Low Voltage Current Mode Switched-Current-Mirror Mixer

Minglin MA[1], Chunhua WANG[2], Sichun DU[3]

[1] School of Computer and Communication Hunan University, Changsha, Hunan P. R. China
[2] School of Information Engineering, Xiangtan University, Xiangtan, Hunan P. R. China

32415684@qq.com, wch1227164@sina.com, Jt_dsc@hnu.cn

Abstract. *A new CMOS active mixer topology can operate at 1 V supply voltage by use of SCM (switched current-mirror). Such current-mode mixer requires less voltage headroom with good linearization. Mixing is achieved with four improved current mirrors, which are alternatively activated. For ideal switching, the operation is equivalent to a conventional active mixer. This paper analyzes the performance of the SCM mixer, in comparison with the conventional mixer, demonstrating competitive performance at a lower supply voltage. Moreover, the new mixer's die, without any passive components, is very small, and the conversion gain is easy to adjust. An experimental prototype was designed and simulated in standard chartered 0.18µm RF CMOS Process with Spectre in Cadence Design Systems. Experimental results show satisfactory mixer performance at 2.4 GHz.*

Keywords

Current mode, switched current mirror, mixer, low voltage, receiver, RF circuit.

1. Introduction

The demand of low cost, low power and small size circuits has been increasing with extensive researches on transceivers architecture and RF circuit design, especially in Bluetooth and 802.11 WLAN areas [1]. Furthermore, mixer is the core module of RF front end. For a conventional mixer, the LNA (Low Noise Amplifier) input FET converts the incoming signal into current, which then becomes a voltage across the load. This voltage drives the transconductance input of the mixer, which once again converts the signal into current. Finally, the mixer differential pairs commutate this current, translating it in frequency, to be read off at the mixer output as voltage [2]. We can see, the I-V (traditional LNA output) and V-I (Gilbert mixer input) conversion are unnecessary, and the conventional voltage mode mixer can not meet the low voltage, low power requirement for modern communication system. Several techniques exist to solve this problem. One group of these circuits operates based on current-squaring circuit [3]. Because of adding the RF input current and LO (Local Oscillator) current together directly, this technique suffers from a very bad isolation between RF and LO. Another group of these circuits operates based on Gilbert mixer. Wan Chicheng proposed a parallel current driven mixer. However, the conversion gain is very low [4]. Eric A. M. Klumperink designed a switched transconductor mixer [5]. Unfortunately, the output is in voltage mode with an unnecessary I-V conversion achieved with a resistor load. Here, we propose a current mode mixer processing of current signal. Current mode approach has some advantages, such as extended bandwidth, ease of addition, subtraction and multiplication of signals, simple circuit structure, higher dynamic range, suitability of operation in reduced power supply environment, low power consumption, low voltage operation, micro-miniaturization [6].

The contents of this paper are as follows. First, we will discuss this mixer-switch problem in Section 2, taking a commonly used active CMOS mixer as a starting point. The "switched current mirror" mixer will then be proposed in Section 3. Experimental results on a switched current mirror mixer realized in 0.18µm CMOS are reported in Section 4, while the conclusion is presented in Section 5.

2. Switch Problem in Conventional Mixers

Active mixers are commonly used in RF CMOS transceiver circuits [6]. Fig. 1(a) shows a single balanced version of a simple active mixer configuration. It consists of a transconductance stage, switches (M_2 and M_3), and a load network. Voltage V_B biases the transconductance stage at a current I_B and transconductance g_m, resulting in a voltage-to-current conversion from V_{RF} to drain–current variation $g_m * V_{RF}$. The switches M_2 and M_3 are driven by anti-phase LO signals, denoted here as V_{LO}+ and V_{LO}-. To mimic multiplication with a square wave with frequency, the LO amplitude must be chosen sufficiently high to fully switch the transconductor current to either I_{O1} or I_{O2}. For the purpose of a first-order functional analysis, we can model the operation of M_2 and M_3 as switches driven by the logic signal LO and its inverse, as shown in Fig. 1(b).

