Design of Voltage Controlled Oscillator for 2.4 GHz Wireless Applications

Vaishnavi AnushaT.P.
M.tech, Digital Communication Engineering
Siddaganga Institute of Technology,
Tumakuru, India

K.C.Narasimhamurthy, PhD
Department of Telecommunication Engineering
Siddaganga Institute of Technology
Tumakuru, India

ABSTRACT
The main focus of this paper is to design a voltage controlled oscillator (VCO) with the oscillation frequency of 2.4 GHz. A completely integrated LC-VCO, compatible with the ISM band is designed using 180 nm CMOS technology and with supply voltage of 1.8 V. The inductor-capacitor (LC) tank uses varactors as tuning elements. The n-type metal-oxide-semiconductor (NMOS) cross-coupled topology is adopted in this design. Simulation is done using HSPICE and performance results are reported. By the measurement results, the designed VCO showed a phase noise of -91 dBc/Hz. By varying the control voltage from 0 to 1.8 V, the tuning range obtained is 300 MHz. The output frequency of the VCO can be varied from 2.21197 GHz and 2.51061 GHz, and can be applicable to 2.4 GHz Bluetooth/WLAN/Zigbee/Wi-Fi applications. In this paper, the designed LC-VCO aims to achieve low phase noise, low power consumption.

Keywords
VCO, LC-Tank, low phase noise, low power consumption, tuning range

1. INTRODUCTION
Technology improvement and market growth, mainly in the communication sector, has in the recent years been pushing for higher quality of service in transmission and reception of information especially in modern wireless communication circuits that are fully integrated into a single chip. The demand of low cost, low power and small size circuits has been increasing with the extensive researches on development of completely integrated transceivers and radio frequency integrated circuit (RFIC) development [1], especially in Bluetooth and 802.11 WLAN areas. As low cost and low power consumption are the most significant considerations to enhance the battery lifetime and to improve the portability, CMOS is the most promising technology used in RFIC design.

Voltage controlled oscillator is an essential building block of communication systems both at transmission and reception ends, especially in frequency synthesizer and Phase Locked Loop (PLL) [2]. VCO is a tunable circuit whose output frequency is a function of the applied input control voltage. Most of radio frequency (RF) systems contain VCO which generates the periodic output signal used to modulate the transmitted or received signal [3]. VCO along with a mixer allows frequency translation and channel selection[4]. The block diagram of an RF front end [5] is as shown in figure1:

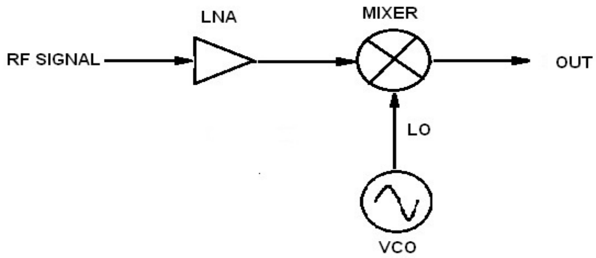


Fig1: Generic Block Diagram Of Rf System

In this paper, a cross-coupled LC-VCO suitable for ISM band applications such as Bluetooth/WLAN/Zigbee/ Wi-Fi using 180nm CMOS technology is analyzed. VCO performance parameters such as oscillation frequency, tuning range, power consumption, output amplitude and phase noise are considered. Three common categories of oscillator circuits are relaxation, ring, and LC-based oscillators[6]. At a given power consumption, cross-coupled LC oscillator topology achieves lower phase noise and ease of integration than a relaxation or ring oscillators[7]. The frequency limitations restrict their use at Gigahertz frequencies. Similarly, noise due to higher active device count restricts the use of ring oscillators at high radio frequencies[8]. The band pass filtering characteristic of the LC tank circuit has better phase noise performance[9]. So LC-tank VCOs are preferred in high quality RF receivers.

2. L-C VCO
Oscillators that employ a combination of inductors (L) and capacitors(C) are commonly used in RF systems[10]. Oscillation frequency is decided by L, C used in tank circuit. To obtain the tuning range, the capacitance is changed by varying control voltage across variable capacitors called varactors[11]. Varactors are used as tuning elements. In LC-VCO design, varactors are implemented using MOSFETs, which act as voltage controlled capacitors. By sweeping a DC voltage across the NMOS transistors, the capacitance changes which in turn varies the output frequency of VCO.

The oscillation frequency is obtained from LC tank as in equation 1:

$$f_{osc} = \frac{1}{2\pi\sqrt{LC(V)}} \quad \text{------ [1]}$$

where L is inductance and C(V) is voltage controlled capacitance of MOS-varactor[12]. For all oscillators, including VCO, there is an amplifier and a positive-feedback as in the circuit model of VCO described as figure2

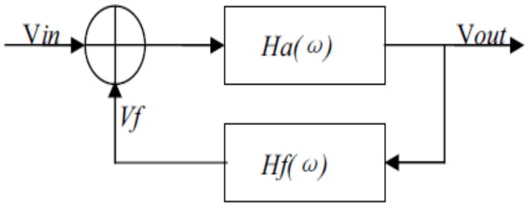


Fig2: Diagram Of Vco Model

The transfer function is expressed as follows

$$H(\omega)=\frac{H_a(\omega)}{1-H_f(\omega)H_a(\omega)} \text{------[2]}$$

Here $H_a(\omega)$ is transfer function of the amplifier, $H_f(\omega)$ is the positive feedback unit[13]. To start oscillation, value of the loop gain should be greater than 1[14].

