Design and Simulation of Low Phase Noise Voltage-Controlled Oscillator

Najmeh Cheraghi Shirazi, Roozbeh Hamzehyan, and Ashkan Masoomi

Abstract— **This paper presents the design and simulation of a low phase noise voltage-controlled oscillator (VCO). The oscillator is based upon the classic LC-tuned negative-resistance topology, with a passive inductor. A fundamental relationship of the channel length of MOS transistors in LC tanks VCO and the phase noise is presented. The proposed VCO in the 0.18μm process is designed which is suitable for system integration in transceiver designs. Using this process, complete pattern VCO is designed in ADS. It operates in the 5.5 GHz frequency range with a 1.8V power supply. The power consumption is 7.592mW. The VCO's phase noise level is -106.4dBc/Hz at 1MHz offset.**

Index Terms— **Spiral Inductors, Voltage Control Oscillator (VCO), Phase Noise, Varactor**.

I. INTRODUCTION

The voltage-controlled oscillator (VCO) is one of the most important blocks in RF communication systems. It is still a challenge to achieve a good performance with low phase noise, low power consumption and wide frequency tuning.

There has to be a trade off among those key requirements. In fact, to achieve low phase noise, the oscillation amplitudes must be maximized. This means either increasing the biasing current or increasing the tank inductance (assuming a given tank quality factor). The former increases the power consumption, while the latter reduces the frequency tuning range due to a lower total tank capacitance [1]- [3].

The passive devices such as inductors, capacitors, resistors and transformers are traditionally considered playing a minor role in comparison with active devices. However, they are actually very critical parts in today's RF ICs.

At low frequency, designers usually emulate the functionality of passive devices with active components to make their design more reliable and cost-effective. This method is generally not applicable at radio frequency. For example, the oscillators based on the active inductors generate unacceptable phase noise. The passive capacitors and resistors are relatively easy to integrate in comparison with the passive planar inductors. However, the inductors are widely used in almost all fundamental building blocks of RF circuits, including oscillators, LNA, filters, transforms and matching circuitry.

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Their quality significantly affects the performance of the overall system. For the integrated inductors, the capacitive and the electromagnetic coupling between individual passive component and the low resistivity substrate used for latch-up suppression degrade their Q factor.

Passive spiral inductors are used in the VCO component design because spiral inductors have a high Q factor, which will let the VCO have a better phase noise performance. Passive spiral inductors are implemented using the two highest metal levels available from the process technology file.

One of the main advantages of the spiral passive inductor is its high-Q factor in comparison with the active inductor, which have a really low Q factor. However, the geometric layout area of the active inductor is just one-tenth of the geometric layout of the spiral inductor with the same value of inductance.

In this paper, a novel methodology to design a LC tank VCO with lower phase is reported and verified. A fundamental relationship of the channel length of MOS transistors in LC tanks VCO and the phase noise is presented. An optimum channel length with lower phase noise is implemented to fabricate a 5.5 GHz VCO. The measured phase noise is -106.4dBc/Hz at 1-MHz frequency offset. The power consumption is 7.592mW.

II. VCO CIRCUIT STRUCTURE

VCO circuit in Fig.1 shows that the LC tank made up of a passive inductor and varactor for frequency control. 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. Negative conductance of cross coupled transistors is also used for compensating the LC tank losses.

A varactor is used as a mechanism for frequency fine tuning, therefore it can used for sensitivity tuning without decreasing of VCO total tuning range.

The inductance of passive inductor is 3nH. Two transistors (M_1-M_2) are in current mirror and used as a circuit bias. MOS in accumulation mode acts as a varactor [4]. 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.
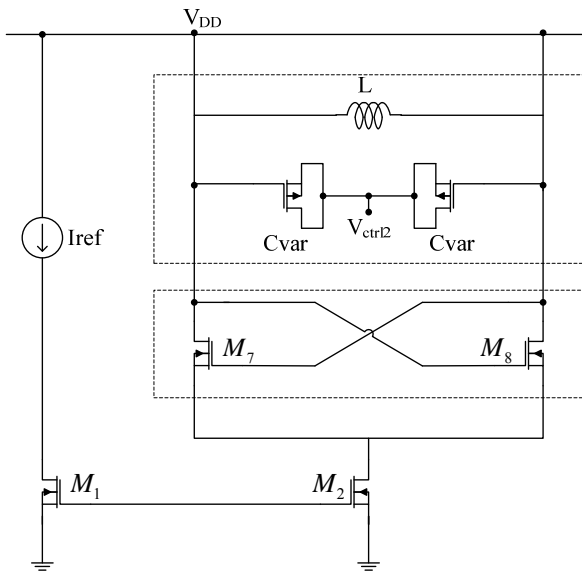
Fig. 1. VCO structure

