A 5.5 GHz Voltage Control Oscillator (VCO) with a Differential Tunable Active and Passive Inductor

Najmeh Cheraghi Shirazi, Ebrahim Abiri, and Roozbeh Hamzehyan, *Member, IACSIT*

***Abstract*—By using a differential tunable active and passive inductor for LC tank, respectively a wide tuning rang and high phase noise performance CMOS voltage control oscillator (VCO) is introduced and compared. In the proposed circuits' structure, the coarse frequency tuning is provided by the tunable active inductor, while the fine tuning is controlled by varactor. Using a 0.18µm CMOS process, complete pattern VCOs are designed in ADS. The output frequency in both structures is 5.5GHz. The design based on active inductor generates unacceptable phase noise in compare with on passive inductor. The measured phase noise in 1-MHz offset is -81 and -106.4dBc in VCO with active and passive inductor respectively. The non existence of passive components in the first structure causes VCO to have the smaller chip area than the circuit with passive inductors.**

***Index Terms*—Differential active inductors, passive inductor, frequency tuning range, phase noise, voltage control oscillator (VCO), wideband**.

I. Introduction

In the modern communication systems, VCOs act as basic building blocks for transmitting the frequency. Due to high phase noise performance, VCO with LC tank are highly utilized with passive inductors and varactors in the radio frequency. Practically the tuning rang of VCO is low and these makes them unsuitable for wideband applications. By utilizing switched capacitors [1], [2] and switched inductors [3], [4], tuning rang of wide frequency can be obtained. The disadvantages are: enlarging the chip area and complexity of control mechanism.

For overcoming these restrictions, the concept of frequency tuning is introduced by active inductors. In this study by using a circuit structure in reference [5] and change the parameters of transistors and increase the central frequency up to 5.5GHz, higher development of wide tuning rang VCO performance with active inductors is reached. Then its results are compared with the same structure by passive inductor. The proposed VCOs in the 0.18µm process are designed which is suitable for system integration in transceiver designs.

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II. Circuit Structure

A. VCO Structure with Active Inductor

VCO circuit in Fig. 1 shows that the LC tank made up of a tunable active inductor and varactor for frequency control. Negative conductance ($-G_m$) is also used for compensating the LC tank losses. An active inductor is used as a mechanism for frequency wide tuning and a varactor for fine tuning. A tunable active inductor consisted of M_1-M_6 transistors. A two port circuit structure results in the complete performance differential VCO. The equivalent inductance of active inductor is controlled by V_{ctrl1}.

MOS in accumulation mode acts as a varactor. The capacitance of varactor is controlled by V_{ctrl2}. The NMOS cross coupled transistors (M_7-M_8) is used for loss compensating and also providing the negative conductance. The NMOS cross coupled transistors with differential active inductor is utilizing for circuit bias and for minimize the power consumption. The open drain buffer transistors (M_9-M_{10}) is employed for driving the 50-load of testing instruments.

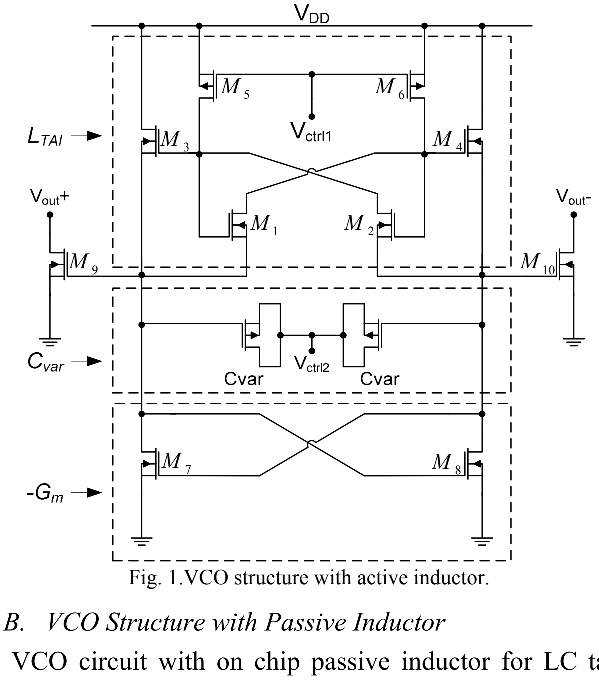

Fig. 1.VCO structure with active inductor.