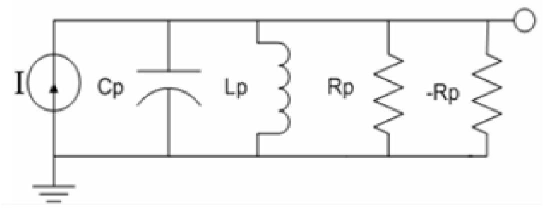


Fig3: Parallel Lc Oscillator Model

As shown in the parallel LC oscillator model in figure3, when an inductor L is connected to a charged capacitor C either in parallel or in series, energy is sloshed between them giving rise to oscillations. The practical L and C have losses associated with them. The tank losses can be represented as parallel resistance Rp. Some amount of the energy is being sloshed between L and C gets dissipated across Rp. In the absence of any replenishing mechanism, all this energy would finally dissipate to zero. Hence an active device is needed to replenish lost energy. Adding negative resistance –Rp which cancels Rp assures stable oscillation[15]. Negative resistance is implemented in practice by a positive feedback configured cross-coupled pair of transistors and it should be sufficient to overcome the parallel resistance of the LC tank circuit to generate the desired oscillation[16].

The LC-VCO consists of LC resonator and cross coupled transistor pair forming active circuit as shown in figure 4

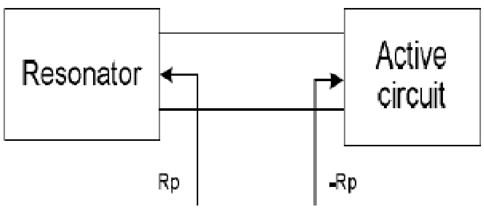


Fig4: A Simple Lc-Vco Block

NMOS transistors are used to provide negative resistance necessary for the stable oscillation. The NMOS only voltage controlled oscillator is the easiest topology to implement and it has the advantage of high transconductance (gm), per unit area due to the fact that it has high electron mobility [17]. Due to the smaller area, a good tuning range can be achieved [18]. The bias current source or tail current source is used to provide large common-mode impedance to reject the noise coupling from ground.

3. CIRCUIT SCHEMATIC

The cross-coupled LC tank oscillator is frequently employed in high frequency wireless communication applications due to its better phase noise performance, low power consumption, ease of integration and differential architecture mitigating undesirable common-mode effects[19]. The LC-VCO circuit is designed in a 180 nm CMOS technology with 1.8 V supply and bias current of 0.5 mA. The designed LC-VCO comprises of inductors L1, L2 and MOS-varactors Mc1 and Mc2, which are used as tuning elements in the resonance LC-tank to obtain the oscillation frequency and tuning range. M1 and M2 are crossed-coupled NMOS transistor pairs that provide negative resistance to compensate the losses of resonant LC tank. The circuit schematic of the cross-coupled LC-VCO design is as shown in figure5.

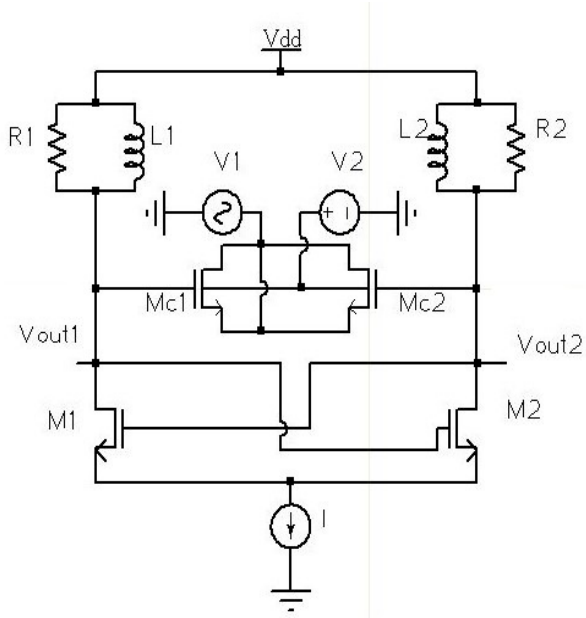


Fig5: Circuit Schematic Of Lc-Vco

Oscillation frequency of VCO is set using LC-tank. The DC voltage V2 is applied across gate and bulk of the MOS varactors Mc1 and Mc2 are used to vary the capacitance which in turn varies the output frequency of the VCO. For particular frequency, capacitance of MOS-varactor is given as

