A Low Flicker-Noise High Conversion Gain RF-CMOS Mixer with Differential Active Inductor

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Abstract -- The design of a low noise figure (NF), high conversion gain (CG) double-balanced, Gilbert-cell mixer is presented. Since the noise figure of the RF CMOS mixer is strongly affected by flicker noise ($1/f$), a dynamic current injection technique is used to reduce the flicker noise corner frequency. The current injection circuitry comprises 3 pMOS to inject current pulses at the switching instants. Differential active inductor (DAI) is employed to tune the tail capacitance at the node between the LO switches and the RF transconductance stages. Thus it reduces the RF leakage through this parasitic capacitance. The mixer is designed using TSMC 0.18 µm CMOS process. Simulations had been performed by Cadence Spectre® simulator. The proposed mixer has a conversion gain of 20dB, a 1-dB compression point of -19.3dBm, while the IIP3 is at -6.55dBm, with -30dBm RF input power. Single side band (SSB) noise figure is 13dB (@ 1MHz) with flicker noise corner frequency of 30KHz.

Index Terms -- CMOS, Gilbert-type mixer, direct conversion receiver, flicker-noise, differential active inductor.

I. INTRODUCTION

The growing demand for efficient wireless communication systems in the recent years has resulted in intensive efforts to develop single chip transceivers to minimize cost, power dissipation, and chip size. Direct conversion receiver (DCR) is one of the best candidates for low complexity, low power, and low cost single chip integration [1]. Unfortunately, all of these advantages come with the fact that the CMOS transistors suffer from a very high intrinsic flicker noise [2]-[4]. CMOS transistors exhibit significantly more flicker-noise than do the bipolar devices, this flicker-noise is inversely proportional to the device area [3]-[4]. Linear RF circuits don’t affected by the flicker noise, such as low noise amplifiers (LNA), since its operating frequency is much higher than the flicker noise corner frequency [4], but in the mixers, the case is different, because the flicker noise lies in the output band of the mixer, specially, low-IF and Zero-IF mixers. Many designs have been proposed to reduce the output flicker noise of the mixer. Static current injection has been proposed in [5], dynamic current injection proposed in [6], and the same design in [6] has been used by J. Yoon et al [7], but a shunt tuning inductor has been added in order to reduce the effect of tail capacitance ($C_p$) at the node between the LO switches and RF transconductance stage. This design in [7] gives a good results but it sacrifices the chip size by using a bulky spiral inductor.

In this paper, we have proposed a mixer circuit using pMOS switches as current injecting circuit, and a differential active inductor has been employed to tune the tail capacitance, as a result, the flicker noise reduction occurred, at the same time we keep the chip size as small as the conventional mixer circuit, this is because a differential active inductor (DAI) is comprises small sized MOSFETs, its size is negligible compared to the spiral inductor. Simulation results verified that this design has good performances compared to other designs.

II. FLICKER-NOISE MECHANISMS IN GILBERT-CELL MIXER

Flicker-noise is one the critical issues in the direct conversion mixers. There are two major mechanisms that generate the flicker noise of the switching pair devices. The first one is the direct mechanism, due to the finite slope of the switching pair transitions. In order to decrease flicker noise in the direct mechanism, the size of the switching pairs needs to be increased, and large switching devices increase the parasitic capacitance of the switching pairs, resulting in the flicker noise indirectly translating to the output. The second mechanism that generates flicker-noise is the indirect mechanism, flicker-noise mainly depends on the tail capacitance ($C_p$) at the node between the LO switches and RF transconductance stage [2]. In order to decrease the flicker-noise in CMOS active mixers, the bias current of the local oscillator (LO) switches should be small enough to lower the height of the noise pulses. The static current injection technique was proposed to reduce the bias current of the LO switches [5]. However, the impedance of the LO switches as seen from the RF stage is increased as we reduce the bias current of the LO switches. In addition, RF leakage current flows through the injection circuit, which decreases conversion gain and also allows more RF current to be shunted by the tail capacitance ($C_p$) at the node between the LO switches and RF transconductance stage.

The tail capacitance should be minimized to decrease the indirectly translated flicker noise [2]. To minimize the tail capacitance, a smaller device size is appropriate for the LO switches, which increases the intrinsic flicker noises. The dynamic current injection technique has also been proposed in [6]-[7] to improve the flicker-noise performance. It injects a dynamic current totally equal to the bias current of the LO switches at only the LO switching event [4].
III. PROPOSED GILBERT-CELL MIXER

In order to reduce direct and indirect flicker-noise generation, as shown in Fig.1, dynamic current injection technique using three pMOS switches already proposed in [6], these pMOS switches, M7-M9, inject a dynamic current equal to the bias current of each pair of switches at only the switching event. $V_{bl}$ is used to control the height of the injected current pulses.

![Fig.1. Proposed Gilbert-cell mixer with dynamic current injection and differential active inductor.](image)

A parallel tuning inductor have been employed to tune out the parasitic tail capacitances ($C_p$) [7], as shown in Fig.1, also, series inductor can used as in [2]. In the proposed design, the spiral inductor is replaced by a DAI, which consumes small chip area and many other benefits will discussed in the next section. DAI is connected to the mixer through two coupling capacitors to prevent the mixer and the DAI bias point deviation from the desired point.

IV. DIFFERENTIAL ACTIVE INDUCTOR (DAI)

Active inductor is now becoming a highly attractive choice for CMOS wireless communication systems. Its interesting and unique advantages over spiral inductors include, occupying smaller die area, high quality factor (Q), and tunable inductance, and the possibility of achieving higher inductance with high resonance frequency [8].

