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A 2.4GHz CMOS Quadrature Voltage-Controlled Oscillator Based on Symmetrical Spiral Inductors and Differential Diodes*

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Abstract: A voltage-controlled oscillator (VCO) which can generate 2.4GHz quadrature local oscillating (LO) signals is reported. It combines a LC VCO, realized by on-chip symmetrical spiral inductors and differential diodes, and a two-stage ring VCO. The principle of this VCO is demonstrated and further the phase noise is discussed in detail. The fabrication of prototype is demonstrated using 0.25μm single-poly five-metal N-well salicide CMOS digital process. The reports show that the novel VCO is can generate quadrature LO signals with a tuning range of more than 300MHz as well as the phase noise —104.33dBc/Hz at 600KHz offset at 2.41GHz (when measuring only one port of differential outputs). In addition, this VCO can work in low power supply voltage and dissipate low power, thus it can be used in many integrated transceivers.

Key words: quadrature VCO; symmetrical spiral inductors; differential diodes

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1 Introduction

Recently, quadrature-downconversion mixers have been used as transceivers due to its merits. In the design of these transceiver systems, a major challenge is the generation of quadrature local oscillating (LO) carrier signals. Ideally, the quadrature LO signals should be of high phase accuracy, good gain matching, and low phase noise. So far, many methods have been proposed to generate quadrature LO signals. Among them, RC phase shift network and poly-phase network methods restrict the phase accuracy and gain matching due to the inaccuracies in actual values of R and C, and the noise performance and driving capability is no good. Positive- or negative-edge triggered flip-flop method requires the oscillator and the flip-flop to work in double carrier frequency, which is difficult to design within the radio frequency range. Another method is to use even-stage voltage-controlled ring oscillator, but its phase noise is large. References [1] and [2] proposed LO oscillators with quadrature outputs, but whose circuits are of poor performance because of the LC tank components and without considering the phase noise.

In this paper, a VCO generating the 2.4GHz quadrature local oscillating (LO) signals is proposed. It combines a LC voltage-controlled oscillator (VCO), realized by on-chip symmetrical spiral inductors and differential diodes, and a two-stage ring VCO. The principle of this VCO is demonstrated and the phase noise is analyzed in detail. The fabrication of a prototype is demonstrated us-

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ing a 0.25μm single-poly five-metal N-well salicide CMOS digital process. The measured results show that the novel VCO is can generate quadrature LO signals with a tuning range of more than 300MHz and phase noise —— 104.33dBc/Hz at 600KHz offset at 2.41GHz (when measuring only one port of differential outputs). In addition, we demonstrate that this VCO can work in low power supply voltage and dissipate low power, thus it can be utilized in many integrated transceivers.

2 Circuit implementation

The schematic diagram of the proposed VCO is shown in Fig. 1. M0 is the a tail current source controlled by bias voltage V_{BLO}; C_0 is a large tail capacitor providing the low impedance path to ac

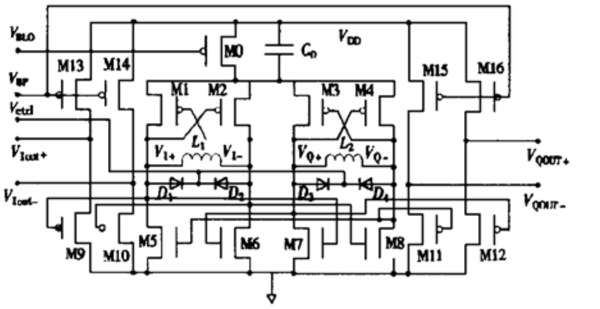

Fig. 1 Schematic diagram of quadrature VCO

ground for higher harmonics, which can attenuate the high frequency noise component of the tail current source and improve the phase noise performance of the whole VCO. In fact, for a completely symmetrical VCO, the effect of the tail current source noise on the VCO phase noise can be ignored. The cross-coupled p-MOSFET differential pairs M1~ M4, in positive feedback, feed the LC tanks to compensate the loss. Their transconductances are given as:

$$g_m = 2G_m = 6/R_p = 6/\omega_0 L Q_{tank}$$

where G_m is the transconductance of the cross-coupled active pairs, R_p is the parallel resistance of the LC tanks at resonance, ω_0 is the resonance frequency, L is the inductor value of the LC tanks, Q_{tnak} is the quality factor of the LC tanks. LC tank is composed of an on-chip symmetrical spiral inductor and differential diodes. Figure 2 shows the symmetrical inductor's layout and the cross section of the differential diode. These differential structures can not only reduce the chip area, but also improve the tank's quality factor and the symmetry of the circuit, as is important to lower the flicker noise up-conversion.

