Design of VCO with a Differential Tunable Active Inductor

N. Cheraghi Shirazi and R. Hamzehyan, *Member, IACSIT*

***Abstract*—This paper presents a wide tuning rang CMOS voltage control oscillator (VCO) suitable for radio frequency operation. The oscillator based upon the classic LC-tuned negative-resistance topology, with a novel low voltage, high performance active inductor. 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 is 5.5GHz. The measured phase noise in 1-MHz offset is -81dBc. The non existence of passive components causes VCO to have the smaller chip area than the circuit with passive inductors.**

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

I. INTRODUCTION

Voltage Controlled Oscillator (VCO) is an essential building block for Radio Frequency receivers. Ideally, a VCO provides a high stable frequency with minimal power consumption. 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. The proposed VCOs in the 0.18μm process are designed which is suitable for system integration in transceiver designs.

II. VCO CIRCUIT STRUCTURE

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.

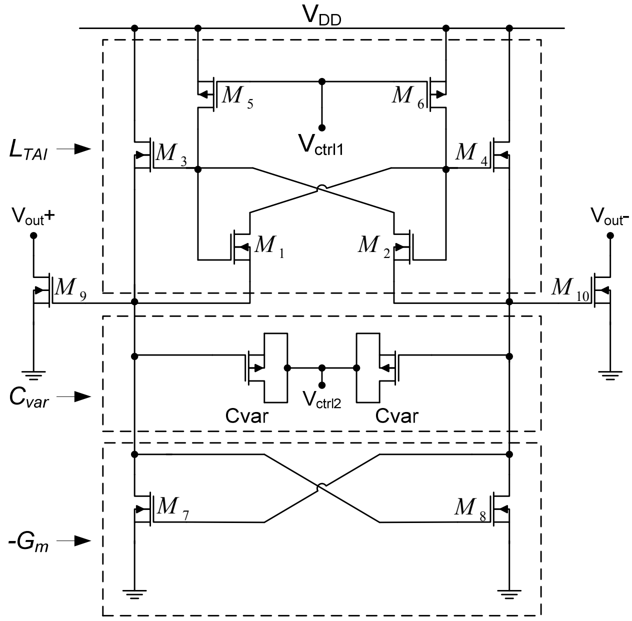

Fig. 1. VCO structure with active inductor.

III. VCO 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.2 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:

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The authors are with the Azad University Bushehr Branch, Bushehr Iran. (e-mail: nch_shirazi@yahoo.com; r_Hamzehyan@yahoo.com).

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

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

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

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

$$G_p = \frac{g_{ds5}}{2} \quad (4)$$

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.

In addition to equivalent inductance, coefficient Q of active inductor is also obtained by small signal analyses. Coefficient Q of an inductor is defined as imaginary part divided by real part of input impedance. Based on (1), coefficient Q is given as follows:

$$Q = \frac{\omega\left(C_{gs1}+C_{gs3}\right)\left(2g_{m1}+g_{m3}-g_{ds5}\right)}{\left(g_{m1}+g_{m3}\right)\left(g_{ds5}-g_{m1}\right)+\omega^2\left(C_{gs1}+C_{gs3}\right)^2} \quad (5)$$

By equating first derivative Q with zero $\left(\partial Q/\partial\omega=0\right)$, maximum coefficient Q and the related frequency are obtained as follows:

$$Q_{\max} = \frac{2g_{m1}+g_{m3}-g_{ds5}}{2\sqrt{\left(g_{m1}+g_{m3}\right)\left(g_{ds5}-g_{m1}\right)}} \quad (6)$$

$$\omega_{Q_{\max}} = \frac{\sqrt{\left(g_{m1}+g_{m3}\right)\left(g_{ds5}-g_{m1}\right)}}{C_{gs1}+C_{gs3}} \quad (7)$$

In consequence coefficient Q of active inductor can be modified at central frequency by appropriate selection of circuit parameters of M_1-M_6 transistors.