Here, the direction of switch current is the same as direction of supply voltage, just like Fig. 1(c). So, V_{dd} is equal to V_{load} (voltage of load) plus V_{switch} (V_{ds} of switch transistor) and V_{tran} (V_{ds} of transconductance stage).

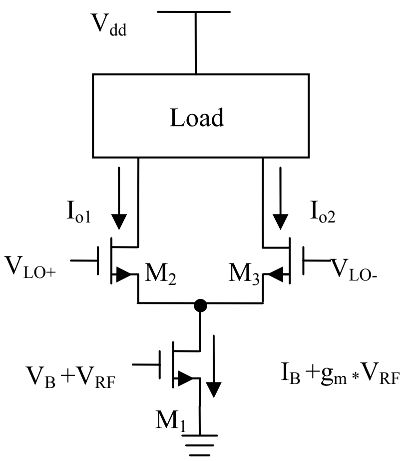

Fig. 1 a

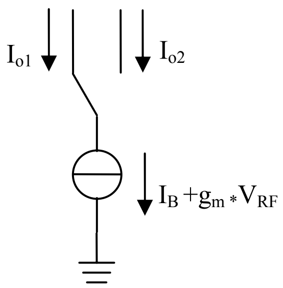

Fig. 1 b

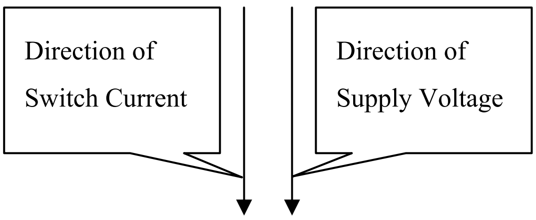

Fig. 1 c

Fig. 1. (a) Conventional Single Balanced Active MOS Mixer (b) Functional Representation for Large Switching Signals, (c) Directions of Supply Voltage and Switch Current.

This voltage mode circuits operate with high impedance nodes such that voltage swings are large. In the next section, we propose a current mode mixer requiring almost no voltage headroom across the switch.

3. Switched Current Mirror Mixer

Fig. 2(a) shows the switched-current-mirror. The key to the new mixer is to make sure that the directions of supply voltage and switch remain quadrature to each other, just like Fig. 2(b). Here, V_{dd} is equal to V_{bias} (V_{ds} of current mirror bias transistor) plus V_{mirror} (V_{ds} of M_1 or M_2). Compared to conventional switching mixer, like Fig. 1(c), V_{switch} does not affect V_{dd}. So, we reduce a cascade transistor. Moreover, we can see there is no current flowing through the switch, which will reduce the switch noise. Fig. 3 shows how the same functionality can be achieved by SCM mixer using four switched-current-mirrors. For canceling the strong output signal at the LO frequency, this mixer is the double-balanced version. For a switched current mirror, just like Fig. 2(a), the current mirror, composed of M_1 (whose width to length ratio equals to *M/L*), M_2 (whose width to length ratio equals to *aM/L*), has an adjusted linear I (I) characteristic. M_2 is either switched on to the V_{gs1} by M_3 (controlled by V_{LO}) or switched off. Thus, effectively, current mirror works, if switch (M_3) is on, and the other way around. Now, if switch_1 and switch_4 is on, (i_{if}+) is equal to a (i_{if}+), and (i_{if}-)is equal to a (i_{if}-). If switch_2 and switch_3 is on, (i_{if}+) is equal to a (i_{if}-), and (i_{if}-) is equal to a (i_{if}+).

For differential current input

$$(i_{rf}+) = -(i_{rf}-) = \cos(\varpi_{rf} t) \tag{1}$$

For SCM mixer

$$\begin{aligned} i_o &= [(i_{if}+) - (i_{if}-)] \\ &= a \times [(i_{rf}+) - (i_{rf}-)] \times \operatorname{sgn}[\cos \varpi_{lo} t] \\ &= 2a \times \operatorname{sgn}[\cos \varpi_{lo} t] \times (i_{rf}+) \end{aligned} \tag{2}$$

Here

$$\operatorname{sgn}[\cos \varpi_{lo} t] = \begin{cases} -1 : \cos \varpi_{lo} t < 0 \\ +1 : \cos \varpi_{lo} t > 0 \end{cases} = \sum_{1}^{\infty} \frac{\sin(n\pi/2)}{n\pi/4} \cos n \varpi_{lo} t \tag{3}$$

