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LETTER

Design and simulation of novel amplifier-based mixer for ISM band wireless applications

Jie Jin[1,2], Chunhua Wang[1,*†], Jingru Sun[1] and Sichun Du[1]

[1]*College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, PR China*
[2]*College of Information Science and Engineering, Jishou University, Jishou 416000, PR China*

SUMMARY

This letter describes a low-voltage low-power (LV-LP) 2.4-GHz mixer for Industrial, Scientific and Medical (ISM) band wireless applications. The approach is based on a two-stage amplifier, and the Gilbert switch stage is inserted between the two amplifier stages. The proposed amplifier-based mixer delivers a remarkable conversion gain of 13 dB with a local oscillator (LO) power of 7 dBm, while consuming only 1.05-mW DC power from a 0.8-V supply voltage. The input-referred third-order intercept point (IIP3) of the mixer is 3.82 dBm, and the chip area is only 0.429 mm^2. The results indicate that this mixer is suitable for the low-voltage low-power applications. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: CMOS; low voltage low power; amplifier; mixer

1. INTRODUCTION

Due to the limitations of battery capacity, the low-voltage low-power and highly integrated circuits are required in the radio frequency (RF) wireless communication systems, such as the IEEE 802.11b WLAN and the Bluetooth technologies working at 2.4-GHz industrial, scientific and medical (ISM) band. Mixer is one of the most important analog blocks in the wireless communication system. Typically, the Gilbert active mixers [1–10] are widely used in the wireless communication systems for their superior conversion gain and port to port isolation. However, conventional Gilbert active mixers generally consume a significant portion of the power of the transceiver, and the LV–LP mixers have received considerable attentions in recent years.

Several techniques have been reported to decrease the supply voltage and the power consumption of the mixers, such as folded technique [11–14] and current reuse technique [15, 16]. In the folded technique, the RF stage is separated from the LO stage, which reduces the number of stacked transistors, and the supply voltage is decreased. However, because of the increased branch currents of the RF stage, the total power consumption does not reduce significantly. In the current reuse technique, the dissipated current in any stage is reused in other stages, but the stacked transistors are not reduced, and the supply voltage is not decreased.

In this work, an amplifier-based mixer is presented. The amplifier consists of a resistor feedback stage and a common source stage with LC loads. The number of stacked transistors of the amplifier is only one, which makes the supply voltage relatively low. The Gilbert switches are inserted between the two amplifier stages, and the Gilbert switches are turned on and off by the LO signals.

*Correspondence to: Chunhua Wang, College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, PR China.
†E-mail: 124900808@qq.com

The second stage of the amplifier works only when the Gilbert switches are opened by the LO signals, which further reduces the power consumption of the mixer.

There are three fundamental issues discussed in this letter: First, novel amplifier-based mixer architecture is presented; second, because the novel mixer is realized based on a two-stage amplifier, and the conversion gain of the mixer is relatively large; the last, the number of stacked transistors of the mixer is one, and the supply voltage is reduced to 0.8 V. Moreover, the turning on and off the second section of the amplifier is controlled by the Gilbert switches, which reduces the power consumption of the mixer. The Cadence IC Design Tools 5.1.41 post-layout simulation results are included to confirm all the theory.

2. CIRCUIT DESCRIPTION

2.1. The conventional gilbert cell mixer

Figure 1 is the circuit schematic of conventional Gilbert mixer. The Gilbert mixer has the advantages of low even order distortion and good port to port isolation. However, there are three stacked transistors in the Gilbert mixer, and the supply voltage is relatively high. Moreover, all the transistors in the Gilbert mixer operate in the saturation region, and the power consumption is high. The conversion gain of the conventional Gilbert cell mixer is [17]:

$$A_V = \frac{2}{\pi} g_{m1} R_L \tag{1}$$

2.2. The two-stage amplifier

Figure 2 is the two-stage amplifier with the Gilbert switch. This amplifier consists of a resistor feedback stage and a common source stage with LC load.

M_1, R_1 and R_f constitute the first resistor feedback stage. A routine circuit analysis reveals that the voltage gain of the first stage is:

$$A_{V1} \approx -g_{m1} \bullet \left(R_1 // R_f\right) \tag{2}$$

where g_{m1} is the transconductance of the transistor M_1.