B. Start- Up Conditions

By considering small signal model of tunable active inductor (Fig.2), simplified equivalent circuit VCO is shown in Fig. 3. 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.

$$g_{m7} \approx 3G_p = \frac{3}{2}g_{ds5} \quad (8)$$

Based on circuit construction of Fig.2, 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.

C. The Range of Frequency Setting

At VCO design, wide frequency tuning is obtained by tunable active inductor while fine tuning is provided by varactor. As shown in (2) equivalent inductance is highly affected by drain conductance g_{ds5}. When controlled voltage V_{ctrl1} is starts to increase from low voltage level, M_5 and M_6 transistors moves from triode to saturated region which results in g_{ds5} and g_{ds6} reduction. Therefore equivalent inductance of active inductor increases and output frequency of VCO decreases. With a simple control mechanism, a very wide tuning range is achieved for VCO design.

Fine tuning range VCO is obtained only by varactor. By increasing the amount of varactor a wide fine tuning range can be achieve with the previous price of oscillation frequency.

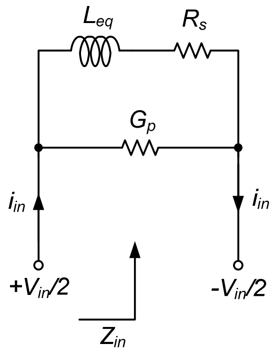

Fig. 2. Simplified circuit model of the active inductor

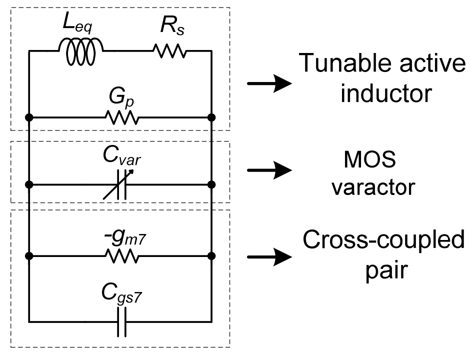

Fig. 3. Simplify model for VCO with active inductor.

IV. VCO 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).

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.

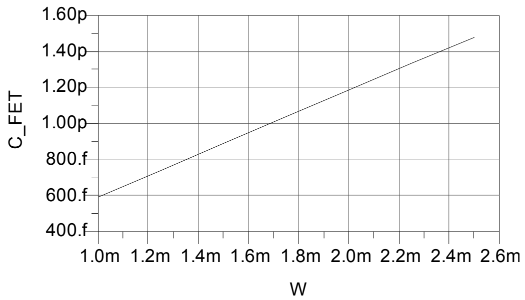

Fig. 4. The effect of changing *W* on capacitance

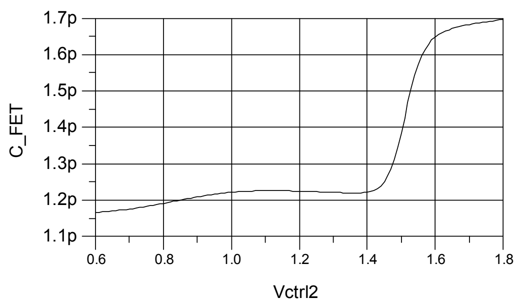

Fig. 5. The effect of changing capacitance by varying voltage control

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 effect 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.

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	$70/0.18$

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

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.4 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. The curve of changing capacitance by varying control voltage is shown in Fig.5.

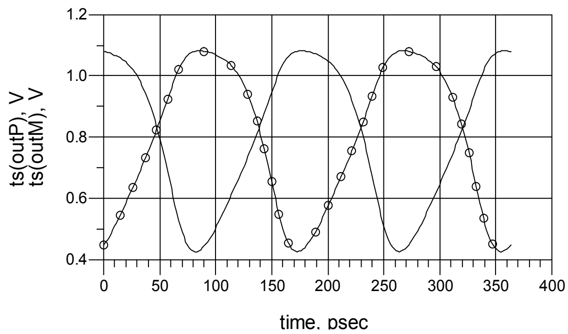

Fig. 6. The output curve of VCO with active inductor

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 inductor are shown in Fig.6. The amount of phase noise of VCO is determined -80.314dBc in offset 1-MHz which are shown in Fig.7. The frequency fine tuning is achieved by the varactor. 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 circuit and also the central frequency vary.