III. VCO CIRCUIT ANALYSIS

A. Start- up conditions

To be sure of oscillation start up in structure, 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_{res}.

For designing VCO, negative conductance is chosen 3 times larger than the needed amount. For VCO structure with passive inductor (Fig.2), the conductance of the resonator circuit with different amount of V_{ctrl2} and different frequency measured in table 1.
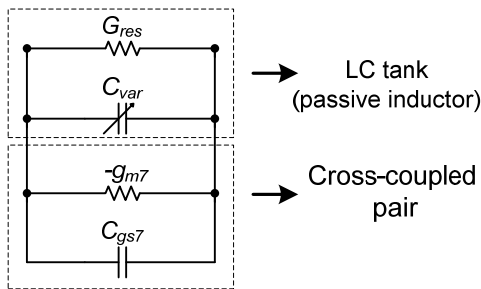

Fig. 2. Simplify model for VCO

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.

TABLE I: THE CONDUCTANCE OF THE RESONATOR CIRCUIT WITH DIFFERENT AMOUNT OF V_{CTRL2} AND DIFFERENT FREQUENCY MEASURED

freq	Gres			
	Vctrl2=500.0 m	Vctrl2=1.000	Vctrl2=1.500	Vctrl2=2.000
3.000 GHz	741.2 u	685.0 u	667.7 u	668.8 u
3.500 GHz	617.2 u	541.1 u	517.6 u	519.1 u
4.000 GHz	557.3 u	458.5 u	428.0 u	430.0 u
4.500 GHz	537.2 u	412.9 u	374.5 u	377.0 u
5.000 GHz	543.8 u	391.4 u	344.3 u	347.5 u
5.500 GHz	569.7 u	386.8 u	330.1 u	334.1 u
6.000 GHz	610.5 u	394.6 u	327.7 u	332.5 u

B. Resonator Circuit

The simulation results of resonator circuit are shown in Fig.3 by using S parameters. Fig.3 shows that the phase of S_{11} is -0.019 for V_{ctrl2}=0.5V and f=5.462GHz. The amount of S_{11}'s amplitude is 0.945 by smith chart curve. This result is used for oscillation start up.
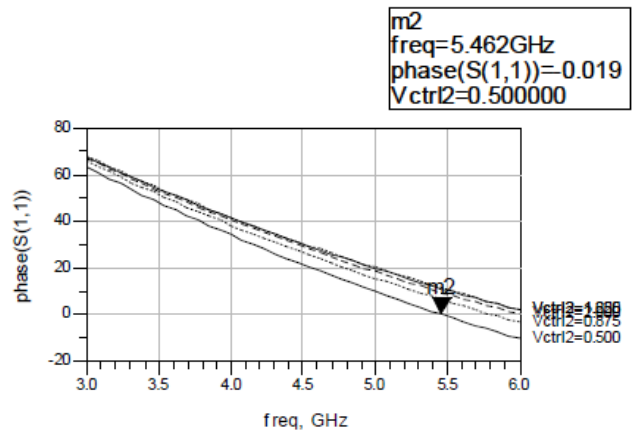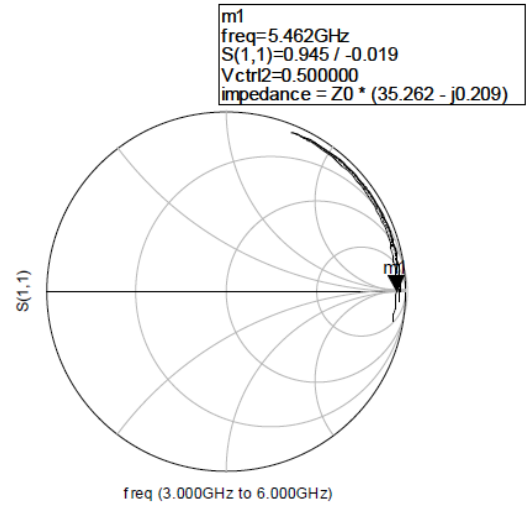
Fig. 3. The amplitude and phase of S_{11} (resonator circuit).