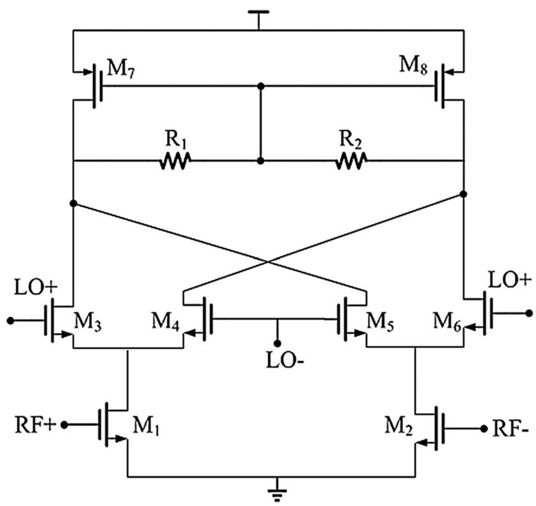

Figure 1. Circuit schematic of the conventional Gilbert cell mixer.

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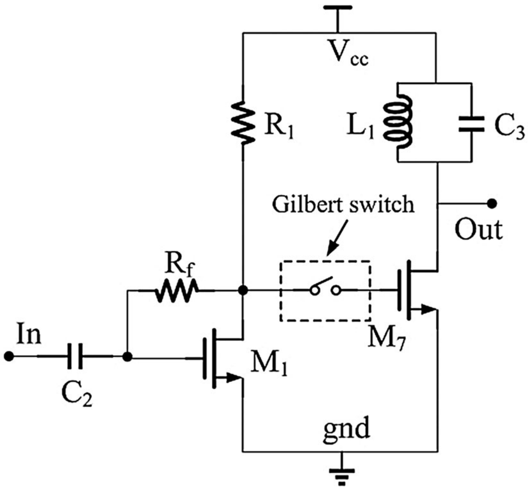

Figure 2. The two-stage amplifier with the Gilbert switch.

M_7, L_3 and C_3 constitute the second common source stage. Similarly, the voltage gain of the second stage is:

$$A_{V2} = -g_{m7}\bullet\left[r_{o7}//\left(j\omega L_1 + \frac{1}{j\omega C_3}\right)\right] \tag{3}$$

where g_{m7} is the transconductance of the transistor M_7, and r_{o7} is the output resistance of M_7.

The paralleled resonant load (L_1 and C_3) is chosen to be resonated at 2.4 GHz, and the voltage gain of the second stage at 2.4 GHz could be expressed as:

$$A_{V2} \approx -g_{m7}r_{o7} \tag{4}$$

From equations (2) and (4), it is clear that, the voltage gain of the two-stage amplifier could be expressed as:

$$A_V = A_{V1}\bullet A_{V2} \approx g_{m1}g_{m7}\bullet\left(R_1//R_f\right)\bullet r_{o7} \tag{5}$$

The Gilbert switch is inserted between the two amplifier stages. When the switch is turned off, the working conditions of the transistor M_7 are not satisfied, and the second stage of the amplifier will not work. When the switch is turned on, M_7 will operate in the saturation region. In other words, the second stage of the amplifier only works when the switch is turned on, which reduces the power consumption of the amplifier.

2.3. The proposed amplifier-based mixer

The proposed amplifier-based mixer is presented in Figure 3. From Figure 3, it is clear that, the number of stacked transistors of the amplifier-based mixer is only one, which makes the supply voltage relatively low.

M_1, M_2, R_1, R_2 and R_f constitute the first amplifier stage of the mixer. M_3–M_6 are the Gilbert switches, and the turning on and off the switches is controlled by the LO signals. Figure 4 is the relationship between the switches and the LO signals. In Figure 4, t_0 to t_5 is a period of the LO signal, From t_1 to t_2, and t_3 to t_4, $(v_{LO+} + V_{bs}) > V_{th}$ or $(v_{LO-} + V_{bs}) > V_{th}$, the transistors M_3 and M_6 or M_4 and M_5 are opened, the transistors M_6 and M_7 work in the saturation region and the whole mixer works properly. From t_0 to t_1, t_2 to t_3 and t_4 to t_5, when the Gilbert switches are closed, and the transistors M_6 and M_7 stop working, which could reduce the power consumption of the mixer.