B. VCO Structure with Passive Inductor

VCO circuit with on chip passive inductor for LC tank shown in Fig. 2. This kind of oscillator provides a very competitive phase noise performance when working at the radio frequency due to the narrow band tank. The passive inductor plays a decisive role in the *LC* oscillator performance, especially the phase noise performance. The cross coupled transistors (M_7-M_8) is used for loss compensating of LC tank and providing negative conductance ($-G_m$). Two transistors (M_1-M_2) are in current

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mirror and used as a circuit bias. The varactor is used in order to fine tuning, therefore it can used for sensitivity tuning without decreasing of VCO total tuning range. The capacitance of varactor is controlled by V_{ctrl2}.

III. Circuit Analysis

A. Small Signal Characteristics of Active Inductor

A wide tuning range VCO is obtained by tunable active inductor design therefore small signal characteristics are used to describe the differential active inductor behavior. Fig. 3 shows a small signal equivalent circuit of active inductor (in Fig.1) consists of transistors M_1-M_6. Based on DC, M_1 and M_2 are two cross coupled transistors while M_3 and M_4 are in drain common mode. At working point transistors M_1-M_4 become saturated and M_5, M_6 act in each of the saturated or triode regions according to the controlled voltage in gate (V_{ctrl1}). Therefore M_5 and M_6 modeled as g_{ds5} and g_{ds6} which represents drain conductance at bias point. The input impedance at the differential point can be obtained as follows:

$$Z_{in} = \frac{2\left[j\omega\left(C_{gs1}+C_{gs3}\right) - g_{m1} + g_{ds5} \right]}{g_{ds5}\left[g_{m1} + g_{m3} + j\omega\left(C_{gs1}+C_{gs3}\right) \right]} \tag{1}$$

As Fig. 3 shows, input impedance of differential active inductor for $2g_{m1}+g_{m3} > g_{ds5}$ can be approximated by small signal model:

$$L_{eq} = \frac{2\left(C_{gs1}+C_{gs3}\right)}{g_{ds5}\left(2g_{m1}+g_{m3}-g_{ds5}\right)} \tag{2}$$

$$R_s = \frac{2\left(g_{ds5}-g_{m1}\right)}{g_{ds5}\left(2g_{m1}+g_{m3}-g_{ds5}\right)} \tag{3}$$

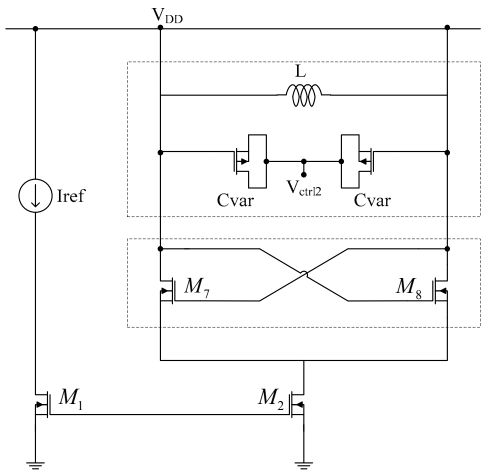


Fig. 2. VCO structure with passive inductor .

$$G_p = \frac{g_{ds5}}{2} \tag{4}$$

An effective method for setting conductance is changing drain conductance g_{ds5} by gate voltage. Therefore V_{ctrl1} can be used as control mechanism for tunable active inductor.

B. Start- Up Conditions

By considering small signal model of tunable active inductor (Fig. 3), simplified equivalent circuit VCO is shown in Fig. 4(a). To be sure of oscillation start up in structures, negative conductance of cross coupled transistors M_7-M_8 should be large enough to compensate for the loss of tank, which affects the equivalent conductance G_p and G_{res} respectively. For designing VCO with active inductor, negative conductance is chosen 3 times larger than the needed amount.

$$g_{m7} \approx 3G_p = \frac{3}{2} g_{ds5} \tag{5}$$

Based on circuit construction of Fig. 3, active inductor and cross coupled transistors commonly make use of similar bias current. Therefore the amount of M_7 and M_8 can be obtained by active inductor.

For second structure with passive inductor (Fig. 4 (b)), the conductance of the resonator circuit with different amount of V_{ctrl2} and different frequency measured**.** This is $0.569 m\Omega^{-1}$ for V_{ctrl2}=0.5V and f=5.5GHz**.** The amount of active circuit conductance for different frequency is also measured. It is $-2.218 m\Omega^{-1}$ for 5.5GHz. It's obvious that the amount of active circuit conductance is at least 3 times larger than the resonator conductance. Therefore the oscillation starts up.

