Progress In Electromagnetics Research C, Vol. 25, 81–91, 2012

A COMPACT SIZE LOW POWER AND WIDE TUNING RANGE VCO USING DUAL-TUNING LC TANKS

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Abstract—A novel 12 GHz VCO designed and fabricated in a 0.18 µm SiGe BiCMOS technology is presented. Strongly magnetic coupled dual *LC* tanks with fixed and tunable capacitive elements are introduced to extend tuning range and improve phase noise. By hybrid using of varactor tuning, loaded transformer tuning and switched capacitor tuning, the proposed VCO achieves a wide tuning range of 4.3 GHz (36%) and output power of −9 dBm with only 4.5 mW power consumption and only 0.17 mm^2 chip area.

1. INTRODUCTION

Voltage-controlled oscillators (VCOs) with wide tuning ranges are highly demanded for today's multi-standard and multiband communication systems to cut down the cost by reducing the required number of the VCO [1–4]. There are different ways to implement the VCO for wideband operation [5–10]. A ring type of oscillator has a wide tuning range but suffers from relative poor phase noise and larger power consumption [5, 6]. By using binary-weighted varactor bank, S. A. Osmany designed a VCO with 17% tuning range [7]. Through tuning varactors in both base node and emitter node of the HBT transistor, a VCO with wide tuning range of 21% was developed by Chiong et al. [8]. Pohl et al. achieved wideband VCO of 30% tuning range by using special designed varactors on a special process [9]. Safarian and Hashemi realized an even wider triple-mode VCO with coupled inductors and three discrete active VCO cores [10].

In this paper, we proposed a wideband VCO design technique by using dual *LC* tanks, which are coupled each other through

Received 13 September 2011, Accepted 28 October 2011, Scheduled 4 November 2011
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strong magnetic coupling of the transformer. The dual strongly magnetic coupled LC tanks with fixed and tunable capacitive elements can further extend tuning range and improve phase noise. At the same time, the chip area is dramatically reduced due to the magnetic enhancement of the transformer. The design method can be implemented on commercial CMOS or BiCMOS process and it also gives a good tradeoff among power consumption, phase noise, and tuning range etc. The proposed technique is investigated and demonstrated by designing a 12 GHz VCO (VCO1). The implemented VCO1 demonstrates a wide tuning range of 36% (4.3 GHz) with a low power consumption of only 4.5 mW and small chip area of 0.17 mm^2. As a contrast to the proposed VCO1, another VCO named as VCO2 designed with conventional topology and approximately similar device sizes is also implemented on the same process for a comparison.

2. PROPOSED VCO ARCHITECTURE

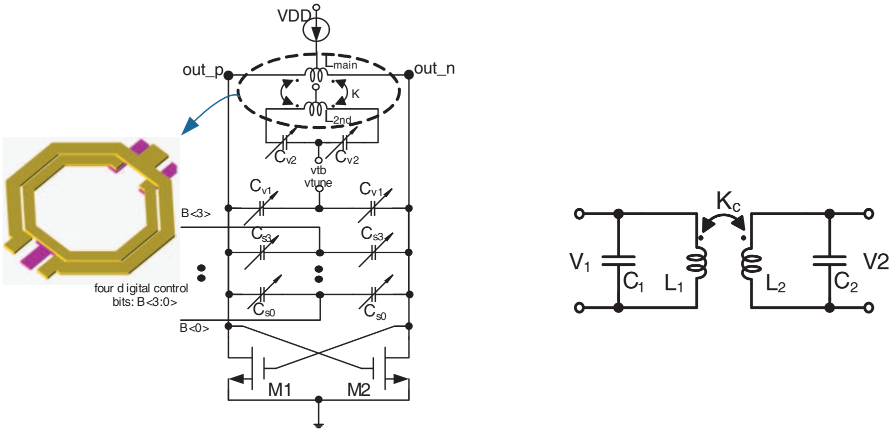
Figure 1(a) illustrates the schematic of the proposed VCO1. Dual strongly magnetic coupled LC tanks are dedicated to extend tuning range and improve phase noise concurrently. The outer coil (L_{main}) of the transformer incorporating with 4-bits digital controlled switched varactors and the analog controlled varactor pair C_{v1} operates as primary LC tank. The inner coil (L_{2nd}) of the transformer and varactor pair C_{v2} work as the secondary LC tank. The capacitance at gate node and drain node of the cross-coupled NMOS transistors M1 and M2 also contributes to the primary LC tank.