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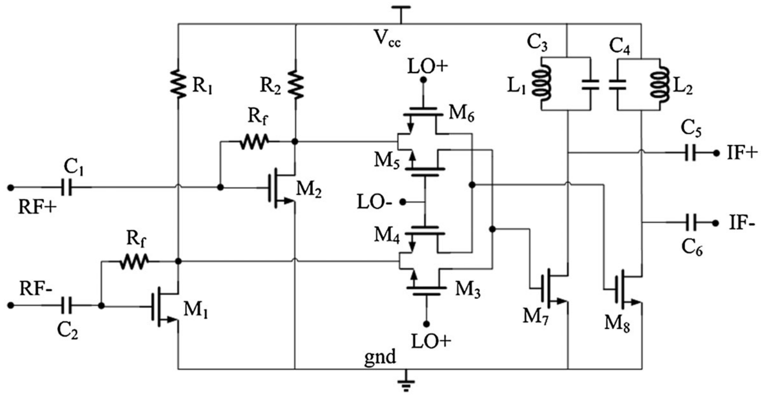

Figure 3. The proposed amplifier-based mixer.

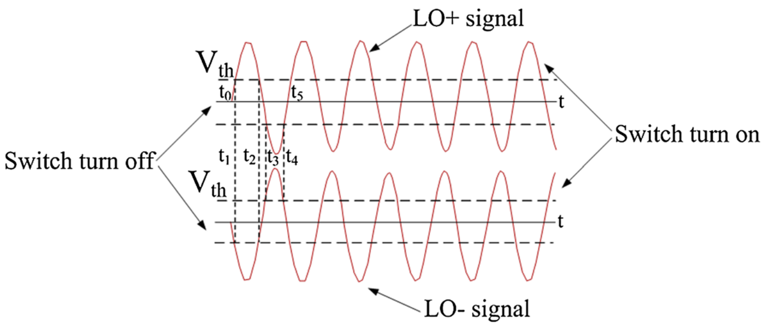

Figure 4. The relations between the switches and the LO signals.

M_7, M_8, L_1, L_2, C_3 and C_4 constitute the second amplifier stage of the mixer. L_1 and C_3, L_2 and C_4 are the two paralleled LC loads, and they resonate at 2.4 GHz. Although the signals get distortion in the time span, t_0 to t_1, t_2 to t_3 and t_4 to t_5, just like the power amplifiers, the use of paralleled LC loads resonating at 2.4 GHz reshapes the output signal and rejects the unexpected interference signals, and the undistorted output waveforms could be obtained.

Moreover, from equations (1) and (5), it is clear that, under the same conditions, the conversion gain of the amplifier-based mixer is larger than the conventional Gilbert mixer.

3. POST-LAYOUT SIMULATION RESULTS

The proposed amplifier-based mixer is realized using Cadence IC Design Tools 5.1.41 Spectre with standard chartered 0.18-µm RF CMOS technology. According to the 0.18 µm MOSFET Model, the threshold voltage of the NMOS is $V_{thN} = 0.42\,V$, and the threshold voltage of the PMOS is $V_{thP} = -0.49\,V$. The supply voltage of the mixer is 0.8 V, the mixer consumes 1.3137 mA from the 0.8 V supply voltage and the power consumption of the amplifier-based mixer is 1.05 mW. The input IF signal is −20 dBm, and its frequency is 10 MHz; the LO signal is 7 dBm, and its frequency is 2.39 GHz.

Figure 5 is the chip layout of the proposed mixer, and it takes a compact chip area of 0.429 mm^2 including the testing pads.

Based on the layout in Figure 5 and considering the parasitics extracted from the chip layout, the post-layout simulation results are presented in Figures 6–9.

Figure 6 is the input third-order intercept point (IIP3) of the proposed mixer, and the IIP3 of the mixer is about 3.82724 dBm. Obviously, from Figure 6, it is clear that the proposed mixer could achieve relatively high linearity.