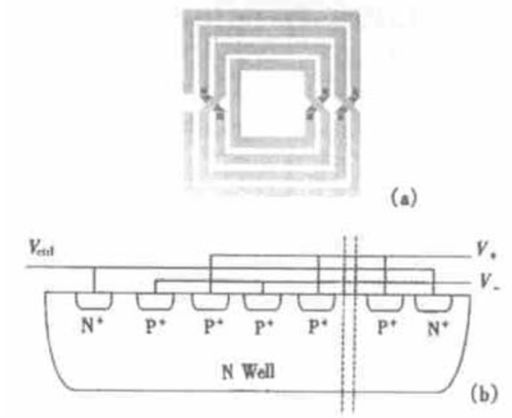

Fig. 2 Symmetrical inductor and differential diode

The n-MOSFETs M5~ M8 comprise a two-stage differential ring oscillator. The outputs of each stage are 90° out of phase. By combining the ring oscillator and LC-VCO, the quadrature LO signals with low phase noise can be got. The constant current source M0, shared by the two sections, will further enhance the accuracy of the quadrature VCO.

The p-MOSFETs M9~ M16 comprise four source followers to drive the off-chip low impedance loads and provide isolation. If the VCO is applied on a system on chip, these followers could be omitted.

3 Phase noise analysis

The phase noise in the $1/f^2$ region has been given in References[4, 5]

$$\varsigma\{f_{off}\} = \frac{1}{8\pi^2 f_{off}^2} \times \frac{L_{tank}^2 \omega^4}{V_{SW}^2} \sum_n \left(\frac{\overline{i_n^2}}{\Delta f} \Gamma_{rms,n}^2\right) \quad (1)$$

where f_{off} is the offset frequency from the carrier, Γ_{rms} is the rms value of the impulse sensitivity function (ISF) and is 0.5 for an ideal sinusoidal waveform. Each $\overline{i_n^2}/\Delta f$ in the sum represents drain current noise, gate noise, inductor noise, and varactor noise. The equivalent differential noise due to the drain current noise and the gate noise of the MOS transistors are given as $2kT\gamma(g_{d0,n}+g_{d0,p})$ and $(2kT\delta\omega^2/5g_{d0})(C_{gsn}^2+C_{gsp}^2)$, respectively, where γ is around 2/3 for long-channel transistors while it may be between two and three in the short-channel region, and δ is about 2γ. g_{d0} is the drain-source conductance at zero V_{DS}. The noise of LC tank is given as $2\times 4kTG_{tank,max}$, where $G_{tank,max}$ is the LC tank conductance at the worst-case condition. By the above method and assuming that γ_n is 2.5, γ_p is 2/3 and Γ_{rms} is 0.5, the good phase noise of VCO is obtained to be −116.8dBc/Hz at 600kHz offset at 2.41GHz.

4 Simulation results

Before fabrication, the proposed circuit was simulated with HSPICE, using BSIM3.1 (Level 49) transistor models. The process provides 5 metal layers and 1 polysilicon layer. The symmetrical spiral inductors are made of the fifth metal layer. A CAD analysis and simulation tool of inductors, ASITIC[3], is used to optimize the inductors and to extract the parasitic component parameters. Each inductor is realized with an inductance 4.16nH, a quality factor 6.539 and an area 0.24mm × 0.24mm. The symmetrical spiral inductors are also fabricated, and the measurement are carried out. The measured inductance is 3.96nH and the series resistance is 6.49Ω at 1MHz. Although the behavior in radio frequency rang is differential from that in low frequency, this measured results can be utilized as the basis of quadrature VCO design.

Each diode is modeled by HSPICE Level 3 Diode model and a low resistance in series. According to the layout strategy, the series resistance of each diode is lower than 0.52Ω.