The coupled primary LC tank and the secondary LC tank can be simply modeled as Figure 1(b), where L_1 and L_2 denote the inductance of the two coils respectively with coupling coefficient of K_c. C_1 and C_2 are the capacitive portions of the two LC tanks. For analysis simplicity, the tank resistance is neglected, since our emphasis here is focused on frequency, which is mainly determined by inductance and capacitance. Based on Figure 1(b), Z_{11} can be derived and expressed as Equation (1). It can be observed from Equation (1) that the transformer based resonator has two possible resonance frequencies f_H and f_L as expressed in Equation (2).

$$Z_{11} = \frac{(j\omega)^3 \cdot (1 - K_c^2)L_1L_2C_1 + j\omega L_1}{1 + (j\omega)^4 \cdot (1 - K_c^2)L_1C_1L_2C_2 + (j\omega)^2 \cdot (L_1C_1 + L_2C_2)} \quad (1)$$

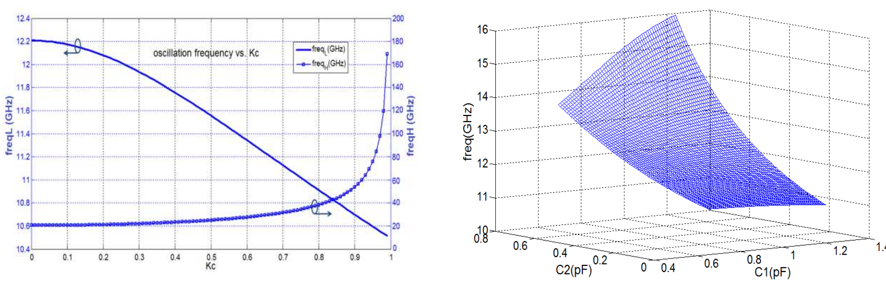
$$f_{L,H} = \sqrt{\frac{2}{f_1^2 + f_2^2 \pm \sqrt{4K_c^2 f_1^2 f_2^2 + (f_2^2 - f_1^2)^2}}} \cdot f_1 f_2 \quad (2)$$

where $f_1 = 1/(2\pi\sqrt{L_1C_1})$ and $f_2 = 1/(2\pi\sqrt{L_2C_2})$ are the resonant



(a) (b)

Figure 1. VCO1 with proposed magnetic coupled dual-tuning *LC* tanks. (a) Simplified schematic. (b) Simplified model of transformer based resonator.



(a) (b)

Figure 2. Oscillations frequency for VCO with magnetic coupled *LC* tanks. (a) f_H and f_L versus K_c. (b) Oscillation frequency f_L versus tank capacitances.

frequencies of the primary *LC* tank and the secondary *LC* tank, respectively.

According to Equation (2), a series of curves can be plotted. Figure 2(a) illustrates the relationship of frequencies f_H and f_L versus K_c for fixed inductive and capacitive elements (L_1, L_2, C_1 and C_2 being set to 0.17 nH, 0.15 nH, 1 pF, 0.4 pF respectively for an example). Theoretically, by proper selection of the coupling coefficient K_c, device sizes, proper switching between high frequency mode and low frequency mode, and also with the assistance of switched capacitor bank to realize a suitable overlap of the high frequency band and low frequency band, it is expected that an ultra wideband frequency tuning range can be achieved. In this paper, we are more interested in the relatively lower oscillation frequency f_L. Generally, the Q-factor of the primary inductor can be enhanced in the lower frequency band f_L, therefore to improve phase noise performance. Hence, we did not switch between f_L and f_H in our designs and only f_L is used.