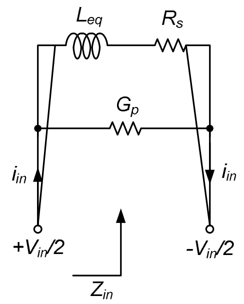


Fig. 3. Simplified circuit model of the active inductor

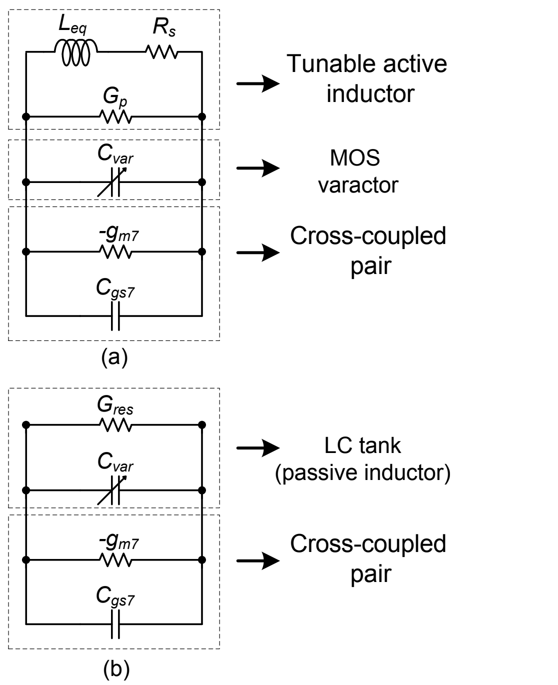


Fig. 4. Simplify model for VCO with (a)active and (b)passive inductor.

IV. Circuit Design

For determining the characteristics of wideband of the circuit, a perfect model VCO is used in technology 0.18μm CMOS. First varactor is investigated. Then circuit parameters are designed for tunable active inductor which is presented in (2) and (4) and compared with the same structure with passive inductor. For having minimum inductance at highest frequency, voltage V_{ctrl1} should be tuned at lowest amount. Also for obtaining large transconductance with lowest gate capacitors, transistors M_1-M_4 should be biased at the high overdrive voltage (V_{GS}-V_T). For making sure of oscillation at the highest frequency, the amount of transistors M_7 and M_8 is determined by (5). As V_{ctrl1} increases, equivalent inductance increases and the frequency VCO decreases. Since bias current of cross coupled transistors reduces during frequency tuning, lowest frequency is obtained when negative conductance is low to compensating for the tank loss. After designing tunable active inductor, a varactor is chosen with maximum capacity 3pF for getting resonance frequency and gain of VCO.

In designing a wideband VCO using tunable active inductor, the phase noise is one of the important cases. The phase noise can be modified by increasing channel length of transistors.

TABLE I: Circuit Parameters of VCO

transistors	size $(\mu m / \mu m)$
M_1, M_2	$30/0.18$
M_3, M_4	$112.5/0.18$
M_5, M_6	$25/0.18$
M_7, M_8	$70/0.18$

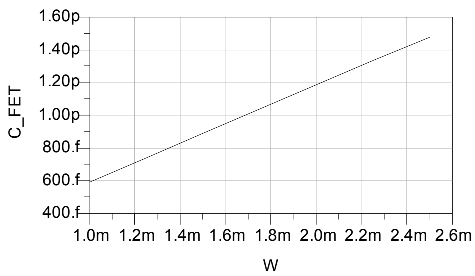


Fig. 5. The effect of changing W on capacitance

In this way extra parasitic capacitor reduces the range of tuning frequency and highest operating frequency. Therefore in this design, transistors MOS with minimum channel length is used to showing the range of optimized tuning for multi standard wireless applications.

V. Simulation

For increasing the control frequency of VCO circuits up to 5.5GHz, some parameters of the circuit that can affect the frequency are chosen. For these purpose the capacitance and inductance of the circuit should be decreased. The capacitance can be reduced by varying the amount of W and L related to varactor. In order to decrease the amount of active inductor, the control voltage of active inductor (V_{ctrl1}) should be reduced, to increase the g_{ds5} and g_{ds6}. By increasing g_{ds5} and g_{ds6}, the inductance of active inductor is decreased, as presented in (2). Also the size of M_1-M_2 transistors has an affect on the amount of active inductor conductance. Therefore the active inductor conductance can also be controlled by varying W and L of this pair of transistors. By reducing amount of inductor or capacitance, for providing oscillation condition the amount of negative resistance of the pair of cross coupled transistor, should also be taken in to consideration account. This amount of negative resistance can be control by varying the amount of W and L of pair of transistors.