Therefore,

$$i_o = 2a \sum_{1}^{\infty} \frac{\sin(n\pi/2)}{n\pi/2} [\cos(n\varpi_{lo} + \varpi_{rf})t + \cos(n\varpi_{lo} - \varpi_{rf})t] \tag{4}$$

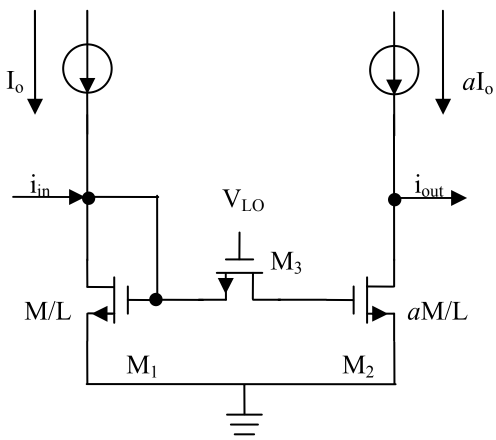

Fig. 2 a

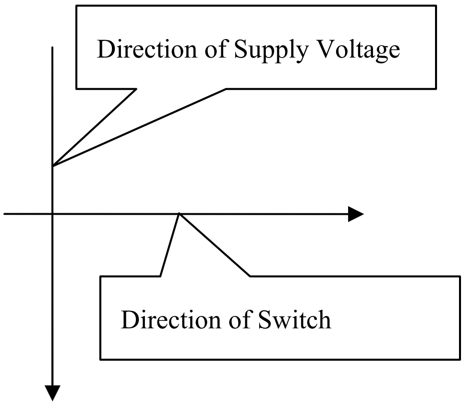

Fig. 2 b

Fig. 2. (a) Switched-current-mirror, (b) Directions of Supply Voltage and Switch.

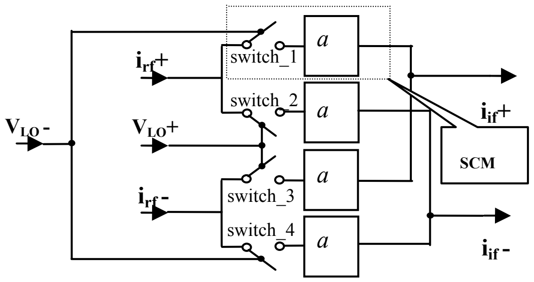

Fig. 3 a

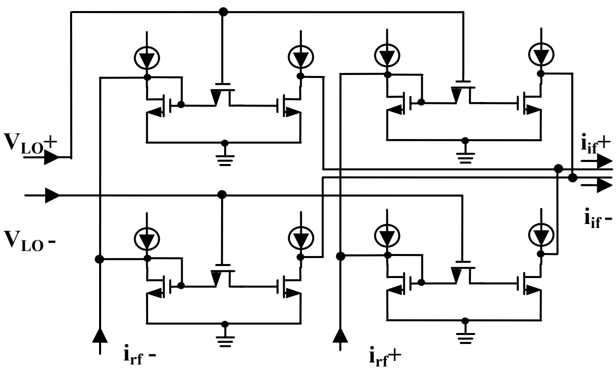

Fig. 3 b

Fig. 3. (a) Functional Representation for SCM Mixer, (b) Schematic of the SCM Mixer

Thus, the circuits implement the same mixer function in a different way: the conventional mixer by a transconductor plus a current switching, and the new current mode mixer by switched current mirror. Compared to conventional active mixer, the SCM mixer, changing the direction of switch, has a benefit of low voltage supply. Moreover, the conversion gain is easy to adjust, just by changing the value of a.

