JOURNAL OF THE KOREA ELECTROMAGNETIC ENGINEERING SOCIETY, VOL. 4, NO. 4, DEC. 2004 JKEES 2004-4-4-05

A Low Phase Noise 5.5-GHz SiGe VCO Having 10 % Bandwidth

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Abstract

A bandwidth-enhanced and phase noise-improved differential LC-tank VCO is proposed in this paper. By connecting the varactors to the bases of the cross-coupled transistors of the proposed LC-tank VCO, its input negative resistance has been widened. Also, the feedback capacitor C_C in the cross-coupling path of the proposed LC-tank VCO attenuates the output common-mode level modulated by the low-frequency noise because the modulated common-mode level jitters the varactor bias point and degrades phase noise. Compared with the fabricated conventional LC-tank VCO, the proposed LC-tank VCO demonstrates 200 % enhancement in tuning range, and 6 – dB improvement in phase noise at 6 MHz offset frequency from 5.4-GHz carrier. We achieved the phase noise of – 106 dBc/Hz at 6 MHz offset, and 10 % tuning range from the proposed LC-tank VCO. The proposed LC-tank VCO consumes 12 mA at 2.5 V supply voltage.

Key words : VCO, Phase Noise, 1/*f* Noise, SiGe, HBT, Varactor Diode.

Ⅰ. Introduction

Recently, the versatile communication system such as SDR(software defined radio) is required to provide different wireless mobile phone services to users. Therefore, a lot of wide-band and low-noise RF components have been researched and developed to implement the versatile communication system[1]~[5].

In the implementation of multi-band and multi-mode transceiver including frequency synthesizer, it is difficult to design wideband and low-phase noise VCO because the varactor diode having both wide capacitance range and low noise is not easy to be fabricated in Bipolar, BiCMOS and CMOS process.

In reference [1] and [2], the accumulation-mode MOS capacitor was manufactured in order to achieve wide capacitance range and low noise characteristics. The accumulation MOS capacitor shows wide capacitance than PMOS. The designed VCO with accumulation MOS capacitor represents about 11 % frequency-tuning range.

Using accumulation-mode MOS capacitor fabricated on SOI substrate, the tuning range of VCO was over 50 %[3]. But the phase noise is degraded due to the high VCO tuning sensitivity. Therefore, for the purpose of reducing the VCO sensitivity and obtaining wideband VCO, the digital switching technique was implemented by using many MOS capacitor in parallel. However, this method makes the frequency synthesizer locking system complicated[4].

The low-frequency noise such as flicker noise injects into the varactor and modulates the varactor capacitance. In this way, the upconverted low-frequency noise degrades phase noise of VCO. At high VCO sensitivity, the phase noise is also increased because of the more low-frequency noise injection into varactor. According to [5] and [6], since the low-frequency noise can be considered as common-mode noise, the differential tuning technique attenuates the low-frequency noise injected into the dual varactor diodes.

In order to achieve both wide tuning range and low phase noise, more than two VCOs are connected in parallel, and then one of them is activated at desired oscillation frequency. However, this method is inefficient in cost since this VCO group take large chip area[7].

A small area of active inductor was developed to reduce both the chip area and the components of VCO. The active-inductor VCO represents the wide-band frequency tuning range over 50 %, but does not display

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Manuscript received July 20, 2004 ; revised November 25, 2004. (ID No. 20040720-026J)

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good phase noise[8].

In order to implement wideband VCO, both wide negative resistance and large varactor capacitance ratio should be achieved. The boosting transformer is utilized for increasing negative resistance in the cross-coupled LC-tank VCO instead of rising up its tail current[9].

In this paper, the varactor connection to the bases of the cross-coupled pair is to increase the negative resistance and widen tuning range of the proposed LC-tank VCO of Fig. 2. The feedback capacitor C_c is used to stop the output common-mode level modulated by the low-frequency noise from varying the varactor bias point. The proposed LC-tank VCO shows about 200 % increment in frequency tuning range, and 6-dB reduction in phase noise at 6 MHz offset frequency from 5.4 GHz carrier. In the proposed LC-tank VCO, we achieved 10 % frequency-tuning range, and low phase noise of −108 dBc/Hz at 6 MHz offset frequency from 5.4-GHz carrier.