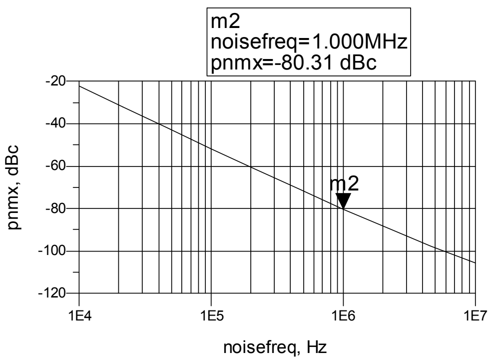

Fig. 7. Phase noise of VCO at 5.5GHz

The amount of output power spectrum is also shown in Fig.8. As shown in Fig.9, the output power is 0.197dBm in relation to the first harmonic.

The amount of power consumption of the circuit VCO with active inductor in central frequency is obtained 29.38mW.

Oscillators in references [5], [7]-[9] are compared with proposed voltage control oscillator (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.

TABLE II: COMPARING THE VCO CIRCUITS

	unit	VCO circuit	[5]	[7]	[8]	[9]
technique	–	Active 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
Central frequency	*GHz*	5.5	2.84	2.0	1.6	1.9
V_{DD}	*V*	1.8	1.8	1.8	1.8	1.8
DC power	*mW*	29.38	22	13.8	26	–
Output power	*dBm*	0.211	−10.69	−29	–	–
Phase noise @ 1MHz	*dBc / Hz*	−80.314	−79.85	−90	−95	−105.5

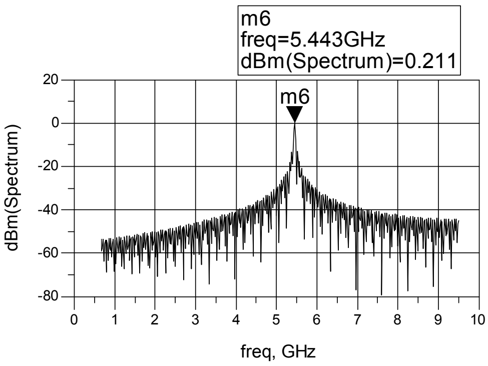

Fig. 8. Measured output power spectrum for VCO with active inductor

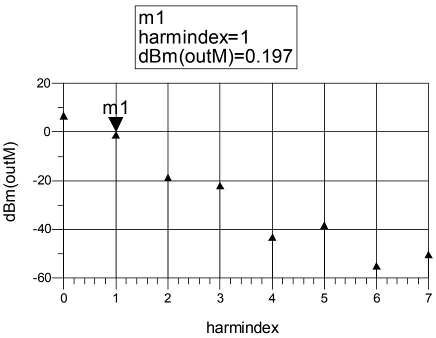

Fig. 9. Output power of the VCO at 5.5GHz

VI. CONCLUSION

A VCO model by using active inductor has been described. In this study by using differential active inductor and a varactor for LC tank a wide tuning range VCO at radio frequency is introduced. The absence of on-chip inductors makes this circuit appropriate for on-chip applications.

This VCO with power supply 1.8V makes use of 0.18µm CMOS technology. The 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. The applications of this circuit are appropriate for integrated RF transmitter. The 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.

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Najmeh Charaghi Shirazi was born in Shiraz, Iran in 1982. She is a student of PHD in Electronic Engineering Tehran science and research branch. She received the B.Sc. degree in Electronics Engineering from Azad University of Bushehr, Iran in 2005, MSc. Degree from Bushehr University in 2009. She has authored more than 9 published technical papers in electronics. Her current research activities include analog circuit and RF Integrated Circuit design and Satellite communication.

Roozbeh Hamzehyan was born in Shiraz, Iran in 1982. He received the B.Sc. degree in Electronics Engineering from Azad University of Bushehr, Iran in 2004, MSc. Degree in communication engineering from Bushehr University in 2008. His current research activities include Detection, RF Integrated Circuit design and Satellite communication.