A study of zero-if double-balanced mixer for WiMAX receivers

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ABSTRACT

Differential approach is becoming highly preferred in radio frequency integrated circuit (RFIC) design due to its advantages, particularly its high immunity to common-mode noises, satisfactory rejection of parasitic coupling, and increased dynamic range. One particular RF front-end building block that is often designed as differential circuit is the mixer. This paper presents a study and design of a differential mixer, particularly the double-balanced mixer implemented on a zero-IF (zero-intermediate frequency) or direct-conversion architecture in a standard 90 nm complementary metal-oxide semiconductor (CMOS) process operating at frequency of 5 GHz, which is a typical frequency for worldwide interoperability for microwave access (WiMAX) receiver. Impedance matching was necessary to fully optimize the mixer design. The zero-IF double-balanced mixer design achieved conversion gain of 11.46 dB and noise figure of 16.53 dB, comparable to other mixer designs.

1. Introduction

Receiver front-end of a radio frequency (RF) system is of particular interest to many integrated circuit (IC) designers and researchers as it proves to be the most critical part in many communication systems and wireless applications such as wireless fidelity (WiFi), Bluetooth, long-term evolution (LTE), and worldwide interoperability for microwave access (WiMAX). The block diagram of a typical receiver is shown in Fig. 1.

Mixer is one of the key front-end building blocks in an RF receiver. It is also called a converter because it converts RF signals into a lower intermediate frequency (IF) by mixing with an offset local oscillator (LO). Depending on the receiver requirements, mixers must undergo a careful design process since a lot of tradeoffs among different performance parameters must be considered and understood. Ultimately, the objective is to study and design a zero-IF double-balanced mixer implemented in a standard 90 nm complementary metal-oxide semiconductor (CMOS) process. Operating frequency is set to 5 GHz, which is a typical frequency for a WiMAX receiver.

2. Background

RF receivers can be categorized as superheterodyne (high-IF), low-IF, and zero-IF or homodyne or direct-conversion based on the resulting IF signal they operate. For the zero-IF receiver, IF is designed to be centered at frequency zero, meaning the LO frequency is equal to the input RF frequency. Image signal is avoided and the analog filtering problem can be easily handled. With zero IF, the desired signal is translated directly to the baseband, allowing analog-to-digital converter (ADC) and digital signal processing (DSP) circuits to perform modulation and other ancillary functions [1, 2]. This eliminates the need for highly complex filters since channel selection only requires a low-pass filter (LPF) as shown in Fig. 2 with sharp cutoff characteristics, and thus allowing the possibility of monolithic integration. With this, smaller and cheaper receivers with low power consumption may be realized for various wireless applications like Bluetooth, WiFi, and WiMAX. Many of the implemented receivers in WiMAX [3, 4, 5] use the zero-IF architecture since the LPFs make sure that the closely-spaced carrier signals do not cause interference with each other.

Designing a mixer must take into account the many trade-offs among the performance parameters. Thus, a careful study of these important parameters must be done in order to design fully-functional mixers. A mixer's efficiency on frequency conversion from RF to IF is characterized by conversion loss or gain. It is the ratio of the desired IF output to the value of the RF input. Conversion gain (CG) may be expressed in voltage or power. In cases when the conversion gain is less than unity or 0 dB, it is aptly termed as a conversion loss.

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Conversion gain is preferred over conversion loss because of the benefit of amplification along with frequency translation. However, it should be noted that conversion gain directly affects the noise figure and linearity of the overall receiver. Hence, design tradeoffs concerning these parameters are inevitable.

Another important mixer parameter is the noise figure (NF). It is a measure of the amount of signal-to-noise-ratio (SNR) degradation introduced by the mixer as seen at the output. Eq. (3) shows the relation between the SNR at the input port and the SNR at the output port of the mixer, often expressed in dB.

\[
NF = 10 \log \left( \frac{SNR_{IN}}{SNR_{OUT}} \right)
\]  

Noise figures of mixers tend to be higher than amplifiers (e.g. low-noise amplifiers, power amplifiers) because of the contribution of noise from other frequencies (apart from input RF signal) that can mix down to the IF. This considerable noise in mixers is the main reason why low-noise amplifiers (LNA) are used in the front-end of a receiver [6].

The selection of mixer architecture depends on the application and the requirements for the different design parameters. The dynamic range of most RF receivers is often limited by the first down-conversion mixer. This leads to many tradeoffs among the performance parameters such as conversion gain, noise figure, linearity and isolation. Integrated mixers are preferred over their discrete counterparts because they can offer high level integration with cost, area, and power savings [7].

Nowadays, the most popular solution for the mixer is based on the double-balanced topology. It operates with differential LO and RF inputs. In this topology, LO products are prevented from getting to the output by combining two single-balanced mixers. As shown in Fig. 3, the two single-balanced mixers are connected in anti-parallel as far as the LO is concerned, but in parallel for the RF signal. Thus, the LO terms sum to zero in the output, whereas the converted RF signal is doubled in the output [6]. This is most desirable for high port-to-port isolation and spurious output rejection applications.