Ⅱ. Wide-Band and Low-Phase Noise VCO Design

2-1 Frequency-Tuning Range Improvement

In this section, a simple method is presented to widen the frequency tuning range of the conventional LC-tank VCO of Fig. 1. For manufacturing wideband VCO, both broad negative resistance and wide varactor capacitance range are necessary. The wide capacitance range has been implemented using MOS capacitor such as accumulation MOS[2],[3]. In reference [2] and [3], however, the negative resistance range is not considered in the conventional LC-tank differential VCO of Fig. 1. As resonant frequency increases, the loss of LC-tank resonator also increases. Accordingly, we must increase the negative resistance of the cross-coupled pair and compensate the increasing loss of LC-tank. As shown in Fig. 3(a), if the varactor capacitor C_v is varied from

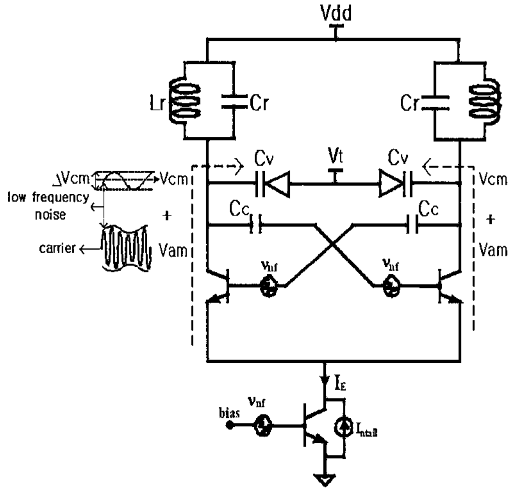


Fig. 1. Conventional LC-tank VCO.

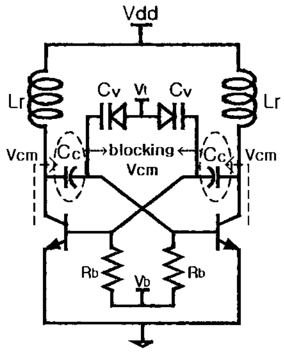
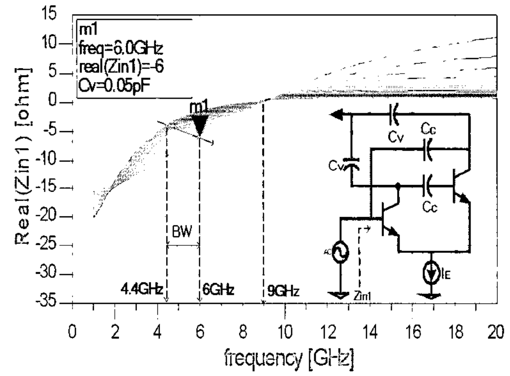
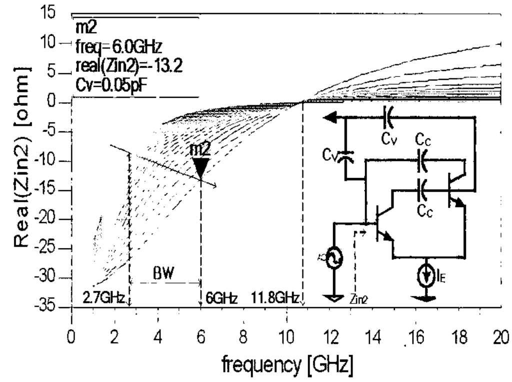


Fig. 2. Proposed LC-tank VCO.



(a)



(b)

Fig. 3. (a) Simulated input resistance of the conventional LC-tank VCO of Fig. 1, (b) Simulated input resistance of the proposed LC-tank VCO of Fig. 2.

1.05 pF to 0.05 pF, that is, oscillation frequency increases, the negative resistance value at oscillation frequency increases, moving to high frequency region for compensating the growing loss of LC-tank. The BW of Fig. 3 represents the effective negative resistance range that can generate oscillation. The wider is the BW, the wider the frequency-tuning range. However, the effective negative resistance bandwidth(BW) of the conventional LC-tank VCO is narrow as 1.6 GHz(from 4.4 GHz to 6.0 GHz) as shown in Fig. 3(a). Accordingly, the conventional LC-tank VCO cannot achieve wide frequency-tuning range. The circuit diagrams in Fig. 3(a) and (b) is used for simulating the input resistances of the conventional LC-tank VCO and the proposed LC-tank VCO.