Inspecting f_L expressed in Equation (2), when C_1 of the primary LC tank incorporates tuning varactors, there is a two-dimensional tuning curve (frequency versus vtune or versus C_1) as traditional VCO designs in literature. In the condition that C_2 of the secondary LC tank also incorporate tuning varactors, the frequency tuning curve would be in the form of three-dimension as shown in Figure 2(b) (L_1 and L_2 being set to 0.17 nH, 0.15 nH; K_c being set to 0.5; C_1 and C_2 sweeping from 0.4 pF to 1.2 pF and 0 to 0.8 pF respectively for an example). Obviously, the tuning range can be extended with introduction of the second tuning varactors of the secondary magnetic coupled LC tank. In this paper, the primary varactors are tuned by vtune, which comes from charge pump output, and the secondary varactors are controlled by vtb. Basically, the three-dimensional form as shown in Figure 2(b) can also have its two-dimensional form with a set of frequency tuning curves versus vtune (corresponding to C_1) for different vtb (corresponding to C_2), which will be shown later in Figure 6(a). The figure will show that the tuning range is indeed extended compared to the conventional VCO design of VCO2 more intuitively.

Practically, transformer based VCO has improved phase noise [11]. It is known that phase noise of VCO designs can be roughly described by the Lesson formula [12]:

$$L(\Delta\omega) \propto F\frac{4KTR_{\tan k}}{V_0^2}\left(\frac{\omega_0}{2Q_{\tan k}\Delta\omega}\right)^2 = \frac{F}{Q_{\tan k}^2}\frac{4KTR_{\tan k}}{V_0^2}\left(\frac{\omega_0}{2\Delta\omega}\right)^2 \tag{3}$$

with F being the noise factor, K being the Boltzmann constant, T being the temperature, V_0 being the signal amplitude and ω_0 being the centre frequency. According to Equation (3), a high tank quality factor Q_{tank} helps to improve phase noise performance. And the quality factor (Q-factor) of the LC tank is determined by the Q-factors of the inductor and capacitor as in Equation (4).

$$1/Q_{tank} = 1/Q_C + 1/Q_L \tag{4}$$

For a conventional single LC tank VCO with inductor L_1 and capacitor C_1, the oscillation frequency is $f_0 = 1/(2\pi\sqrt{L_1C_1})$. When incorporating a secondary coil L_2 into inductor L_1 with coupling coefficient $0 < K_c < 1$, the inductance of the primary coil changes to $L_{1\_2} = (1 + K_c)L_1$. The capacitive elements C_1 of the primary LC tank remains unchanged. To maintain the oscillation frequency $f_0 = 1/(2\pi\sqrt{L_1C_1})$, the length of the primary coil should be reduced to meet $(1 + K_c) \cdot L_{1reduced} = L_1$. Therefore the electrical length (which is associated with inductor loss) of the primary coil is reduced to $L_{1reduced} = L_1/(1 + K_c)$ (for our case, the extracted $K_c \approx 0.5$). As both the DC and AC resistances of the inductor is roughly proportional to the value or length of the inductor, the reduced inductor length leads to the reduced resistance of the inductor and thus an improved Q_L is achieved. The improved Q-factor of the inductor contributes to the improved Q-factor of LC tank and thus the phase noise of the proposed transformer-based VCO designs.

Therefore, concurrent tuning range extension and phase noise improvement is possible to be achieved based on the proposed idea. In practice, at frequencies around 10 GHz and less, Q_L is less than Q_C, hence Q_L dominates Q_{tank}. In this case, when the secondary LC tank is used to enhance frequency tuning range, the effect of the secondary varactors may not be so significant to eliminate the benefit from the enhanced Q-factor of the inductor due to magnetic coupling. Therefore the phase noise performance still can be superior compared to the conventional designs. Of course, the secondary varactors cannot be unlimited large to have unlimited tuning range enhancement effect. The widest tuning range might be expected at the point when the benefit from the enhanced Q-factor of the inductor is totally eliminated by the secondary varactors.