As earlier mentioned, the goal of the paper is to study and design a zero-IF double-balanced mixer implemented in a standard 90 nm CMOS process, operating at frequency of 5 GHz which is a typical frequency for a WiMAX receiver. The target specifications of the figures of merit or the critical parameters are based on the performance comparison in terms of conversion gain and noise figure of past researches on direct-conversion.
active mixer topologies given in Table 1.

3. Methodology

The topology of double-balanced mixer can provide high conversion gain, very low noise figure, and high degree of LO-IF isolation. The main disadvantage of this topology is its physical implementation. A balun transformer is required to convert the single-ended input to a differential RF input signal of the mixer. Transformers with very low insertion loss are difficult to realize in monolithic integration, hence this forces the use of an off-chip transformer which occupies more board space and cost [11].

It is of high importance to determine the proper biasing and sizing of all the transistors such that RF transistors (M1-M2) will operate in the saturation region while the LO transistors (M3-M6) operate near the boundary of the saturation and linear regions. The mixer design used nmos (NMOS standard Vi) which is the typical model for the transistor. Shown in Fig. 4 is the schematic design of the double-balanced mixer.

One way to increase the performance of the mixer in terms of conversion gain and noise figure is to apply impedance matching in the circuit. \( Z_{11} \) and \( Z_{22} \) can be obtained using s-analysis (s-parameter analysis) which is swept from \( f_1 = 700 \text{ MHz} \) to \( f_2 = 6 \text{ GHz} \). Actual inductor and capacitor values at frequency of 5 GHz can be computed from the L-network reactances.

To supply differential LO input to the mixer, a port PORT2 with a matching resistor (set to 50Ω) is used which is then fed into an ideal passive balun to convert the single-ended signal into differential. For the differential RF input of the mixer, same setup as the LO is used with PORT1. To use the differential output for measurements, matching the IF output port PORT3 to the output impedance of the mixer is necessary. PORT1 is set to DC source type with \( f_{LO} \) = 5 GHz and \( P_{LO} \) = 0 dBm.

For the impedance matching, the input matching network is applied before the differential RF input of the mixer instead of placing it before the balun. This will result to an adjustment on the value of \( L_1 \), which will decrease, since the balun circuit has self-inductance. The adjusted value of \( L_1 \) can be determined using the \( sp \)-analysis swept from \( f_1 = 700 \text{ MHz} \) to \( f_2 = 6 \text{ GHz} \). Moreover, inductors with small inductances are more realizable in actual designs than their larger counterparts. The final values of the L-networking are summarized in Table 2.

Software design tools ASITIC (analysis and simulation of spiral inductors and transformers for ICs) [12, 13] and SpiralCalc (integrated spiral inductor calculator) [14, 15] are used for the design of the inductors. Table 3 shows the design parameters obtained for the design of the spiral inductors using ASITIC while Table 4 shows that of using SpiralCalc.

In ASITIC, the spiral inductors are designed such that desired inductances are achieved and the Q-factors are optimized with eddy-current option enabled to include the effects of substrate induced eddy current losses. \( L_1 \) have smaller Q-factor than \( L_2 \) because of its high inductance value. For the inductor design using SpiralCalc, same parameter values from the ASITIC parameters are used except for the metal width and the number of turns of the spiral inductor. These parameters are tweaked such that the desired inductances are achieved for the inductors.

The n2port from the analogLib library is used as a model block for all the ASITIC inductors. Touchstone format of S-parameter file is used as file input of the n2port component since the actual S-parameters using ASITIC are given in touchstone format. The figures of merit such as

| Paper | RF (GHz) | Conversion Gain (dB) | Noise Figure (dB) | Topology         |
|-------|----------|----------------------|-------------------|------------------|
| [4]   | 2–11     | 21.5–22.8            | 21.5–25.8         | Double-balanced  |
| [5]   | 3.4–3.85 | 10                   | 10                | Single-balanced  |
| [8]   | 2        | 19.5                 | 10.2              | BiCMOS Double-balanced |
| [9]   | 20–40    | 16                   | –                 | BiCMOS Single-balanced |
| [10]  | 5.2      | 9.3                  | 10.5              | Double-balanced  |

| Parameters       | Inductors |
|------------------|-----------|
| Desired L        | \( L_1 \) | \( L_2 \) |
| No. of sides     | 4         | 8         |
| Length, D        | 300 μm    | 190 μm    |
| Metal width, W   | 10.886 μm | 10.901775 μm |
| Spacing, S       | 1         | 1         |
| No. of turns, N  | 4.25      | 2.5       |
| Metal layer      | 7         | 7         |
| Inductance, L    | 12.711454 nH | 1.328515 nH |
| Q-factor, Q      | 2.32165   | 5.693986  |

