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A CMOS LC VCO with 3.2～6.1GHz Tuning Range*

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Abstract: The design and implementation of a CMOS LC VCO with 3.2～6.1GHz tuning range are presented. This is achieved by enhancing the tuning capability of the binary-weighted band-switching MIM capacitor. The circuit has been implemented in a 0.18μm RF/Mixed-Signal CMOS process. The measured phase noise is −101.67dBc/Hz at 1MHz offset from a 5.5GHz carrier, and the VCO core draws 9.69mA current from a 1.8V supply.

Key words: wideband; LC VCO; CMOS; MB-OFDM UWB
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1 Introduction

A voltage-controlled oscillator (VCO) must have a wide enough tuning range and low enough phase noise to satisfy wireless communication protocol. Compared with a ring oscillator, CMOS LC VCO has quite low phase noise but a relatively narrow tuning range. A wideband CMOS LC VCO seems unnecessary for the GSM, GPRS, CDMA, and other narrow-band communication systems. But the emergence of UWB or IEEE 802.15.3a, which covers the frequency range from 3.1 to 10.6GHz, has introduced a demand for an ultra wideband VCO.

It has been revealed that the shift of working state with frequency tuning is another handicap for tuning range besides the tuning range of the LC tank[1]. On this discovery, a CMOS LC VCO with tuning range of 31～111MHz was designed by dividing the cross-coupled MOSFET pair into several switchable parts[2]. This technology works well in VHF band applications. But in a GHz VCO, the tuning range of the LC tank plays the dominant role for the frequency coverage of the VCO. This paper proposes an ultra wideband VCO with a tuning range of 3.2 to 6.1GHz, which can cover the center frequency of bands 1 to 5 in the MB-OFDM UWB protocol.

2 Circuit design: considerations and optimization

In GHz applications, a CMOS LC VCO always adopts the LC tank shown in Fig. 1. It is made up of a single on-chip spiral inductor with fixed inductance and limited quality factor, and binary-weighted band-switching MIM capacitors to adjust the output frequency coarsely and a MOS varactor with continuous effective capacitance to cover the output frequency seamlessly. The required tuning range capacity of this circuit has been accomplished[3]. Assuming that the MIM branches can be increased arbitrarily, the ultimate tuning range of the VCO is determined by the limit

$$\lim_{n\to\infty}\mathrm{TR}=\sqrt{\frac{\beta_a\beta_p+\beta_a}{\beta_p+\beta_a}}\qquad(1)$$

where n is the number of switched MIM capacitor branches, β_a is the on/off ratio of effective capacitance of MIM capacitor branch, and β_p is the ratio of the total tank capacitance at the lower frequency end to the total parasitic capacitance. This limit indicates that the tuning range is mainly determined by the MIM branches and the portion of parasitic capacitance in the LC tank.

As shown in Frame II of Fig. 1, four-band binary-weighted MIM capacitor branches are used to adjust the output frequency coarsely. These ca-

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pacitors are scaled up by 2 and are indexed by i from 0 to 3. When the control logic V_{SWi} is 1, the corresponding branch is on. By simulation, MCS0 is designed to be 3/0.18μm for the unit 18μm × 18μm MIM capacitor branch. The simulation results show that β_a, the quality factors of the branch in on-mode, are 9.9 and 8.5, respectively. The high value of β_a is achieved at a cost of lowering the quality factor. This will result in that more power consumption is required to sustain the start-up condition in the low frequency end.

