Journal of Southeast University (English Edition) Vol.20 No.1 Mar. 2004 ISSN 1003—7985

Low phase noise LC VCO design in CMOS technology

Li Zhiqun[1] Wang Zhigong[1] Zhang Liguo[1] Xu Yong[1,2]

([1] Institute of RF & OE-ICs, Southeast University, Nanjing 210096, China)

([2] Institute of Science, PLA University of Science and Technology, Nanjing 210007, China)

Abstract: This paper presents the design and the experimental measurements of two CMOS LC-tuned voltage controlled oscillators (VCO) implemented in a 0.18 μm 6-metal-layer mixed-signal/RF CMOS technology. The design methodologies and approaches for the optimization of the ICs are presented. The first design is optimized for mixed-signal transistor, oscillated at 2.64 GHz with a phase noise of −93.5 dBc/Hz at 500 kHz offset. The second one optimized for RF transistor, using the same architecture, oscillated at 2.61 GHz with a phase noise of −95.8 dBc/Hz at 500 kHz offset. Under a 2 V supply, the power dissipation is 8 mW, and the maximum buffered output power for mixed-signal and RF transistor are −7 dBm and −5.4 dBm, respectively. Both oscillators make use of on-chip components only, allowing for simple and robust integration.

Key words: RF integrated circuit; CMOS technology; mixed-signal transistor; RF transistor; voltage controlled oscillator; phase noise

The continuous increase of data speeds in radio communications has motivated the design and implementation of RF integrated circuits in the range of 2 to 6 GHz[1−4]. The representative systems include wireless LAN (WLAN) systems in the US and European high performance radio LAN (HIPERLAN). The CMOS technology is attractive from the standpoints of integration, power, and cost. With the feature size scaling down to 0.18 μm and below, the CMOS technology is becoming the most interesting process for RF integrated circuits.

Integrated LC-tuned VCOs are common functional blocks in modern RF communication systems and generally used as local oscillators for signal up- and down-converting. Due to the ever-increasing demand for bandwidth, very stringent requirements are placed on the spectral purity of local oscillators. Low phase-noise is required to avoid corrupting the mixer-converted signal by close interfering tones.

The design of two LC VCOs is presented in this paper. The first is optimized for a mixed-signal transistor, and the second is optimized for an RF transistor. Both circuits are implemented in TSMC's 0.18 μm CMOS technology.

1 Circuit Design

The schematic of the LC VCO is shown in Fig.1. It is a cross-coupled differential VCO with both PMOS and NMOS cross-coupled amplifiers, which generate negative resistance to cancel losses of the LC tank. The tank consists of an inductor and four junction varactors. The outputs are buffered using source-followers (M_5, M_6) for the purpose of measurement. The sources of M_5 and M_6 are connected to external bias-Ts to provide high AC impedance. In this way small transistors can be used to provide enough output current driving without loading the VCO core excessively.

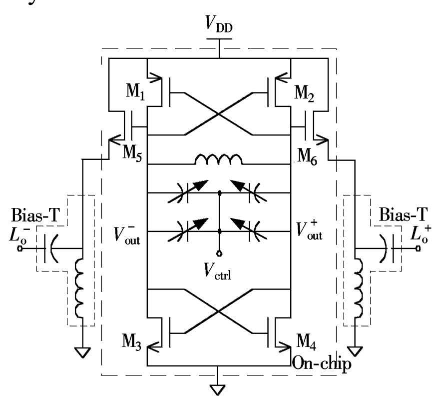

Fig.1 LC VCO with varactor tuning

1.1 Phase noise

An important parameter of VCO is the phase noise in the vicinity of the center frequency f_0. The output phase noise at an offset Δf from f_0 can be approximated by the following relationship

$$L\{\Delta f\} = kT(1+A)Z_0\frac{1}{Q_{tank}}\left(\frac{f_0}{\Delta f}\right)^2\frac{1}{V_{rms}^2} \quad (1)$$

where k is the Boltzman's constant, T is the absolute temperature, A is the noise factor safety margin necessary to ensure oscillation start-up, V_{rms} is the root-mean-square voltage at the oscillation node, $Z_0 = \sqrt{L/C_{tank}}$ is characteristic impedance of the tank, and

Received 2003-11-24.