The amount of transistors is given in Table I.

After simulation, the amount of central frequency based on the first harmonic is obtained 5.5GHz in both structures.

MOS transistors are used as a voltage control capacitor (varactor). MOS transistors act as a 2 port device (capacitor) with C capacitance, when drain, source and bulk are connected with each other [6]. As shown in Fig. 5 by changing the length and width of transistors, the amount of capacitance can be varied. By increasing the amount of W and L, the capacitance is linearly enhanced.

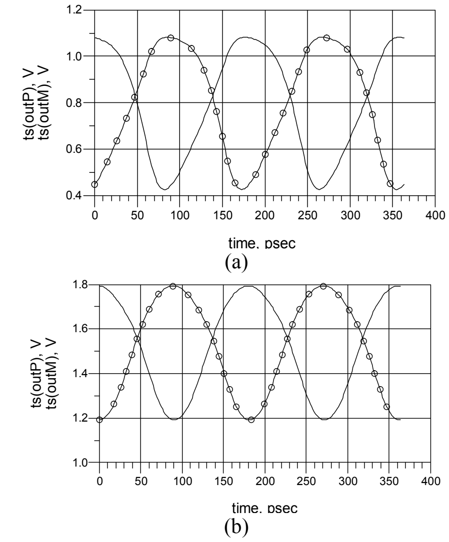


Fig. 6. The output curve of VCO with (a)active and (b)passive inductor

In this step the amount of G_m concerning active circuit should be compared with the amount of resonance circuit's conductance. The amount of G_m should be more than G_p in order to meet the condition of oscillation. The output curves of the circuit with active and passive inductor are shown in Fig. 6 (a), (b) respectively. The amount of phase noise of the first circuit is determined -80.314dBc and for the second one is -106.4dBc in offset 1-MHz which are shown in Fig. 7 (a), (b) respectively. This amount of phase noise is obtained with V_{ctrl1}=0.5V and V_{ctrl2}=0.6V. If these control voltages change, the phase noise of the circuits and also the central frequency vary. As shown in Fig. 7 (a), (b) the phase noise performance of the second circuit with the passive inductor is better than the first one.

The amounts of output power spectrum are also shown in Fig. 8 and 9 for both structure of VCO.

The amount of power consumption of the circuit VCO with active and passive inductor in central frequency is obtained 29.38mW and 7.592mW respectively. The power consumption of the second circuit also is better than the first one.

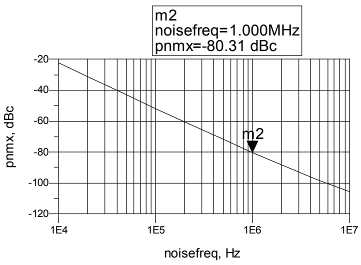
TABLE II: COMPARING THE VCO CIRCUITS

	unit	First circuit	Second circuit	[5]	[7]	[8]	[9]
technique	–	Active inductor	Passive inductor	Active inductor	Active inductor	Ring oscillator	Ring oscillator
technology	–	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS	0.18μm CMOS
Central frequency	GHz	5.5	5.5	2.84	2.0	1.6	1.9
V_{DD}	V	1.8	1.8	1.8	1.8	1.8	1.8
DC power	mW	29.38	7.592	22	13.8	26	–
Output power	dBm	0.211	–0.454	–10.69	–29	–	–
Phase noise @ 1MHz	dBc / Hz	–80.314	–106.4	–79.85	–90	–95	–105.5

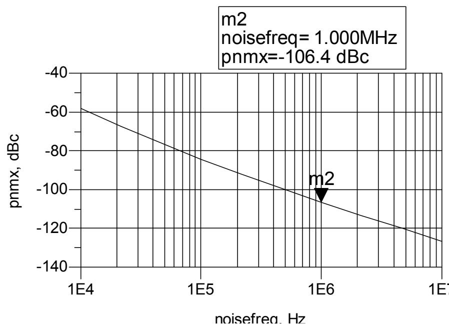
Oscillators in references [5], [7]-[9] are compared with proposed two voltage control oscillators (VCO) regarding central frequency, the amount of the circuit power supply, consumption power and output power and also phase noise of the circuit in offset 1-MHz, the results of which are given in Table II.