In this paper, the proposed LC-tank VCO of Fig. 2 is presented to widen the effective negative resistance (BW), accordingly. As shown in Fig. 3(b), the effective negative resistance(BW) of the proposed LC-tank VCO has been widened as 3.3 GHz(from 2.7 GHz to 6.0 GHz). The effective negative resistance(BW) of the proposed LC-tank VCO has been increased about 1.7-GHz compared to the conventional LC-tank VCO, and hence the proposed LC-tank VCO can achieve over two times the frequency-tuning range of the conventional LC-tank VCO. As shown in Fig. 3, also, the maximum frequency representing negative resistance is 9 GHz in the conventional LC-tank VCO, but then the maximum frequency of the proposed LC-tank VCO is higher than the conventional as 10.8 GHz. The approximate input impedances of the conventional LC-tank VCO and the proposed LC-tank VCO are given by

$$Z_{in1} = -\frac{2g_m C_c(C_c - 2C_v)}{g_m^2(C_c - 2C_v)^2 + \omega^2 C_c C_v} - j\frac{2\omega C_c^2 C_v}{g_m^2(C_c - 2C_v) + \omega^2 C_c C_v}\,[\Omega] \tag{1}$$

$$Z_{in2} = -\frac{2g_m(C_c + C_v)}{C_c(g_m^2 + 4\omega^2 C_v^2)} - j\frac{4\omega C_v(C_c + C_v)}{C_c(g_m^2 + 4\omega^2 C_v^2)}\,[\Omega] \tag{2}$$

where g_m is the transconductance of Q_1 and Q_2, C_v is the varactor capacitance, C_c is DC-decoupling capacitance or feedback capacitance. From (1) and (2), it is well known that when the value of C_c gets larger, C_v gets ignored, and hence the input negative resistance of (1) and (2) gets similar as (3) and (4).

$$Re(Z_{in1}) = -\frac{2g_m}{g_m^2 + \omega^2 C_v / C_c}\,[\Omega], \quad \text{if } C_c \gg C_v \tag{3}$$

$$Re(Z_{in2}) = -\frac{2g_m}{g_m^2 + 4\omega^2 C_v^2}\,[\Omega], \quad \text{if } C_c \gg C_v \tag{4}$$

This is because the circuit topologies of Fig. 1 and Fig. 2 get identical if C_c is shorted. Therefore, the effective negative resistances of Fig. 3(a) and Fig. 3(b) represent similar range. However, if C_c gets comparable to C_v, the effective negative resistance of the proposed LC-tank VCO gets larger and wider as C_v decreases from 1.05 pF to 0.05 pF. But, the effective negative resistance of the conventional LC-tank VCO gets smaller and narrower than the proposed LC-tank VCO due to the subtraction factor($C_c - 2C_v$) of Real (Z_{in1}) of (1). From the proposed LC-tank VCO of Fig. 2, the frequency-tuning range was simulated from 4,760 MHz to 5,700 MHz. The simulation result showed about 500 MHz bandwidth increment compared to the conventional LC-tank VCO.

2-2 Low-Frequency Noise Suppression

The low-frequency noise not only disturbs the sine waveform, but also degrades phase noise. This low-frequency noise voltage v_n is included in the Lesson's phase noise model as (5)[10].

$$L = 10\log\left\{ \left(\frac{f_c}{2Qf_{off}}\right)^2 \left(\frac{FkT}{2P_o}\left(1 + \frac{f_{1/f}}{f_{off}}\right)\right) + \left(\frac{K_{vco} v_n}{2f_{off}}\right)^2 \right\} \tag{5}$$

where f_c is the signal frequency, f_{off} is the offset frequency, P_o is the signal output power, $f_{1/f}$ is flicker noise frequency, K_{vco} is the VCO gain in Hz/V, v_n is all the low-frequency noise voltage, and other parameters are described in [10]. From (5), the phase noise can be reduced by means of increasing the Q-factor of LC-tank resonator and the signal power, and also decreasing the low-frequency noise power.