Figure 3 shows the simulated transient waveforms of two quadrature outputs from VCO core ($V_{I+}-V_{I-}$, $V_{Q+}-V_{Q-}$), which have the same frequency and differential peak-to-peak amplitude of 2.40V with a supply voltage of 2.5V. The phase difference is 90°.

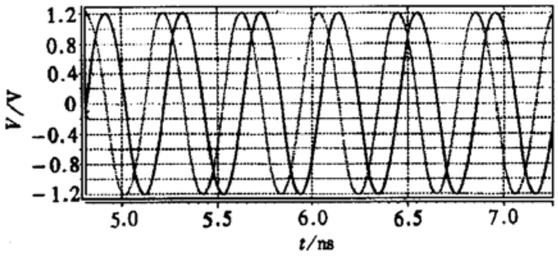

Fig. 3 Transient simulated waveforms of two quadrature outputs from VCO core

To obtain the quadrature performance of the outputs in the mismatch of two sections, the transient simulations and FFT analysis were performed under 1% mismatch of the inductors and diodes. Table 1 lists the experimental results. It can be seen from Table 1 that the maximum phase error is less than 2.1° and the amplitude rate is less than 1.01 when the mismatch of the inductors and the diodes are both 1% at the center frequency.

Table 1 Effect of the mismatched degree of the LC tank components on the phase accuracy and gain matching

	f = 2.445G			
Mismatched degree	L: 0 C: 0	L: 1% C: 1%	L: 1% C: 0	L: 0 C: 1%
Core phase error: $V_I\sim V_Q$	0.003	2.09	1.22	0.87
Out phase error: $V_{IOUT}\sim V_{QOUT}$	0.000	2.06	1.20	0.85
Core amplitude rate: V_I/V_Q	1.000	1.009	1.004	1.006
Out amplitude rate: V_{IOUT}/V_{QOUT}	1.000	1.011	1.004	1.006

5 Measured results

To verify the performance of the quadrature VCO, the proposed circuit was fabricated in 0.25μm single-poly five-metal N-well salicide 2.5V CMOS digital process. Figure 4 shows the microphotograph of the fabricated VCO and the test box. The die size is 0.83mm×0.68mm. A significant portion of the die is occupied by the pads and two inductors, and the core circuit area is only 0.62mm×0.41mm.

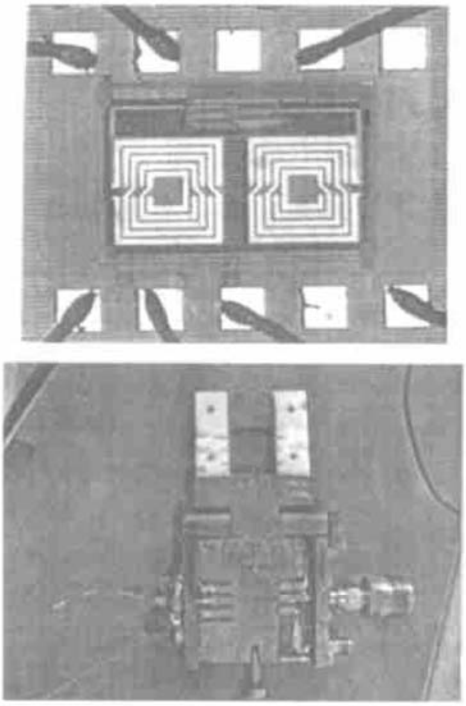

Fig. 4 Microphotograph of the fabricated VCO and the test box

Experimentally measured VCO transfer function is showed in Fig. 5. When the control voltage varying from 0.8V to 3.5V, the oscillation frequency will vary from 2.160GHz to 2.465GHz. Therefore, a tuning rang more than 300MHz can be obtained. Such a very wide frequency rang can satisfy many kinds of applications.