VI. CONCLUSION

A VCO model is studied and simulated by using active and passive inductor. In this study by using differential active inductor and a varactor for LC tank a wide tuning range VCO at radio frequency is introduced and compared with the VCO by passive inductor.



(a)



(b)

Fig. 7. Phase noise of the (a) first and (b)second VCO at 5.5GHz

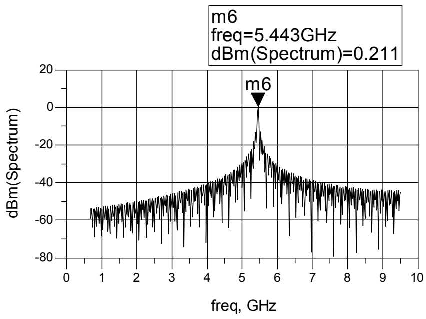


Fig. 8. Measured output power spectrum for VCO with active inductor

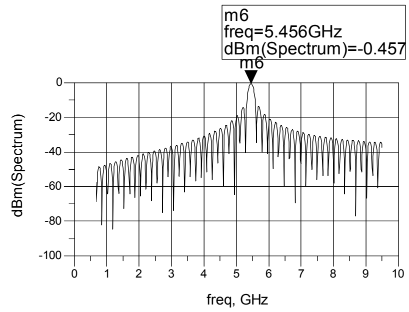


Fig. 9. Measured output power spectrum for VCO with passive inductor

These VCOs with power supply 1.8V makes use of 0.18μm CMOS technology. The first suggested VCO represents a wide frequency tuning range, while the operation of the circuit is kept constant considering phase noise and output power in all frequency range and the second one has a high phase noise performance. The applications of these circuits are appropriate for integrated RF transmitter. The first designed model with active inductor at 5.5GHz has output power 0.211dBm and consumption power 29.38mW in addition the phase noise of this VCO in offset 1-MHz is -80.314dBc, And for the second one with passive inductor at 5.5GHz, the output power and power consumption is -0.454dBm and 7.592mW respectively. This model has phase noise -106.4 in 1-MHz offset.

REFERENCES

[1] A. D. Berny, A. M. Niknejad, and R. G. Meyer, "A 1.8-GHz LC VCO with 1.3-GHz tuning range and digital amplitude calibration," *IEEE J. Solid-State Circuits*, vol. 40, no. 4, Apr. 2005, pp. 909–917.

[2] A. D. Berny, A. M. Niknejad, and R. G. Meyer, "A wideband low-phase-noise CMOS VCO," in *IEEE Custom Integr. Circuits Conf.*, Sep. 2003, pp. 555–558.

[3] F. Herzel, H. Erzgraber, and N. Ilkov, "A new approach to fully integrated CMOS LC-oscillators with a very large tuning range," in *IEEE Custom Integr. Circuits Conf.*, May 2000, pp. 573–576.

[4] Z. Li and K. K. O, "A 1-V low phase noise multi-band CMOS voltage controlled oscillator with switched inductors and capacitors," in *IEEE Radio Freq. Integr. Circuits Symp. Dig.*, Jun. 2004, pp. 467–470.

[5] L. Lu and Y. Liao, "A wide tunning-range CMOS VCO with a differential tunable active inductor," in *IEEE Radio Freq. Integr. Circuits Symp. Dig.*, Sep. 2006, pp. 467–470.

[6] P. Andreani and S. Mattisson, "On the use of MOS Varactors in RF VCO's," *IEEE J. Solid-State Circuits*, vol. 35, no. 6, Jun. 2000, pp. 905–910.

[7] R. Mukhopadhyay, Y. Park, P. Sen, N. Srirattana, J. Lee, C.-H. Lee, S. Nuttinck, A. Joseph, J. D. Cressler, and J. Laskar, "Reconfigurable RFICs in Si-based technologies for a compact intelligent RF frontend," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 1, Jan. 2005, pp. 81–93.

[8] Y. H. Chuang, S. L. Jang, J. F. Lee, and S. H. Lee, "A low voltage 900 MHz voltage controlled ring oscillator with wide tunes range," in *IEEE Asia–Pacific Circuits Syst. Conf.*, Dec. 2004, pp. 301–304.

[9] Y. A. Eken and J. P. Uyemura, “A 5.9-GHz voltage-controlled ring oscillator in 0.18-_m CMOS,” *IEEE J. Solid-State Circuits*, vol. 39, no. 1, Jan. 2004, pp. 230–233.

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