Optimization of Monolithic Gilbert Cell Mixer for Frequency Band 935-960 MHz

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Abstract. This paper presents the electrical and layout design and optimization of Gilbert Cell mixer for frequency band of 935-960 MHz with LO-frequency of 915 MHz. The obtained maximum conversion gain is 22.2 dB, IM3 is -11.5 dBm, and ICP is -25.5 dBm, respectively. The design consists of a generic Gilbert Cell mixer with differential RF input and IF amplifier with differential output. The technology of choice is VTT08 with bipolar junction transistors (BJT).

1. Introduction

The Gilbert Cell is the most commonly used mixer in RF front-ends. The design with bipolar transistors consists of four BJTs for LO feed, which operate as switches and two BJTs for differential RF input. The Gilbert Cell mixer is inherently double balanced and it offers remarkable benefits compared to single-ended or balanced mixers: isolation between all ports, even harmonic rejection, effective LO AM noise rejection and increased linearity. Moreover, in comparison to normal active mixers, BJT-based Gilbert Cell mixers offer excellent LO-IF isolation up to 60 dB. A Generic Gilbert Cell mixer and bias circuit with BJTs is shown in Figure 1.

![Generic Gilbert mixer cell with current mirror for biasing. Both RF and LO are fed differentially. According to [1].](image)

Gilbert Cell based mixers have been in use for long in general electronics, i.e., at frequencies, where the parasitic elements are negligible. Since the late nineties the GaAs [2] and since the early twenties the SiGe [3] based technologies have enabled the use of Gilbert Cells at RF and microwave regions. Recently, the advances in CMOS technology have made it possible to fabricate high quality
Gilbert Cell mixers on silicon wafer for mobile phone receivers [4],[5]. The use of CMOS technology enables cheap mass production of receiver front-ends. In addition to mixers, The Gilbert Cells are also commonly used in multipliers and modulators [6],[7].

This paper presents the electrical and layout design and optimization of a fully monolithic Gilbert Cell Mixer with differential RF input and an IF amplifier with differential output. The LO frequency is 915 MHz and it is differentially fed to the four LO transistors seen in Figure. 1. The mixer is designed for frequency band of 935-960 MHz and the RF signal is fed differentially to the RF transistor seen also in Figure. 1. The resulting IF frequency is amplified with IF buffer amplifier. The design is optimized in order to achieve maximum conversion gain using RF frequency of 960 MHz. In the layout design, the emphasis has been in saving space.

2. Gilbert Mixer Theory
The fundamental mixing theory is out of the scope of this paper and only the most important aspects of it are discussed here. Comprehensive overview of this interesting topic can be found in [8]. Usually, two frequencies, $\omega_{LO}$ and $\omega_{RF}$ are incident on a non-linear device (in our case, LO-transistors). The waveforms are multiplied, and the resulting frequencies are $n\omega_{LO}\pm m\omega_{RF}$, where n and m are integers. From these frequencies, the intermediate frequency, usually $|\omega_{LO}-\omega_{RF}|$, is filtered and often amplified with post-mixer circuit. In Gilbert Cell mixer, the RF frequency is differentially fed to the lower transistor pair in Figure. 1. These transistors operate at linear region (or they are supposed to) and the RF frequency is amplified with voltage to current conversion. From the collectors of the lower transistor pair, the signal continues to the LO transistors, which perform the actual mixing, being the non-linear devices of the Gilbert Cell. From the collectors of the LO transistors, the signal continues to buffer amplifier and is amplified and the differential output of the IF signal is possible from the collectors of the IF amplifiers. After this, the unwanted frequencies, which have survived the very convenient features of the double balanced mixer, (even harmonic rejection, effective LO AM noise rejection) would be filtered out with IF band pass filters. Very important figures of merit in mixer design are input compression point (ICP) and third order intermodulation point (IM3). ICP is defined to be the input power, where the conversion gain has dropped 1 dB from its maximum value.

In order to determine IM3, two closely spaced input signals, $\omega_{1}$ and $\omega_{2}$ are applied to the input of the signal. IM3 is the theoretical input power point, where the mixing products $(2\omega_{1}-\omega_{2})-\omega_{LO}$ and $(2\omega_{2}-\omega_{1})-\omega_{LO}$ would have the same output power than that of the actual input signal. This point is never reached in mixers of amplifiers, because non-linear devices are saturated before that. Intermodulations points IM5 and IM7 could be determined as well, but these are omitted here for they are considered to have minor importance for the circuit performance.