Foundation item: The National High Technology Research and Development Program of China (863 Program) (No.2002AA1Z1600).

Biographies: Li Zhiqun (1959—), male, doctor, associate professor, zhiqunli@seu.edu.cn; Wang Zhigong, male, doctor, professor, zgwang@seu.edu.cn.

Q_{tank} is the quality factor[5]. Eq.(1) indicates that maximizing the quality factor of the tank circuit would improve the noise performance considerably.

1.2 Integrated inductor

Because the phase noise is primarily dependent on the inductor's quality factor, on-chip inductors are very critical to the design of a fully integrated VCO. The on-chip spiral inductor is designed to optimize geometric parameters such as diameter, number of turns, etc. in order to achieve a minimum loss. The turns of the inductors provided by Foundry are 2.5, 3.5, 4.5, 5.5, 6.5, 7.5. The inductor used for our design has been chosen between these inductors for a maximum quality factor. It has a quality factor above 9 between 2.0 and 3.0 GHz for 2.5 turns with a diameter of 120 μm realized on the top layer of 2 μm thick metal, and the inductance is 2.3 nH.

1.3 The varactors

The variable capacitor needed for frequency tuning can be implemented in an MOS varactor and p^+n junction varactor. Our oscillator is simulated with a p^+n junction varactor and an MOS varactor, respectively, and the oscillation waveforms are observed. The simulation results demonstrate that the oscillator using the p^+n junction varactor has much better oscillation waveforms than that using the MOS varactor. Also the first one has a spectrum of greater purity than the second one. Thus, p^+n junction varactors have been used in the oscillator.

Each junction varactor uses 37 P^+ strips. Each strip has a width of 0.42 μm and a length of 40 μm; the capacitance varies from 1.12 to 1.48 pF. To obtain a center frequency of 2.7 GHz, four junction varactors are used: two in the series are connected in parallel with two other varactors in a series as shown in Fig.1.

1.4 The cross-coupled amplifiers

Two cross-coupled amplifiers provide negative resistance to compensate the losses in the LC resonator. The resistance of one cross-coupled amplifier (see Fig. 2) can be calculated as

$$v_{in} = v_{gs2} - v_{gs1} \tag{2}$$

$$i_{in} = g_{m1} v_{gs1} = -g_{m2} v_{gs2} \tag{3}$$

From Eqs.(2) and (3), the input resistance R_{in} can be expressed as

$$R_{in} = \frac{v_{in}}{i_{in}} = -\frac{1}{g_{m1}} - \frac{1}{g_{m2}} \tag{4}$$

where g_{m1} and g_{m2} are transconductances of transistors M_1 and M_2, respectively. With $g_{m1} = g_{m2} = g_m$, Eq.(4) becomes

$$R_{in} = -2/g_m \tag{5}$$

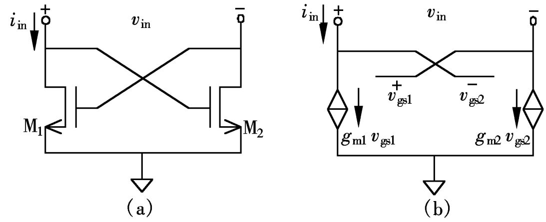

Fig.2 Cross-coupled amplifier. (a) Amplifier circuit; (b) Equivalent circuit

For the two cross-coupled amplifiers shown in Fig.1, the negative resistance is simply the negative resistance of transistors M_1/M_2 in parallel with that of the transistors M_3/M_4, and it can be expressed as

$$R_{in} = -\frac{2}{g_{m12} + g_{m34}} \tag{6}$$

where g_{m12} and g_{m34} are transconductances of transistors M_1/M_2 and M_3/M_4, respectively. The condition to ensure stable oscillation is that the loss of LC resonator must be cancelled by the negative resistor given by Eq. (6). When the total loss is expressed by an equivalent resistance R_P which is in parallel with the LC tank, the condition of oscillation is

$$R_P \geqslant \frac{2}{g_{m12} + g_{m34}} \tag{7}$$

Note that the circuit with two cross-coupled amplifiers can satisfy Eq.(7) more easily than a single cross-coupled one.

