”, a research laboratory joint between Università di Pavia and ST Microelectronics, and partially by Istituto Universitario Studi Superiori (IUS). The chip has been fabricated by STMicroelectronics.

REFERENCES