All low-frequency noises such as flicker noise are emerged from the cross-coupled transistors and the tail current source as shown in the conventional LC-tank VCO of Fig. 1. In Fig. 1, V_{nf} represents low-frequency noise due to flicker noise, and I_{ntail} represents thermal noise from tail current. The low-frequency noise source V_{nf} modulates the carrier amplitude as well as the output common-mode level V_{cm}[5],[6]. As shown in Fig. 1, the low-frequency modulation of tail current I_E modulates the oscillation amplitude, and thus causes a frequency shaking and phase noise. This is called amplitude modulation (AM)-to-frequency modulation

(FM) conversion effect. V_{am} of Fig. 1 represents the amplitude modulation signal. Also, the low-frequency modulation of the output common-mode level V_{cm} fluctuates the varactor tuning voltage V_t and thus induces a frequency variation and degrades phase noise. That is, the output common-mode voltage V_{cm} is varied about ΔV_{cm} because the low-frequency noise modulates the tail current I_E. This is called common-mode modulation(CMM)-to-frequency modulation(FM) conversion effect. The varactor bias voltage variation due to the commode-mode modulation is given by

$$V_{con} = V_t - V_{cm} = V_t - (V_{dd} - \alpha_F \cdot I_E \cdot R_{par}) \qquad (6)$$

where V_{con} is the total bias voltage to the varactor, R_{par} is the parasitic parallel resistor of LC-tank resonator. α_F is common-base forward short-circuit current gain. As shown in (6) and (7), the modulated output common -mode voltage due to the variation of I_E directly modulates the capacitance C_v. This varactor modulation shows up as jitter in time-domain sine waveform as expressed by

$$C_v = C_o + K_{vco} \cdot V_{con} = C_o + K_{vco} \cdot (V_t - V_{cm})[F] \qquad (7)$$

$$f_{c1} = \frac{1}{\sqrt{L_r(C_r + C_v)}}[Hz] \qquad (8)$$

$$f_{c2} = \frac{1}{\sqrt{L_r C_v}}[Hz] \qquad (9)$$

where C_o is the zero bias capacitance, K_{vco} is the VCO gain in Hz/V, f_{c1} is the carrier frequency of the conventional LC-tank VCO, f_{c2} is the carrier frequency of the proposed LC-tank VCO. From (7)~(9), if C_v is varied due to the low-frequency modulation of V_{cm}, the carrier frequencies f_{c1} and f_{c2} shake, and thus phase noise is induced.

After all, the tail current variation due to the low-frequency noise results in both AM and CMM modulation, and thus degrades the phase noise of VCO.

In this paper, two methods in the proposed LC-tank VCO of Fig. 2 are presented to reduce the phase noise of the conventional LC-tank VCO. First, the DC decoupling capacitor or feedback capacitor C_c prevents the modulated output common-mode voltage from injecting into the varactor and modulating the varactor bias point. Therefore, the phase noise degradation due to the common-mode modulation is lessened because the output common-mode voltage is cut off by C_c. Nevertheless, the varactor in the proposed LC-tank VCO of Fig. 2 suffers from the DC base voltage variation due to the low-frequency noise at the bases of the cross-coupled transistors, and hence this common-mode variation cannot be completely avoided. But then, the low-frequency modulation of the base voltage is insignificant compared to the output common-mode modulation V_{cm}.

Secondly, the phase noise is improved by increasing signal swing at the collectors of the cross-coupled transistors. The collector-base junction of the cross-coupled transistors is hindered from being forward-biased in order to increase signal swing at the collector node. The capacitor divider, composed of C_c and C_v, prevents the forward bias of the collector-base junction, and hence the signal swing in the LC-tank resonator can be increased. Therefore, phase noise can be reduced due to high signal swing.