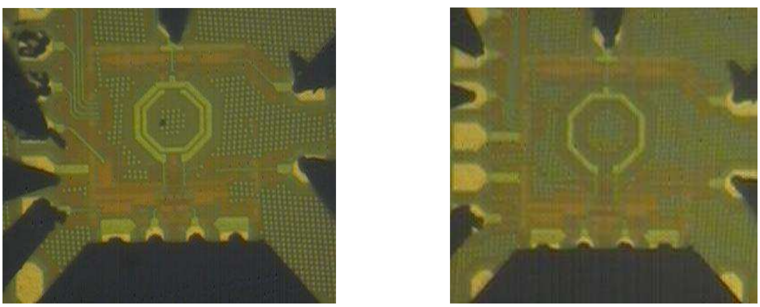
3. IMPLEMENTATION AND MEASUREMENT RESULTS

The 12 GHz VCO1 with proposed technique is implemented based on Jazz 0.18 µm SiGe 1P6M BiCMOS process with only CMOS devices. For a transformer, the important parameters are coupling coefficient K_c, inductance L_1 and L_2 of the primary coil and the secondary coil. In addition, the parasitic resistance dominates the quality factor. And the parasitic capacitance affects the operating frequency. To reduce resistive loss and parasitic capacitance to ground, the transformer is implemented with top metal layer as shown in Figure 1(a). Since the primary focus of this paper is to introduce a novel VCO based on coupled LC tanks through the transformer, there is no accurate scalable model of the transformer. Fortunately, foundry's accurate process parameters are used to carry electromagnetic (EM) simulation with ADS Momentum to get the S-parameter files of the presented transformer. The EM based S-parameters are used to extract the transformer parameter such as K_c, L_1, L_2 etc.. Basically, the inductance for the primary coil is around 0.34 nH (differential); the inductance for the secondary coil is around 0.26 nH (differential) and K_c is around 0.5. The primary coil has a Q-factor of around 17 at 12 GHz range, while the Q-factor of the secondary coil is slightly lower. The parameters of the transformer will affect the performance of the VCO designs. The selection of the parameters must be taken care of.

In addition to the 4-bits binary-weighted MOS varactor bank for coarse frequency tuning, analog tuning MOS varactors are also used in both the primary LC tank and the secondary LC tank, controlled by vtune and vtb respectively. From our investigation, the varactor size for the main LC tank is designed to make the single curve tuning range to be around 600 MHz, otherwise if the tuning range is too large (corresponding to a large K_{VCO}), it will degrade phase noise performance due to DC noise modulation.

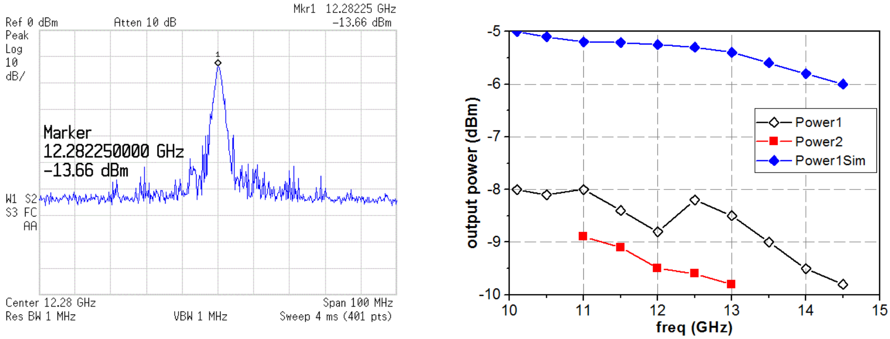
As a contrast case, VCO2 based on the conventional topology with only one LC tank is also designed and fabricated. The die photos of VCO1 and VCO2 are shown in Figure 3. Both VCOs have the same buffer stage and chip size of $0.41\,\text{mm} \times 0.43\,\text{mm} = 0.17\,\text{mm}^2$. The two VCOs are measured with on-wafer probe testing system with similar testing setup, including equipments and biasing voltages etc.. Through the testing, we keep a relative constant current consumption of around 2.5 mA for both VCO1 and VCO2 all over the tuning range, which is also the current we used for simulations of both VCO1 and VCO2.