2 IC Fabrications

The oscillator was designed in TSMC's 0.18 μm 1P6M CMOS technology in two versions, one with a mixed-signal transistor and the other with an RF transistor as shown in Fig.3 and Fig.4, respectively.

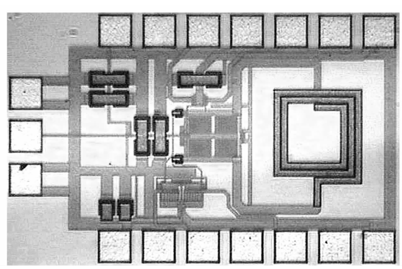

Fig.3 Microphotograph of oscillator with mixed-signal transistor

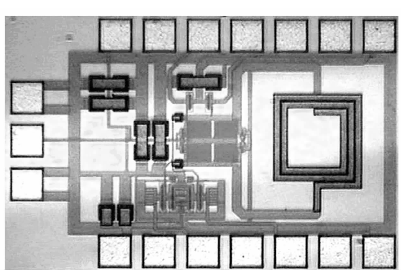

Fig.4 Microphotograph of oscillator with RF transistor

3 Measurement

3.1 Frequency tuning

The implemented VCOs were measured using on-wafer probing together with a 22 GHz HP8593A spectrum analyzer. The frequency-voltage characteristics were measured for V_{ctrl} between 1.2 V and 3.0 V with 2 V V_{DD} as shown in Fig. 5. The frequency tuning ranges measured are about 8.6%.

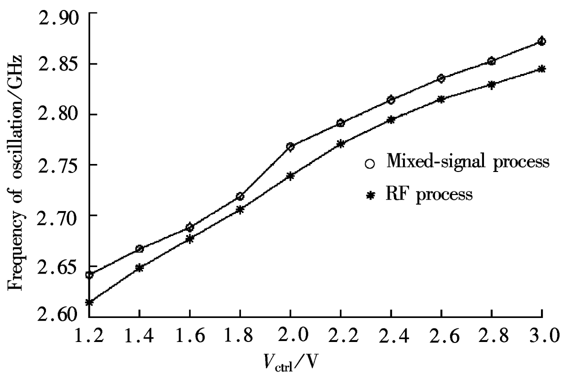

Fig.5 Frequency vs. tuning voltage

3.2 Phase noise

The phase noise was measured using an HP8593A spectrum analyzer. For the measurement of the phase noise, the control voltage of the varactor is set internally to 1.2 V to avoid the external interference to the oscillator with a power supply of 2 V. The oscillator with the mixed-signal transistor oscillates at 2.641 8 GHz with phase noise −93.5 dBc/Hz at 500 kHz, and the oscillator with RF transistor oscillates at 2.614 3 GHz with phase noise −95.8 dBc/Hz at 500 kHz, and the measured results are shown in Fig.6 and Fig.7, respectively.

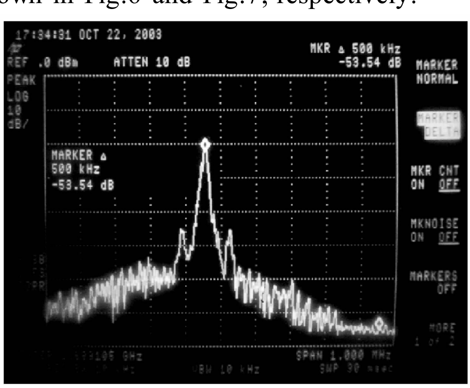

Fig.6 Spectrum output of VCO with mixed-signal transistor

By comparing the measured results of Fig.6 and Fig.7, the phase noise with RF transistor is 2.3 dB less than that with the mixed-signal transistor. The mixed-signal transistor is a pure transistor. The RF transistor