Taking finite switch-time into account, as in [7], a first-order approximation of the current conversion gain CCG of the SCM mixer becomes

$$CCG \approx \frac{2a}{\pi}\left(\frac{\sin(\pi f_{lo}\tau_{sw})}{\pi f_{lo}\tau_{sw}}\right) \tag{5}$$

4. Simulation Result

In order to verify the new mixer concept experimentally, a down–conversion mixer was designed to operate at 1-V supply voltage. The new mixer was simulated in standard chartered 0.18µm RF CMOS Process with Spectre in Cadence Design Systems. A mixer's frequency converting action is characterized by conversion gain or loss. The power conversion gain is the ratio of the power delivered to the load and the available RF input power. Fig. 4 shows the gain of the mixer with different a. We can see that the conversion gain is easy to adjust. Because the noise from the mixer is moderated by the LNA's gain, it places a limit on how small a signal can be resolved. The sensitivity of the receiver is then adversely affected. Noise is measured using the noise figure (NF), which is a measure of how much noise the mixer adds to the signal relative to the noise that is already present in the signal. An NF of 0 dB is ideal, meaning that the mixer adds no noise. An NF of 3 dB implies that the mixer adds an amount of noise equal to that already present in the signal. For a mixer alone, an NF of 15 dB is typical. Fig. 5 shows the noise of this mixer. The linearity is verified by Harmonic Balance analysis. Fig. 6 illustrates the two-tone simulation results with a conversion gain of 4.9 dB, a P_{IIP3} of 1.6 dBm and a P_{OIP3} of 6.51 dBm, a P_{IIP2} of 85.3 dBm and a P_{OIP2} of 90.2 dBm. This is good enough for RF circuit. Fig. 7 shows the transient simulation results with input RF signal at 2.4 GHz and the LO signal at 2.39 GHz. So the output IF signal is at 10 MHz. The transient difference output is equal to V_{if+} minus V_{if-}. Fig. 8 shows the layout diagram of the current mode SCM mixer which occupies the active area of 0.49 × 0.51 mm^2 including biasing circuits, scribble line, testing pads and DC blocking capacitors.

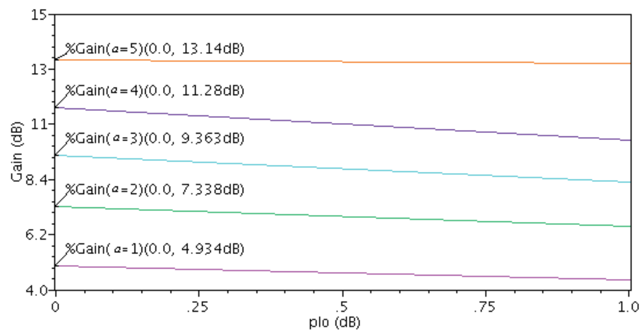

Fig. 4. Gain of the Mixer vs PLO and a .

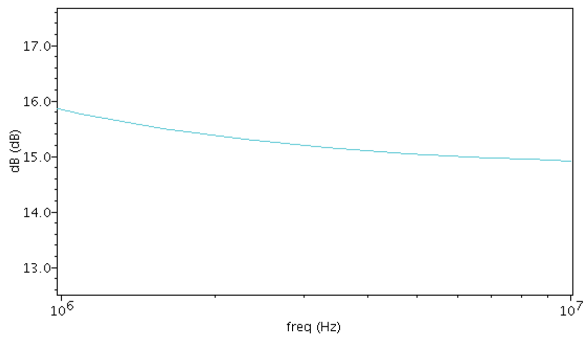

Fig. 5. Noise of the mixer.

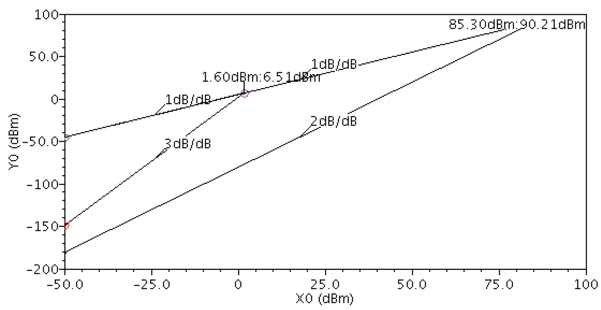

Fig. 6. The two-tone analysis of the proposed current-mode mixer.