Figure 4(a) shows the measured spectrum of VCO1. Taking into account the additional 4.6 dB loss from coaxial cable and adaptors



(a) (b)

Figure 3. Die photos: (a) VCO1 with proposed magnetic coupled LC tanks; (b) VCO2 with normal LC tank and same parameter settings.

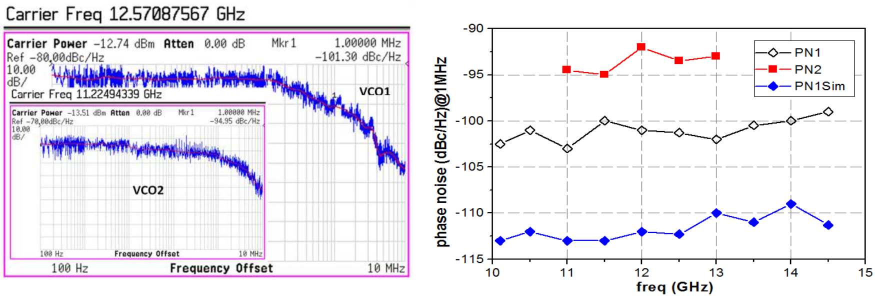


(a) (b)

Figure 4. Measurement results. (a) Measured output spectrum of VCO1. (b) Output power of VCO1 and VCO2 of the entire tuning range (with 4.6 dB cable and interface adaptors loss taken into account).

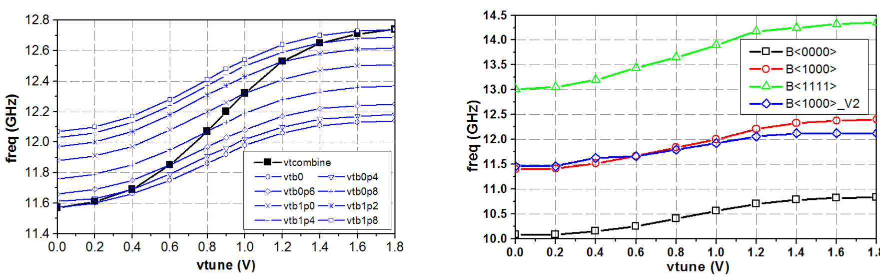
for measurement connection at 12 GHz, the output power of VCO1 is around −9 dBm. The output power of the entire tuning range for VCO1 and VCO2 as well as the simulated output power of VCO1 is illustrated in Figure 4(b), where the 4.6 dB cable and adaptor loss has been taken into account. The figure indicates that the output power of the proposed VCO1 is around 1 dBm higher than VCO2. This should be the benefit of the enhanced Q-factor of the tank due to magnetic coupling. However it is around 3 dBm lower than the simulation results. It should come from the under-estimated parasitic including pad loss and some interconnects loss. The output power can be further increased by increasing the current of VCO core or output buffer properly.

Figure 5 presents the phase noise performance of the two versions VCO designs. From the die photo shown in Figure 3, it can be found that there are quite a number of external biasing pads in the two VCOs. Owing to testing limitation, we do not have so many voltage sources with elaborate filtering at the time. Several off-chip low-pass filters (LPFs) and Bias-Tees are used to help to filter out the noise from various DC supplies/biasing. The measured phase noise of VCO1 is around −101.3 dBc/Hz at 1 MHz offset as shown in Figure 5(a). It is around 6 dBc better than that (−95 dBc/Hz) of the conventional VCO2, which is tested with the same testing setup. The phase noise performance of the entire tuning range for the two VCO designs is illustrated in Figure 5(b). The result shows that the measured phase noise of VCO1 deviates from its simulated results. One of the reasons is



(a) (b)

Figure 5. Measurement results. (a) Phase noise of VCO1 and VCO2. (b) Phase noise performance of VCO1 and VCO2 of the entire tuning range.