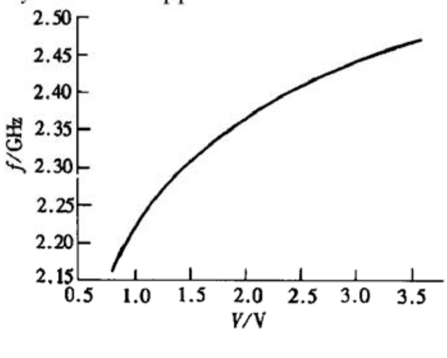

Fig. 5 Experimentally measured VCO transfer function

Figure 6 shows 2.35GHz output spectrum of the VCO when the control voltage is 2.0V. The phase noise is − 104.33dBc/Hz at 600kHz offset at 2.41GHz as shown in Fig. 7. The measurement is done on one port of the differential outputs to reduce the package pins. In case the differential outputs are drawn out, the measured phase noise would be more than 6dBc. It can be explained as: when we measure on the differential output, the oscillation amplitude will be twice larger. According to Eq. (1), the phase noise would be 6dBc; and differential outputs can reduce the common-mode noise, so the phase noise will be more than − 110.33dBc/Hz at 600kHz offset at 2.41GHz if the different outputs are utilized. This result is similar to the simulated result.

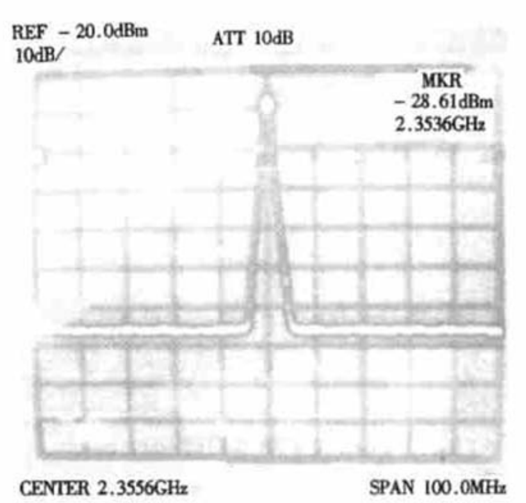

Fig. 6 Output spectrum of the VCO

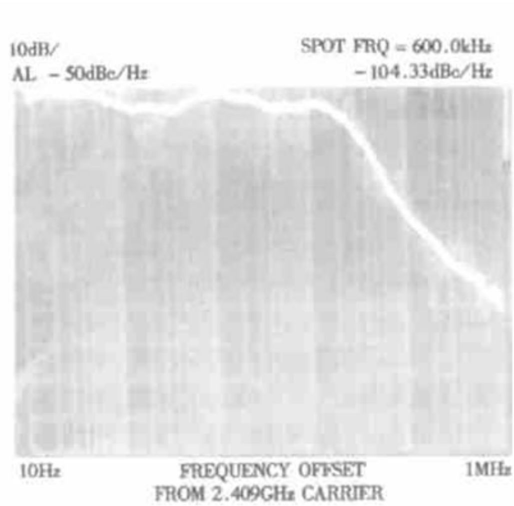

Fig. 7 Measured phase noise performance on one port of differential

With the power supply voltage of 2.5V and the oscillation frequency of 2.36GHz, the total supply current is only 21mA (four buffers are included) and the total power consumption is only 52.5mW (four buffers are included). So each LC-VCO only consumes 26.3mW or less (including two buffers), which is very efficient.

6 Conclusion

A quadrature VCO is proposed and fabricated, which can generate quadrature LO signals with high phase accuracy and good gain match under low power, good phase noise and small area. The measured results have proved the proposed circuits with good performance can be used in many integrated transceivers.

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基于对称螺旋型电感和差分二极管的 2.4GHz CMOS 正交输出压控振荡器*

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摘要: 提出了一种产生 2.4GHz 正交本地振荡信号的方法. 它将 LC-VCO 和两级环路振荡器两种结构组合起来以实现正交输出的低相位噪声压控振荡器. LC 网络是由在片对称螺旋型电感和差分二极管组成的. 详细论述了 VCO 原理及其噪声性能. 该电路已经用 0.25μm 单层多晶、五层金属 N 阱 CMOS 数字工艺制作. 测量结果表明: 它可以提供正交的本地振荡信号, 其振荡频率可以在 300MHz 的范围内调节, 当仅对差分输出振荡信号的一端进行测试时, 振荡频率为 2.41GHz 时, 去偏移中心为 600kHz 时的相位噪声为 - 104.33dBc/Hz. 而且, 它能在很低的电源电压下工作, 功耗也很低, 所以, 它在集成收发机中将得到广泛的应用.

关键词: 正交压控振荡器; 对称螺旋型电感; 差分二极管

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