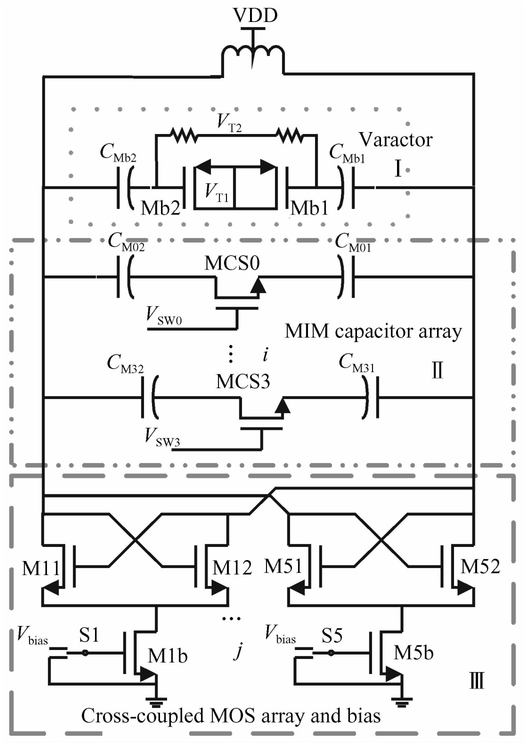

Fig.1　Schematic of the ultra wideband VCO

In Frame I of Fig. 1, by applying the differential control voltages, V_{T1} and V_{T2}, to the symmetry MOS varactors Mb1 and Mb2, the effective control voltage applied to the varactors changes from +1V to ±1.0V. The simulation result shows that C_{max}/C_{min} increases from 2.14 to 2.65.

The selected inductor must satisfy both the frequency range constraint and the start-up constraint. Since the nonlinear characteristic is weighted by $\sqrt{L/C}$[1], a large inductance requires a small MOSFET to maintain the output amplitude for the start-up constraint, and vice versa. On the other hand, the frequency tuning range requires a smaller inductance for a larger capacitance in the tank. But a larger transistor can lower β_p by introducing more parasitic capacitance proportional to its size. A tradeoff must be carried out to balance the total size of the MOSFET and the inductance. As a result, a symmetric middle-tapped inductor built by the top metal is used in this oscillator with three turns, 12μm wire width, 2μm space, 2μm thickness and 50μm inner diameter. The simulations by ADS show that its inductance, quality factor, and parasitical capacitance at 6GHz are 1.0622nH, 9.67, and 25.56fF, respectively.

With the selected inductor, the lowest frequency requires the total width/length ratio of the cross-coupled MOSFET pair to be 186/0.18μm. In Frame III of Fig. 1, the total size is divided into five scaling-down-by-2 parts, which are indexed by j from 1 to 5. The size of the minimal part is 6/0.18μm. The parasitic capacitance introduced by the MOSFET is about 190fF. In view of the parasitic capacitance of the wire and load, β_p is about 8.

For the above elaborate design, a die photograph of the circuit is shown in Fig. 2. The die size is 1260μm × 670μm, including pads and guard rings. The VCO core occupies only about a quarter of the die area. In this figure, the capital characters 'A' through 'G' represent the symmetric inductor, the bias transistors, the symmetric MOS varactor, the cross-coupled MOSFET, the four-band-switching generic-weighted MIM capacitor, the control logic unit, and the output buffer, respectively.

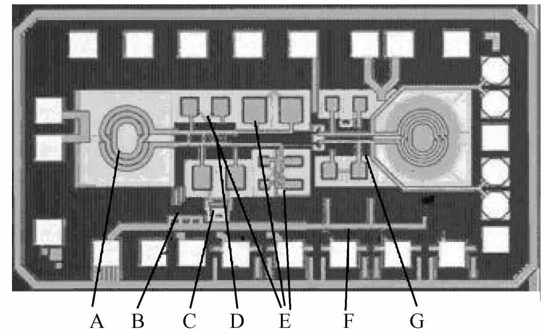

Fig.2　Die photograph

3　Measured results

Figure 3 shows the measured frequency tuning range of the designed VCO. The band is indexed in the manner of $1+\sum_i V_{\mathrm{SW}i}\times 2^i$. The x-axis represents the differential control-voltage applied to the varactor, $V_{\mathrm{T1}}-V_{\mathrm{T2}}$. With 16 bands, the oscillator can cover a tuning range of 3.2 to 6.1GHz. By switching S1 to S5 according to the setting of $V_{\mathrm{SW}i}$, the current drawn by the VCO core is adjusted from 7mA at the high frequency end to 45mA at the low frequency end, and the output amplitude is maintained between −17～−13dBm. The phase noise at 5.5GHz carrier is shown in Fig.4.