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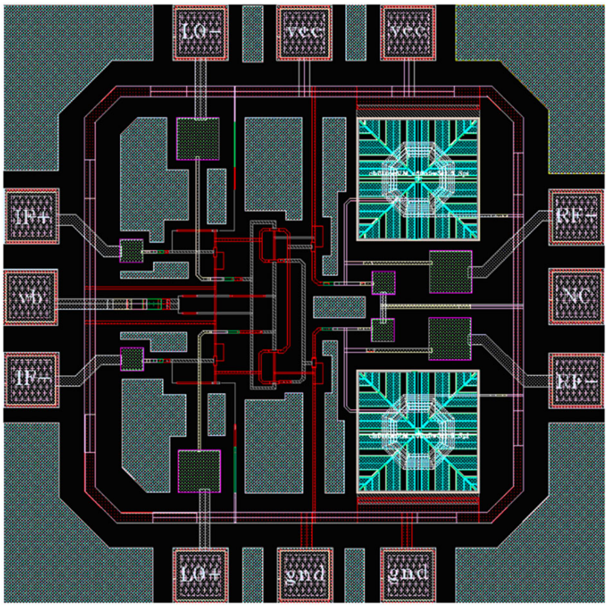

Figure 5. The layout of the proposed mixer ($0.650 \times 0.66\,mm^2$).

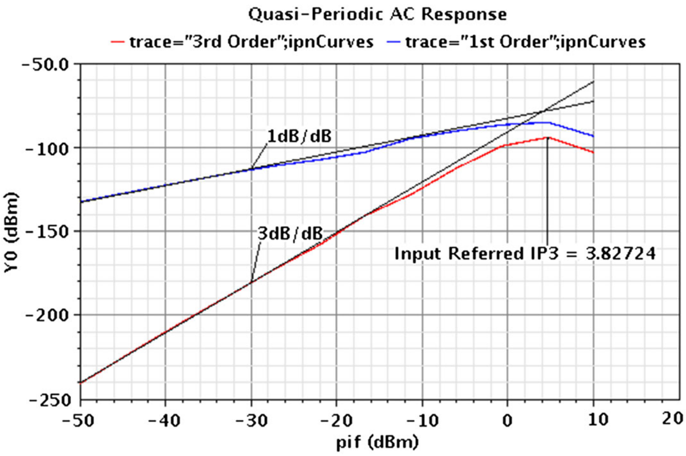

Figure 6. The IIP3 of the proposed mixer.

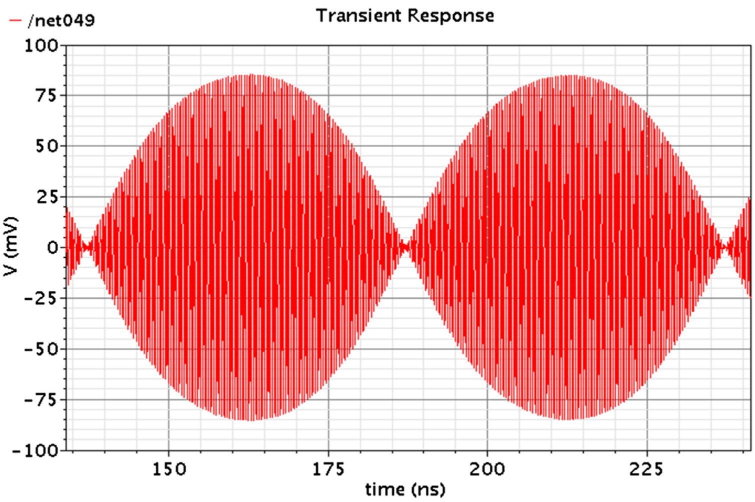

Figure 7. The transient analysis of the proposed mixer.