III. Measurements

For the purpose of demonstrating the improved frequency-tuning range and phase noise of the proposed complete VCO circuit in Fig. 5, we manufactured the conventional complete VCO circuit of Fig. 4 using 0.8-

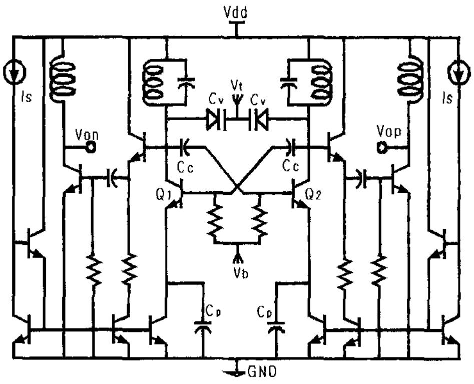


Fig. 4. Full schematic of the conventional LC-tank VCO.

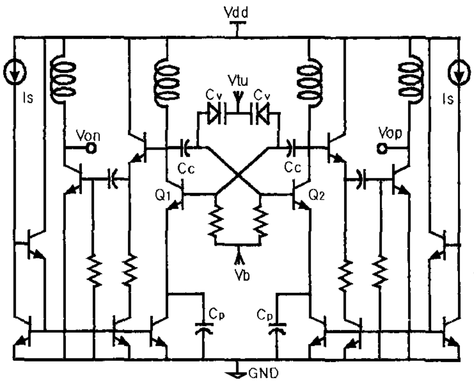
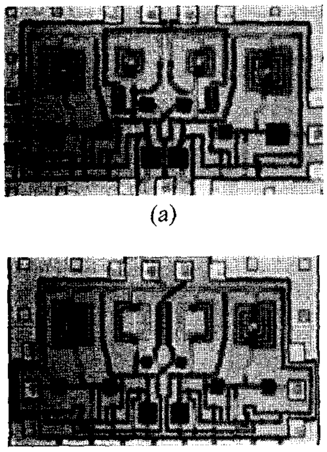


Fig. 5. Full schematic of the proposed LC-tank VCO.

μm SiGe HBT process. The shunting capacitance C_p in VCO circuits of Fig. 4 and Fig. 5 has a role to shunt fundamental frequency and harmonics to ground, but also filters out the thermal noise I_{ntail} around even harmonics coming from tail current. As shown in Fig. 4 and 5, the Darlington pairs are used for buffering the differential outputs of the LC-tank VCOs. Their chip photographs are shown in Fig. 6. Their chip sizes are almost the same as 1.0 mm×0.8 mm areas.

The measured phase noises of the VCOs in Fig. 4 and 5 are compared in Fig. 7. The proposed LC-tank VCO displays phase noise of −108 dBc/Hz at 6 MHz offset frequency from 5.4-GHz carrier, and represents phase noise reduction by 6-dB. Therefore, it is proven that C_c has prevented the modulated output common-mode level from injecting into the varactor, and the signal power in LC-tank has been increased by the capacitor divider prevention of the forward bias of the collector-base junction of the cross-coupled pair. As shown in Fig. 8(a) and (b), the tuning range of the proposed LC-tank VCO is measured from 5,100 MHz to 5,600 MHz, but then that of the conventional LC-tank VCO from 5,384 MHz to 5,520 MHz. Accordingly, about 370 MHz enhancement in frequency-tuning range has been achieved from the proposed LC-tank VCO. The performance results of the conventional LC-tank VCO and the proposed LC-tank VCO are summarized in Table 1.


(a)

(b)

Fig. 6. Chip photographs of (a) the conventional LC-tank VCO and (b) the proposed LC-tank VCO.