3. Electrical Design and Optimization

3.1 Circuit Schematic
The electrical design tool of choice is circuit simulator APLAC 8.2. The complete transistor models for VTT08 process and bipolar technology are available from the foundry and APLAC based simulations are expected to yield results congruent to that of the actual behavior of the mixer. The complete mixer block contains Gilbert Cell, IF amplifier, biasing buffers for LO and RF transistors and current mirror biasing for the IF amplifier. The complete circuit design is shown in Figure. 2. In the electric design phase, the Gilbert Cell and IF amplifier were tested separately for maximum reliability. The goal in electrical design was to achieve as high gain, ICP, and IM3 as possible. This work does not include the noise analysis of Gilbert Cell mixer.
3.2 Optimization

In order to achieve the maximum conversion gain, the Gilbert Cell, IF amplifier and the biasing circuit were tested separately. In the case of the Gilbert Cell, the load resistors were optimized by hand and assuming that due to the symmetric structure of the Cell, both transistor values were changed the same amount. The optimization resulted in load resistance values of 640 Ω. It was also concluded, that the gain is near maximum between resistance values of 550 Ω to 680 Ω. The bias circuit were optimized in the same manner, but their values had only minor impact on the overall performance of the mixer. The load resistors of the IF amplifier have important role in gain determination. Their optimization yielded impedances of 500 Ohms.

3.3 Simulation results

To illustrate the gain behavior, the optimized values for other resistors were fixed and the Gilbert Cell load resistor values were changed step by step manually. The results of the gain simulations are show in Figure. 3. Maximum gain is 22.2 dB with load resistor values of 640 Ω. Important figures of merit for mixer, ICP and IM3 were also simulated, and values of -11.5 dBm and -25.5 dBm were obtained for ICP and IM3, respectively. The difference between ICP and IM3 is congruent with the value reported in [9]. The results for ICP and IM3 are shown in Figure. 4 and 5.
The load resistors of the Gilbert cell are changed step by step manner.

Figure 4. The input compression point of the Gilbert cell mixer.

Figure 5. Third order intermodulation results for the Gilbert Cell mixer.

4. Layout Design

They layout design tool is the Mentor Graphic 2004.1 on the Solaris workstation. Mentor 2004.1 is an integrated design environment for IC-circuit design. The optimized monolithic Gilbert Cell mixer is shown in the Figure 6. The transistors pairs in the Gilbert Cell, IF amplifier and LO have been grouped together by guard ring. This Gilbert mixer design follows the foundry’s design rules, and the layout is checked by running the DRC of Mentor Graphic. If the layout area is not optimized, more wafers are needed to produce wanted the wanted number of circuits and hence the cost per single circuit will be greater. Here, the layout is strictly designed with the design rules, and optimized in order to reach minimum area. In some aspects, not only minimum area should be under consideration, but also the interference between two neighbour metal layers, thus granularity is in some cases larger than the minimum in the design rules. We made one mistake in layout design because of misunderstanding, the Gilbert Cell load resistors should be $640 \, \Omega$, but they are $690 \, \Omega$ in layout. According to simulations, this would reduce the gain to $19.3 \, \text{dB}$. 

Figure 3. Total gain of the Gilbert Cell mixer.
5. Conclusions

In this paper, the electrical and layout design and optimisation of the Gilbert Cell mixer for the frequency band of 935-960 MHz is presented. Simulated results are given for gain, input compression point, and third order intermodulation point. The layout design tool is the Mentor Graphic 2004.1 on the Solaris workstation. Mentor 2004.1 is an integrated design environment for IC-circuit design. The optimized monolithic Gilbert Cell mixer is shown in the Figure 6. The transistors pairs in the Gilbert Cell, IF amplifier and LO have been grouped together by guard ring. This Gilbert mixer design follows the foundry’s design rules, and the layout is checked by running the DRC of Mentor Graphic. If the layout area is not optimized, more wafers are needed to produce wanted number of circuits and hence the cost per single circuit will be greater. Here, the layout is strictly designed with the design rules, and optimized in order to reach minimum area. In some aspects, not only minimum area should be under consideration, but also the interference between two neighbour metal layers, thus granularity is in some cases larger than the minimum in the design rules. We made one mistake in layout design because of misunderstanding, the Gilbert Cell load resistors should be 640 Ω, but they are 690 Ω in layout. According to simulations, this would reduce the gain to 19.3 dB.
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