| Parameters       | Inductors |
|------------------|-----------|
| Desired L        | \( L_1 \) | \( L_2 \) |
| No. of sides     | 4         | 8         |
| Length, D        | 300 μm    | 190 μm    |
| Metal width, W   | 11.2 μm   | 10 μm     |
| Spacing, S       | 1         | 1         |
| No. of turns, N  | 6         | 2         |
| Inductance, L    | 12.885 μm | 1.326 μm  |
| Current Sheet    | 12.739 μm | 1.326 μm  |
| Monomial Fit     | 12.624 μm | 1.394 μm  |
simulation results for conversion gain and noise performance of the circuit, as indicated in Figs. 8 and 9. It can be observed that adding to the total noise model, the model block n2port introduces noise to the system, hence, it can also be used to determine the noise figure of the circuit. Noise figure from a sweep range of -10 dBm to 30 dBm can now be determined and plotted using these analyses. The plots are shown in Figs. 5, 6, and 7.

Based on the conversion gain simulation results, input and output impedance matching contribute to better conversion gain performance. Moreover, using ideal inductors for impedance matching produced better performance as compared to using non-ideal ASITIC inductors through the n2port. It can be observed from the simulation plots that the conversion gain of the mixer only is higher than the conversion gain of the whole circuit consisting of the mixer and the balun. This is because the balun in the circuit, which is a passive balun, has insertion loss and thus incapable of producing gain. When a passive balun is cascaded with another block, the overall gain is degraded.

For the noise figure, Pnoise (periodic noise) analysis with PSS analysis is used. In addition, PSP (periodic S-parameters) analysis with PSS analysis can also be used to determine the noise figure of the circuit. Noise figure from a sweep range of -10 dBm to 30 dBm can now be determined and plotted using these analyses. The plots are shown in Figs. 8 and 9.

Input and output impedance matching also contribute to better noise performance of the circuit, as indicated in Figs. 8 and 9. It can be observed that using ideal inductors for impedance matching produced lower noise figure as compared to using non-ideal ASITIC inductors through the n2port model. The model block n2port introduces noise to the system, hence, adding to the total noise figure of the circuit. Table 5 shows a summary of simulation results for conversion gain and noise figure at $P_{LO} = 0$ dBm.

It is evident that input and output impedance matching contribute to better performance based on the figures of merit presented for the double-balanced mixer design. It is observed that the conversion gain of the zero-IF double-balanced mixer is higher than the conversion gain of the circuit consisting of the mixer and the balun. The reason is that the conversion gain performance at the system-level perspective is greatly influenced by the performance of the initial or preceding blocks, for this case the passive balun. Henceforth, it is of high importance to consider the contribution of the input or previous circuit (and as well as the output or succeeding circuit) in studying and designing the mixer.

4. Results and discussion

A double-balanced mixer’s frequency converting action is characterized by conversion gain or loss. Voltage conversion gain is the ratio of the RMS voltages of the IF and RF signals. The formulae for conversion gain are also given in Eq. (1). The variations of conversion gain with the power of LO signal ($P_{LO}$) can be measured using swept PSS (periodic steady-state) analysis with PAC (periodic AC) analysis. The PAC analysis will then compute the voltage conversion gain in dB20 of the whole circuit with PORT3 as the output port (with output harmonic of 0, which is 5 GHz) and PORT1 as the input port (with input harmonic of -1, which is 0 GHz). Setting the input port to RF + port, which is located after the balun circuit, will compute the voltage conversion gain of the mixer only. Simulation plots of the conversion gain swept from $P_{LO} = -10$ dBm to $P_{LO} = 30$ dBm are shown in Figs. 5, 6, and 7.

5. Conclusions

A design of zero-IF double-balanced mixer was implemented and optimized on this study. Proper biasing and sizing of all the transistors were necessary to ensure the required mode of operation for all the transistors. Conversion gain and noise figure were determined to measure the mixer’s performance. These performance parameters can be greatly enhanced by applying impedance matching in the circuit. The effect of the passive balun was also presented, showing the decrease in the conversion gain of the overall circuit. Ultimately, the zero-IF double-balanced mixer design achieved conversion gain of 11.46 dB and noise figure of 16.53 dB (using Pnoise analysis) at 5 GHz, comparable to other mixer designs from past researches.
For future mixer studies, linearity could be further analyzed along with CG and NF parameters for complex tradeoffs, as done in [19, 20]. Moreover, active baluns [20, 21] could be used instead of passive baluns for monolithic design and implementation. Active baluns are capable of producing gain and if cascaded in a double-balanced mixer to supply the differential RF and LO inputs, the overall performance of the mixer can be improved. Although active baluns are unidirectional converters, they are also used for their large bandwidth, which is beyond what non-ideal passive baluns can provide.

Declarations

Author contribution statement

Frederick Ray I. Gomez: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Maria Theresa G. De Leon: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.
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