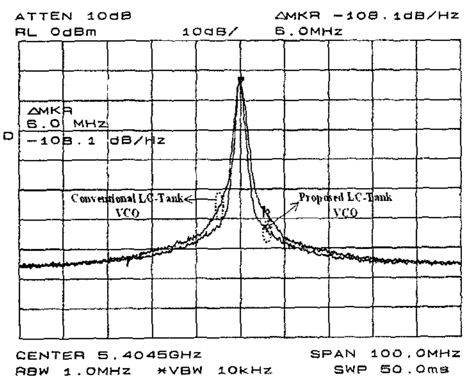
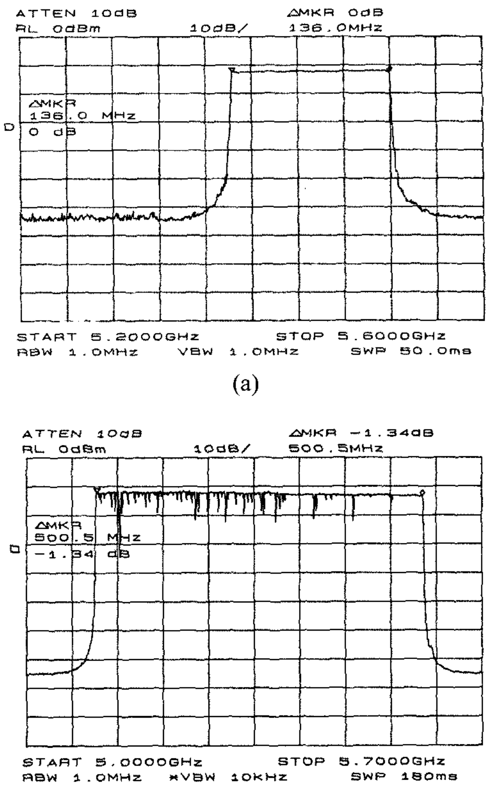


Fig. 7. Measured phase noises of the conventional LC-tank VCO and the proposed LC-tank VCO.



(a)

(b)

Fig. 8. Measured frequency-tuning ranges of (a) the conventional LC-tank VCO and (b) the proposed LC-tank VCO.

FOM(figure of merit) is used to compare the performances of two VCOs as shown in (8).

$$FOM = 10\log f_c^2 - 10\log(f_{off}^2 P_d) - dB[L(f_{off})] \qquad (10)$$

where P_d is dissipated power in mW, $L(f_{off})$ is measured phase noise.

The FOMs of the conventional LC-tank VCO and the proposed LC-tank VCO are calculated as 145 dB and 153 dB, respectively. Therefore, the proposed LC-tank VCO is better than the conventional LC-tank VCO in performance by 8-dB.

Table 1. Summary of performance parameters about the conventional LC-tank VCO and the proposed LC-tank VCO

VCO type / Parameters	Conventional LC-tank VCO	Proposed LC-tank VCO
V_{cc} [V]	2.5	2.5
I_{total} [mA]	14	12
P_{out} [dBm]	- 12.0	- 12.0
Tuning range [MHz]	5,380~5,520	5,100~5,600
Harmonics [dBc]	< -23	< -21
Phase noise [dBc/Hz]	- 102@6 MHz	- 108@6 MHz
Phase noise [dBc/Hz]	- 108@10 MHz	- 113@10 MHz
Figure of merit [dB]	145@6 MHz	153@6 MHz

Ⅳ. Conclusion

In this proposed LC-tank VCO, DC-decoupling capacitor C_c is used to prevent the modulated output common-mode level injection into the varactor, and this reduces phase noise. Also, the capacitor divider, consisting of C_c and C_v, is used to increase the signal power of the LC-tank resonator, and this results in improved phase noise. Therefore, the proposed LC-tank VCO shows 6-dB improvement of phase noise compared to the conventional LC-tank VCO. Also, the varactor connection to the bases of the cross-coupled pair results in extending the effective negative resistance and broadening the frequency-tuning range. Accordingly, the proposed LC-tank VCO shows 200 % increment of tuning range compared to the conventional LC-tank VCO. In conclusion, this paper presents a simple, low-cost and effective method to improve the phase noise and frequency-tuning range of the conventional LC-tank VCO.

This work was supported by the Ministry of Information and Communication, Republic of Korea.

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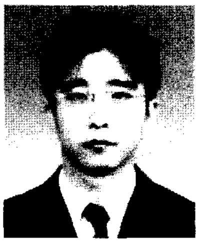

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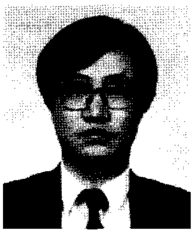

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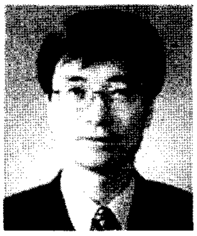

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