The schematic of the active inductor proposed by Lu et al. is shown in Fig.2. It is a differentially configured gyrator-C active inductor [9]-[10] in a simplest geometry, so the same structure is chooses in this paper. Transistors M14 and M15 are biased in the triode region and behave as a voltage-controlled resistors whose resistances are controlled by the gate voltage $V_{b2}$. All other transistors are biased in the saturation. From the small-signal equivalent circuit shown in [9], the input impedance at the differential port can be expressed as:

$$Z_{in} = \frac{2j\omega(C_{gs10}+C_{gs12})-g_{m10}+g_{dr14}}{g_{dr14}[g_{m10}+g_{m12}+j\omega(C_{gs10}+C_{gs12})]}.$$  \hspace{1cm} (1)

![Fig.2. Differential active inductor and its equivalent circuit.](image)

The parameters of the RLC equivalent circuit of the active inductor are given by:

$$L = \frac{2(C_{gs10}+C_{gs12})}{g_{dr14}[2g_{m10}+g_{m12}-g_{dr14}]}.$$  \hspace{1cm} (2)

$$R_s = \frac{2(g_{ds14}-g_{m10})}{g_{dr14}(2g_{m10}+g_{m12}-g_{dr14})}.$$  \hspace{1cm} (3)

$$R_p = \frac{2}{g_{ds14}}.$$  \hspace{1cm} (4)

where $g_{ds14}$ is the channel conductance of M14, which is equal to the channel conductance of M15. Note that $2g_{m10}+g_{m12} > g_{dr14}$ and $g_{dr14} > g_{m10}$ are required in order for $R_s$ and $L$ to have a positive value. The inductance of the active inductor can be tuned by varying $V_{b2}$ [9].

V. SIMULATION RESULTS

The proposed mixer in Fig.2 is designed by TSMC 0.18um 1P6M technology, and simulated by Cadence Spectre®. The input RF and LO frequencies are 2.41GHz and 2.4GHz, respectively, to obtain 10MHz IF frequency. The DAI equivalent inductance plotted versus frequency is shown in Fig.3, the equivalent inductance about 6.4nH is obtained at 2.4GHz, this value in optimized to tune the tail capacitance, which can be noticed by the reduction of the NF.

![Fig.3. Equivalent inductance versus frequency.](image)

Fig.4 shows the noise figure simulation results for three configurations of Gilbert mixer, one is the conventional mixer, second is the Gilbert-cell with dynamic current injection and spiral tuning inductor, and third is the proposed Gilbert mixer with dynamic current injection and DAI as a tuning inductor.
According to Fig.4, the SSB NF of the proposed mixer is about 13dB @ 1MHz, which is 4.5dB lower than the conventional mixer, also it is close to the NF on the mixer with spiral inductor, less than 1dB difference. Spiral inductor in this circuit has a 5.5 turns with 30um inner radius, which means a large chip area compared with the DAI. The proposed mixer has a 30 kHz flicker noise corner frequency, which is better than the conventional mixer that has a corner frequency around 1MHz.

Table I shows a comparison between the proposed mixer with Ref. [7]. It shows that the proposed mixer using dynamic current injection and DAI has a good performance, specially, with a high conversion gain. Linearity of the proposed mixer is small compared to the Ref. [7], mixer linearity can be improved at the expense of higher power dissipation, but the proposed mixer has approximately 12% increase in chip size as the DAI has been added, whereas the mixer employing a spiral inductor [7] has about 53% larger chip area due to tuning spiral inductor addition. Fig.7 shows a comparison between two layouts of proposed mixer and mixer with tuning spiral inductor. It’s clear how the spiral inductor consumes a large silicon area compared to the DAI circuit.

The conversion gain comparison between the conventional mixer and the proposed one as a function of LO power is shown in Fig.5. When the LO power is about 0dBm, a conversion gain of 20dB is achieved, while the input RF signal is -30dBm. The proposed mixer has an input 1-dB compression point of -19.3dBm, and an input third order intercept point (IIP3) of -6.55dBm as shown in Fig.6. Finally, we should point to that the power consumption of the DAI circuit is 1mW.

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| Technology | 0.13 µm | 0.18 µm |
| RF frequency (GHz) | 2.4 | 2.4 |
| Conversion Gain (dB) | 11.4 | 20 |
| IIP3 (dBm) | 4.4 | 2.4 |
| SSB NF (dB) @ 1MHz | 13.2 | 13 |
| Increase in chip area (due to tuning inductor) | 53% | 12% |

Fig.3. Simulated Inductance of the differential active inductor circuit.

Fig.4. Noise figure comparison of three Gilbert mixer circuits.

Fig.5. Conversion gain vs. LO power of the proposed mixer.
Fig. 6. Third order intercept point (IIP3) of the proposed mixer.

Fig. 7. (a) Layout of the proposed Mixer (b) Layout of Mixer with tuning spiral inductor.

VI. CONCLUSION

A new double-balanced Gilbert cell mixer using dynamic current injection and differential active inductor has been proposed and tested by simulations using Cadence Spectre®. The proposed mixer designed using TSMC 0.18um 1P6M technology. It has an advantage of low flicker noise and small chip area, because both, direct and indirect, flicker noise sources have been minimized. The mixer has a 13dB NF @ 1MHz. The mixer gives 20dB conversion gain with 0dBm LO power, also, it has a 1-dB compression point of -19.3dBm, and IIP3 of -6.55dBm. The mixer operates under 1.8v supply voltage.

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