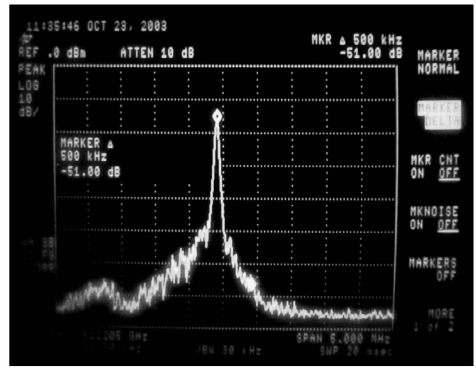

Fig.7 Spectrum output of VCO with RF transistor

is a transistor with an RF isolation ring around it with the substrate connected to the ground, so the interferences of peripheral devices' pulse currents and noise of the substrate are decreased. This results in the phase noise of the oscillator implemented with RF transistor being better than that with the mixed-signal transistor. Since the RF transistor occupies more area than the mixed-signal transistor with the same number of fingers, this means the RF transistor has more parasitic capacitance. Therefore, the oscillation frequency of the oscillator with the RF transistor is lower than that with mixed-signal transistor, and this is verified by the measured results.

4 Conclusion

Optimization methodologies to design low phase noise and high frequency LC VCOs were presented. The comparison of performance of two oscillators reported that the oscillator with RF transistor has lower phase noise than that with the mixed-signal transistor due to the good isolation of noise and interference of the RF transistor.

References

[1] Fong Neric, Plouchart Jean-Olivier, Zamdmer Noah, et al. A low-voltage multi-GHz VCO with 58% tuning range in SOI CMOS [A]. In: **Proc IEEE CICC** [C]. Orlando, Florida, 2002. 423−426.

[2] Vaananen P, Metsanvirta M, Tchamov N. A 4.3 GHz VCO with 2 GHz tuning range and low phase noise [J]. *IEEE J Solid-State Circuits,* **2001, 36**(1): 142−146.

[3] Kinget P. A fully integrated 2.7 V 0.35 μm CMOS VCO for 5 GHz wireless applications [A]. In: *ISSCC Dig Tech Papers* [C]. San Francisco, 1998. 226−227.

[4] Lam C, Razavi B. A 2.6 GHz/5.2 GHz CMOS VCO [A]. In: *ISSCC Dig Tech Papers* [C]. San Francisco, 1999. 402−403.

[5] Craninckx J, Steyaert M, Miyakawa H. A fully integrated spiral-LC CMOS VCO set with prescaler for GSM and DCS-1800 systems [A]. In: *Proc IEEE CICC* [C]. Santa Clara, 1997. 403−406.

CMOS 工艺的低相位噪声 LC VCO 设计

李智群[1] 王志功[1] 张立国[1] 徐 勇[1,2]

([1] 东南大学射频与光电集成电路研究所, 南京 210096)
([2] 解放军理工大学理学院, 南京 210007)

摘要: 本文介绍了用 0.18 μm 6 层金属混合信号/射频 CMOS 工艺设计的 2 个 LC 谐振压控振荡器及测试结果, 并给出了优化设计的方法和步骤.第 1 个振荡器采用混合信号晶体管设计, 振荡频率为 2.64 GHz, 相位噪声为 −93.5 dBc/Hz@500 kHz.第 2 个振荡器使用相同的电路结构, 采用射频晶体管设计, 振荡频率为 2.61 GHz, 相位噪声为 −95.8 dBc/Hz@ 500 kHz.在 2 V 电源下, 它们的功耗是 8 mW, 最大输出功率分别为 −7 dBm 和 −5.4 dBm. 2 个振荡器均使用片上元件实现, 电路的集成简单可靠.

关键词: 射频集成电路; CMOS 工艺; 混合信号晶体管; 射频晶体管; 压控振荡器; 相位噪声
中图分类号: TN402