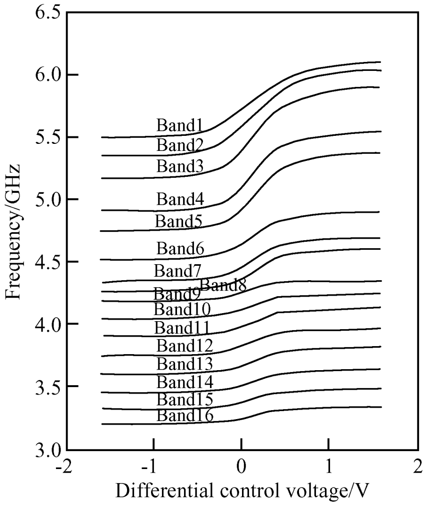

Fig.3 Measured frequency tuning characteristic

A comparison of tuning ranges between this work and recent reports about VCOs beyond GHz is listed in Table 1. This work is outstanding in both output frequency range and absolute frequency coverage, $f_{\mathrm{H}}-f_{\mathrm{L}}$. Compared to Refs.[4,5], which were in the 5GHz band, the tuning range of this work is more than twice as wide. Although its relative tuning range is a little bit narrower than that of Ref.[3], the output frequency is almost triple that of Ref.[3]. Although the high/low frequency ratio of this work is similar to that of Ref.[6], the absolute frequency coverage is 200MHz more than that of Ref.[6], and the output amplitude does vary only less than 5dB, while this deviation in Ref.[6] is more than 10dB. The phase noise of this work is worse than that of Refs.[3～5], but better than that of Ref.[6].

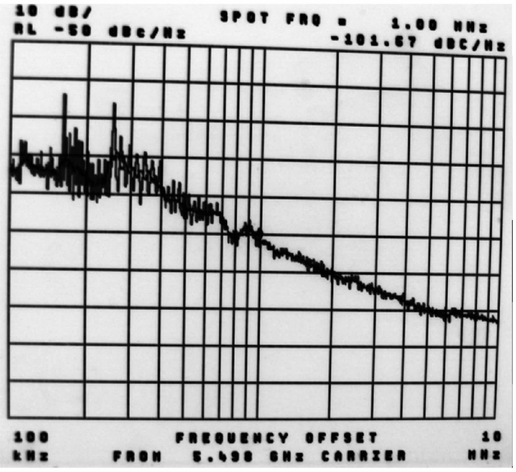

Fig.4 Phase noise at 5.5GHz carrier

Wideband performance is achieved at a cost of power consumption. Especially at the low end of the frequency, since the quality factor is depressed during the optimization of generic-weighted capacitor array, the power consumption is more than 6 times that at the upper frequency end. This work and Reference [3] achieve comparable tuning ranges with different β_{a} and β_{p}. Some tradeoff between these parameters would lead to better tuning range performance.

Table 1 Comparison of tuning ranges

	CMOS process	Tuning range/GHz	$f_{\mathrm{H}}/f_{\mathrm{L}}$	$f_{\mathrm{H}}-f_{\mathrm{La}}$ /GHz	Power /mW	Max KVCO /(MHz/V)	Phase noise
Ref.[3]	0.18	1.14～2.46	2.15	1.32	2.6～10	270	−123.5@600kHz
Ref.[4]	0.13-SOI	3.816～5.712	1.50	1.9	2.3～2.7	～300	−117@1MHz
Ref.[5]	0.13-HR	4.6～5.9	1.27	1.3	3.84	NA	−126@1MHz
Ref.[6]	0.18	2.7～5.4	2	2.7	18.4	1687	−90～−95@1MHz
This work	0.18	3.2～6.1	1.91	2.9	12～81	～1800	−95～−101@1MHz

4 Conclusion

This paper presents the design of an ultra wideband CMOS LC VCO with a tuning range of 3.2～6.1GHz. This frequency range can cover the center frequency of band 1 to 5 in MB-OFDM UWB protocol. The VCO is fabricated in 0.18μm CMOS technology. Typical measured phase noise is －101.67dBc/Hz at 1MHz offset from 5.5GHz carrier frequency for a core power consumption of 17.5 mW from a 1.8V supply.

In GHz application, the determinant factor for the tuning range performance is the tuning range of the LC tank due to its poor characteristics. Although the switchable cross-coupled MOSFET can elevate the tuning range in the low frequency band effectively, it seems helpless in a GHz band CMOS LC VCO since the state-shift is not so severe in the tuning range capability of the LC tank.

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频率覆盖 3.2～6.1GHz 的 CMOS LC VCO*

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摘要：通过提高 MIM 电容的调整范围，实现了一个覆盖 3.2～6.1GHz 的 CMOS LC VCO. 该 VCO 使用 0.18μm 射频 CMOS 工艺制作，芯片面积约为 1260μm × 670μm. 当输出 5.5GHz 时，VCO 内核消耗功率为 17.5mW；在 100kHz 频偏处的相位噪声是 -101.67dBc/Hz.

关键词：宽带；UWB；压控振荡器；CMOS

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