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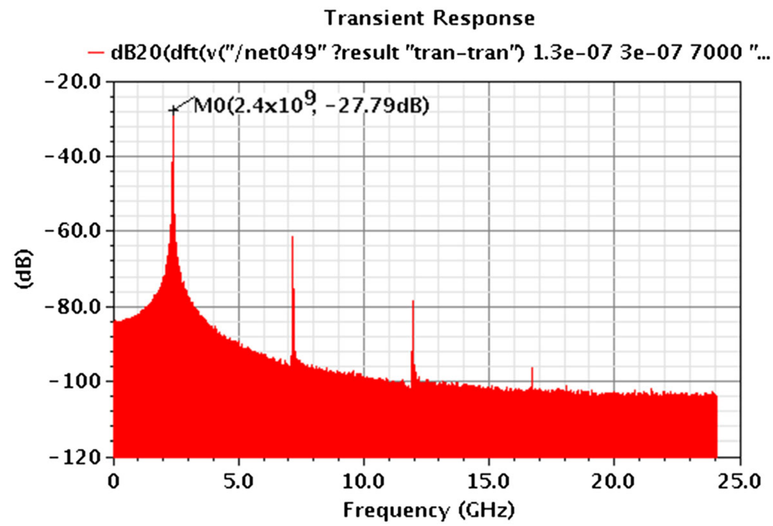

Figure 8. The output spectrum of the proposed mixer.

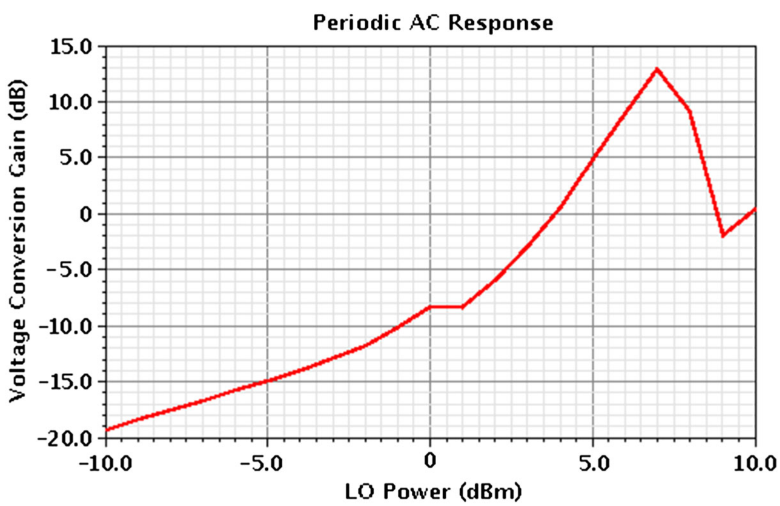

Figure 9. The voltage conversion gain of the mixer.

Figure 7 is the transient analysis of the proposed amplifier-based mixer. The input IF signal is chosen as 10 MHz, and its signal level is −20 dBm. The signal in Figure 7 is the output RF signal ($V_{RF} = V_{RF+} - V_{RF-}$), and its frequency is 2.4 GHz.

Figure 8 is the output spectrum of the proposed mixer. From Figure 8, it is clear that, the magnitude of the output spectrum of the proposed mixer is −27.79 dB. From Figure 8, it is clear that the output power of the mixer is concentrated at 2.4 GHz, and the other interference signals are relatively smaller.

Figure 9 is the voltage conversion gain versus LO power of the proposed amplifier-based mixer. From Figure 9, it is clear that the proposed amplifier-based mixer could provide a relatively large voltage conversion gain when the input LO power changed from 5 to 9 dBm, especially, the amplifier-based mixer could provide 13-dB voltage conversion gain when the LO power is 7 dBm.

4. CONCLUSION

A low-voltage low-power 2.4-GHz mixer for ISM band wireless applications is presented in this letter. By inserting the Gilbert switches in the amplifier, a novel LV–LP mixer is achieved. The number of

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stacked transistors of the mixer is one, and the supply voltage is reduced to 0.8 V; The turning on and off the second section of the amplifier is controlled by the Gilbert switches, which reduces the power consumption of the mixer; moreover, the gain of the amplifier is large, and the conversion gain of the amplifier-based mixer is also relatively large. The Cadence IC Design Tools 5.1.41 post-layout simulation results show that the voltage conversion gain of proposed amplifier-based mixer is 13 dB with a LO power of 7 dBm; the supply voltage is 0.8 V, and the power consumption is only 1.05 mW; the whole chip area is only 0.429 mm^2.

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