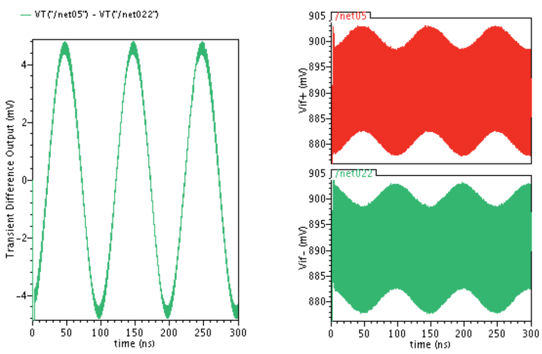

Fig. 7. The transient analysis of the mixer.

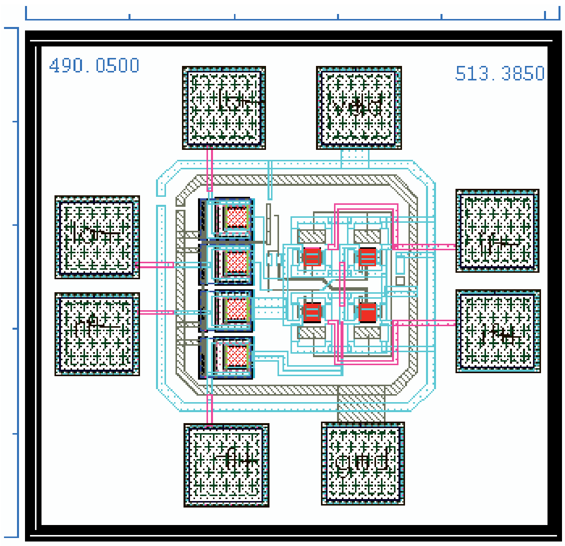

Fig. 8. The layout diagram of the SCM mixer.

Tab. 1 summaries the performance of this design and lists the performance of the previously published CMOS mixers. The current-mode mixer reported in this paper can achieve very low power consumption of 2.2 mW from 1-V supply. Compared to current mode mixer [3], this work has much smaller power consumptions and much smaller active area. Compared to current mode mixer [4], this work has much smaller power consumptions and much larger gain.

	This work	[3]	[4]
Technology	0.18μm CMOS	0.13μm CMOS	0.6μm CMOS
Supply voltage	1 V	1 V	1.2 V
Gain (dB)	4.9 (a = 1)	1.3	-8
PIIP3 (dB)	1.6	-8.75	9.5
POIP3 (dB)	6.5	-7.44	1.5
NF (dB)	15	--	--
Power of mixer	2.2 mW	3.89 mW	3 mW
Chip Area	0.5*0.5 mm^2	1.5*1.1 mm^2	0.4*0.4 mm^2

Tab. 1. Performance summaries and comparisons.

5. Conclusion

A CMOS SCM mixer has been presented, which can operate at 1-V supply voltage in a 0.18μm CMOS technology. It requires no voltage headroom across the switch, because the directions of supply voltage and switch are quadrature to each other. There is no passive component in the mixer core, and it is easy to adjust the current conversion gain. All these show that the current mode SCM mixer has excellent performance in comparison with other CMOS mixers.

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About Authors.

Minglin MA was born in Hu Nan, China, in 1978. He received the B.S. degree in electrical engineering from Xiangtan University, in 2002, and the M.S. degree in electrical engineering from Xiangtan University, in 2005. He is studying in Hunan University for the Ph.D. degree. He is currently a teacher of School of Information Engineering, Xiangtan University, Xiangtan, China. From 2002 to 2009, his interests are focused on the RF front-end design for wireless LANs.

Chunhua WANG was born in Yongzhou, China, in 1963. He received the B.S. degree from Hengyang Teacher's College, Hengyang, China, in 1983, the M.S. degree from Physics Department, Zheng Zhou University, Zheng Zhou, China, in 1994, the Ph.D. degree from School of Electronic Information and Control Engineering, Beijing University of Technology, Beijing, China, in 2003. He is currently a professor of School of Computer and Communication, Hunan University, Changsha, China.

Sichun DU is studying in Hunan University for the Ph.D. degree. He is interested in the RF front-end design for wireless LANs. He is currently a teacher of School of Computer and Communication, Hunan University, Changsha, China.