(a) (b)

Figure 6. Tuning range. (a) Tuning curves of VCO1 with digital bits setting to <1,0,0,1>. (b) Total tuning range of VCO1 (with control signals vtune and vtb combined), and tuning range of VCO2 with digital bits setting to <1,0,0,0>.

that the filtering effect of the LPFs (with bandwidth of 30 MHz, which is not narrow enough) on the low frequency noise from DC supplies are not so efficient. Another reason should be the device modeling and parasitic. Anyway, the results indicate that the transformer-based VCO1 has improved phase noise performance about 5 dBc to 7 dBc better compared with the conventional VCO2 design. This should demonstrate our idea that the proposed magnetic coupled dual-tuning LC tanks benefit phase noise performance.

Figure 6(a) shows the tuning curves of VCO1 when the four digital control bits B<i> (i = 3, 2, 1, 0) set to <1,0,0,1> referred to Figure 1(a). For a fixed vtb such as 0.8 V (expressed as vtb0p8 in Figure 6(a)), the curve has around 600 MHz tuning range, which is actually close to the tuning range of VCO2. When vtb varies from

Table 1. Summary of VCO performance.

Ref	Technology	Central freq (GHz)	Tuning range	PN@1MHz (dBc/Hz)	P_{DC} (mW)	FOM (dBc/Hz)	Area (mm^2)
[8]	InGaP-AsGa	13.3	21%	−117	75	−184	3.0
[13]	0.18µm CMOS	11.22	2.67%	−109.4	6.84	−170.3	0.3
[14]	0.18µm CMOS	11.55	5.45%	−110.8	8.1	−177.7	0.44
[15]	InGaP-AsGa	11.87	3.78%	−108	25.7	−167	0.54
[16]	InGaP-AsGa	12	4.76%	−113.8	36	−173	0.57
VCO1	**0.18µm SiGe**	**12.1**	**36%**	**−101**	**4.5**	**−187**	**0.17**

0 V to 1.8 V, there are a series of tuning curves with a total range of 1.17 GHz (from 11.57 GHz to 12.74 GHz), which is almost doubled compared with VCO2. Besides the above-mentioned case that vtune and vtb are controlled separately to get a series of curves, there is a special case that vtune and vtb are controlled by the same voltage named vtcombine to get a single curve for simplicity, as the thick solid black curve shown in Figure 6(a). This curve also has a tuning range around 1.17 GHz.

As the digital bits increase from <0,0,0,0> to <1,1,1,1>, the total tuning range of VCO1 is as large as 36%, which is around 4.3 GHz from 10.1 GHz to 14.4 GHz as demonstrated in Figure 6(b). Figure 6(b) also shows with digital bits setting to <1,0,0,0>, the conventional VCO2 obtains 630 MHz tuning range (curve B<1000>_V2), which is only around 60% of VCO1 (curve B<1000>). This further proves the proposed technique.

The performance of VCO1 and several 12 GHz VCO designs in literature are summarized in Table 1. The comparison demonstrates the advantage of wide tuning range, low power, compact size and compatible phase noise performance for the proposed VCO architecture.

The figure of merit (FOM) taking the frequency tuning range ratio (FTR) into account for VCO designs is expressed as [15]:

$$FOM = L(\Delta f) - 20\log\left(\frac{f_0}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1\,\text{mW}}\right) - 20\log\left(\frac{FTR}{10\%}\right) \quad (5)$$

4. CONCLUSION

A technique using strongly magnetic coupled dual-tuning LC tanks with fixed and tunable capacitive elements, which help to extend VCO tuning range and improve phase noise, is presented and demonstrated in this paper. The proposed dual-tuning VCO is also useful for narrow-band applications, since usually the measured frequency deviates from simulation results. The VCO can still cover the required frequency band by adjusting vtb only. Thereafter the binary-weighted capacitor or varactor bank can be reduced to further improve phase noise and reduce chip area. Especially, the proposed low power compact VCO with the dedicated idea can be easily integrated on-chip with other blocks.

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