C. Active Circuit

For checking the active circuit, the resonator circuit should be omitted from Fig.1. As shown in table 2 the real part of impedance is negative, that is necessary for startup oscillation. The conductance of active circuit is -2.218m in 5.5GHz.

TABLE II: THE CONDUCTANCE OF ACTIVE CIRCUIT IN DIFFERENT FREQUENCIES

freq	Y(1,1)	Gm
3.000 GHz	-2.315m + j1.205m	-2.315 m
3.500 GHz	-2.299m + j1.400m	-2.299 m
4.000 GHz	-2.281m + j1.593m	-2.281 m
4.500 GHz	-2.261m + j1.785m	-2.261 m
5.000 GHz	-2.240m + j1.976m	-2.240 m
5.500 GHz	-2.218m + j2.165m	-2.218 m
6.000 GHz	-2.194m + j2.352m	-2.194 m

To be sure that oscillation start up, by using S parameters in smith chart, it is necessary that:

$$S_{in} S_{res} > 1 \qquad (1)$$

$$phase(1/S_{in}) = phase(S_{res}) \qquad (2)$$

where S_{in} is the S_{11} of active circuit and S_{res} is the S_{11} of resonator circuit. Fig.4 shows the amplitude and phase of active and resonator circuit. The phase in both points m_1 and m_3 are the same and $S_{in}.S_{res} > 1$.
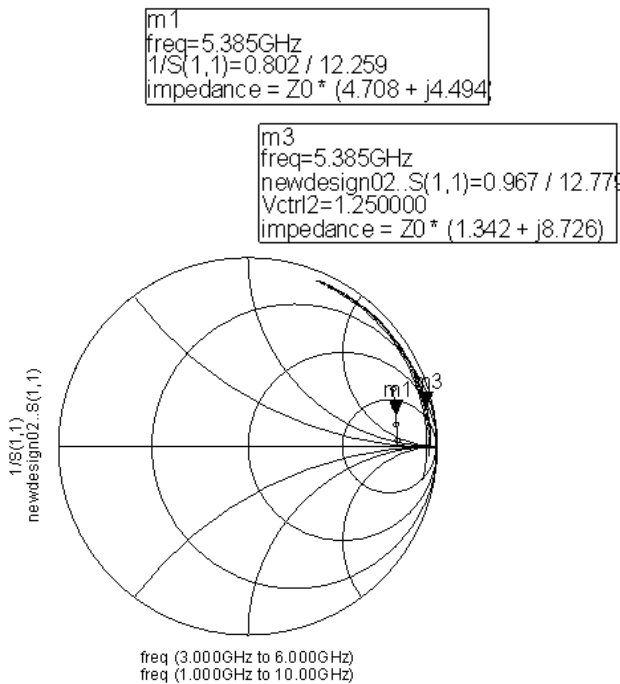

Fig. 4. The Curve of active (m_1) and resonator (m_3) circuit.

IV. 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.

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.

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 [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.

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 curve of the circuit is shown in Fig.5.
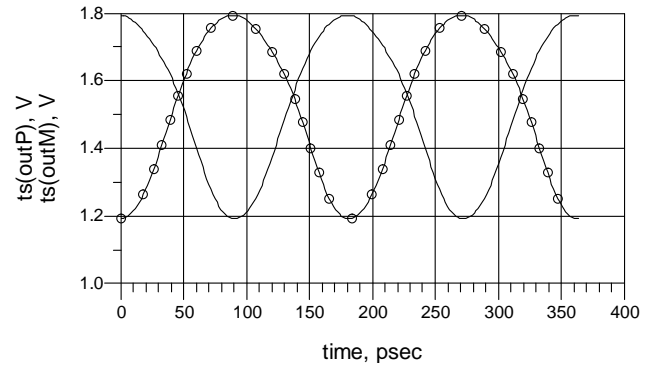

Fig. 5. The output curve of VCO

The amount of phase noise of VCO is determined -106.4dBc in offset 1-MHz which is shown in Fig.6. The frequency fine tuning is achieved by the varactor. This amount of phase noise is obtained with V_{ctrl2}=0.6V. If these control voltages change, the phase noise of the circuit and also the central frequency vary.

The amount of output power spectrum is also shown in Fig.7. As shown in Fig.8, the output power is -0.454dBm in relation to the first harmonic.
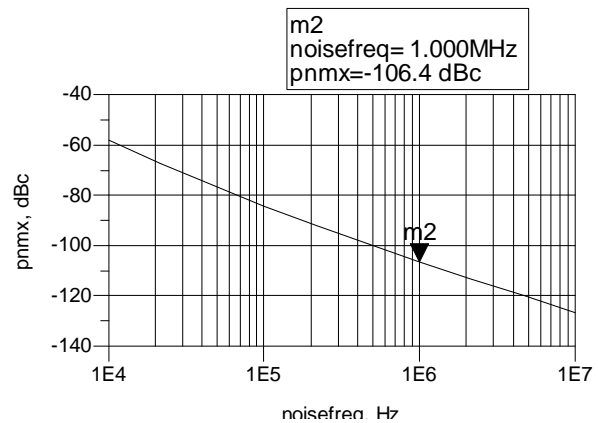

Fig. 6. Phase noise of VCO at 5.5GHz

The amount of power consumption of the circuit VCO in central frequency is obtained 7.592mW.

Oscillators in references [5-9] 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 III.
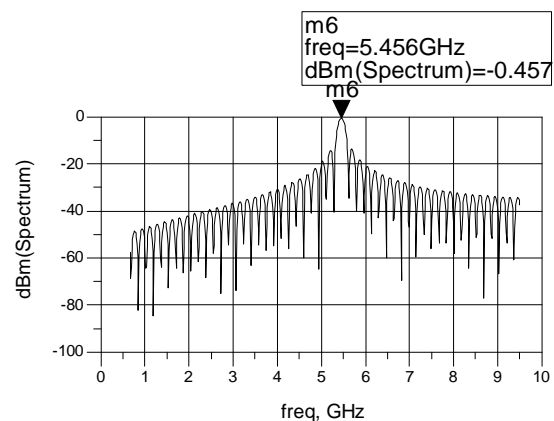

Fig. 7. Measured output power spectrum for VCO

TABLE III. COMPARING THE VCO CIRCUIT

|	unit	VCO circuit	[5]	[6]	[7]	[8]	[9]
technique	–	Passive inductor	Active inductor	Active inductor	Active inductor	Ring oscillator	Ring oscillator
technology	–	$0.18\mu m\ CMOS$	$0.18\mu m\ CMOS$	$0.18\mu m\ CMOS$	$0.18\mu m\ CMOS$	$0.18\mu m\ CMOS$	$0.18\mu m\ CMOS$
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	7.592	29.38	22	13.8	26	–
Output power	dBm	−0.454	0.211	−10.69	−29	–	–
Phase noise @ 1MHz	dBc/Hz	−106.4	−80.314	−79.85	−90	−95	−105.5
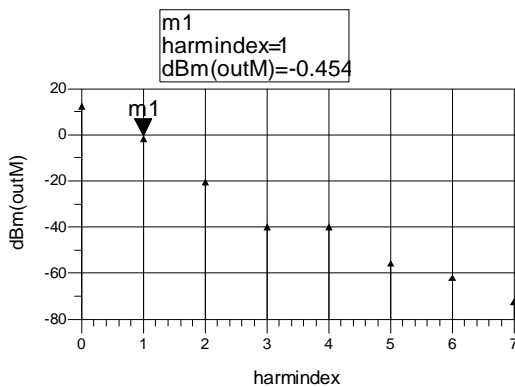
Fig. 8. output power of the VCO at 5.5GHz

V. CONCLUSION

A VCO model has been described. In this study by using passive inductor and a varactor for LC tank a low phase noise VCO at radio frequency is introduced.

This VCO with power supply 1.8V makes use of 0.18μm CMOS technology. The applications of this circuit are appropriate for integrated RF transmitter. The designed model at 5.5GHz has output power -0.454dBm and consumption power 7.592mW in addition the phase noise of this VCO in offset 1-MHz is -106.4dBc.

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