$$C(V)=\frac{1}{4\pi^2 F_{osc}{}^2 L} \text{------------[3]}$$

The dimensions[W,L] of mosfet used as varactor are found by calculating the area $A=\frac{c_{ox}t_{ox}}{\varepsilon_o\varepsilon_r}$ --------[4], and as the length is fixed for considered CMOS process technology(180 nm), width is obtained from calculated area $W=\frac{A}{L}$

c_{ox} is oxide capacitance

t_{ox} is thickness of oxide $=4nm$

ε_o dielectric constant of oxide $=8.854pF/m$

ε_r relative permittivity of silicon dioxide $=3.9$

A area is product of width W and length

The maximum capacitance is due to oxide capacitance

$$C_{\max} = C_{ox} \text{ -----[5]}$$

The minimum capacitance is due to depletion capacitance and oxide capacitance which is obtained as

$$C_{\min} = \frac{C_{ox} \times C_{dep}}{C_{ox} + C_{dep}} \text{ --------[6]}$$

Cdep is the depletion region capacitance which is electronically variable through control voltage.

Cox is the fixed oxide capacitance.

3.1. Mosfet As Varactor

Varactors are sources of variable capacitances, and are used as frequency tuning elements in the LC-tank VCOs[20]. In this design, NMOS are used as variable capacitors to vary the frequency of the LC-VCO. The illustration of MOS-varactor is as shown in the figure6.

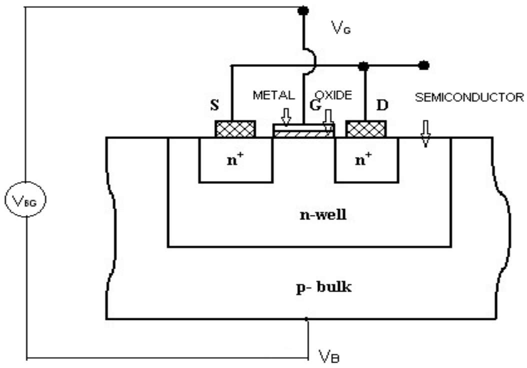


Fig6: Mosfet Varactor

An NMOS varactor can have the same structure as an NMOS transistor[21], with control voltage applied to vary MOSFET capacitance as shown in figure6. The tuning range of VCO is obtained by sweeping a DC voltage V_{BG} across gate and bulk of MOS varactors. As the control voltage is varied, the capacitance changes which in turn varies output frequency of VCO.

The varactor capacitance is modulated depending on the control voltage applied across it. The applied variable DC voltage across the MOS-varactor changes the effective capacitance of the tank. The required tuning range can be obtained by changing capacitance values of varactor from minimum to maximum. For small positive voltage, holes get repelled into the substrate and depletion region is formed. The capacitance due to dipole in the transition region is referred as depletion capacitance, which is dominant when junction is reverse biased. The depletion region capacitance Cdep is electronically variable capacitance which is function of variable control voltage applied across the varactor. The minimum capacitance Cmin is dependent both on the fixed oxide capacitance Cox of varactor as well as Cdep, the variable capacitance formed in depletion region of varactor. As the voltage is increased, the inversion of electrons takes place and varactor operates in the inversion region. The maximum capacitance Cmax is mainly driven by the fixed oxide capacitance Cox of the varactor.

3.2. Phase Noise Of LC-VCO

The spectrum of an oscillator in practice deviates from an impulse and is "broadened" by the noise of its constituent devices called "phase noise"[21]. It can be described as short-term random phase or frequency fluctuations of a signal. It is measured in the frequency domain. Phase Noise is specified in dBc/Hz, called "dB with respect to the carrier," the unit dBc signifies normalization of the noise power to the carrier power. It represents the noise power relative to the carrier contained in a 1 Hz bandwidth centered at an offset frequency from the carrier as in figure 8.

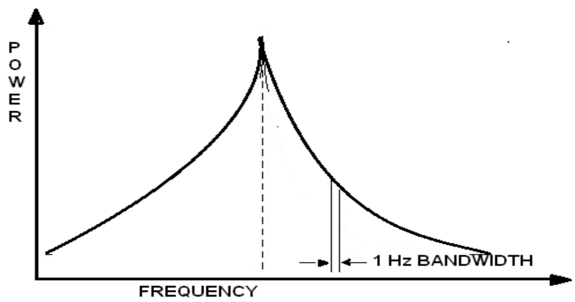


Fig8: Output Power Spectrum Of Vco

The spectrum has power distributed around the desired oscillation, in addition to power located at harmonic frequencies. The phase noise is a measure of oscillator stability[22]. When trying to receive a signal in one channel in the presence of a stronger signal in an adjacent channel, phase noise of the local oscillator is modulated onto the stronger signal at the intermediate frequency, thereby reducing the signal to noise ratio of the desired signal at intermediate frequency. This phenomenon is referred to as reciprocal mixing, and limits how closely channels can be placed. Phase noise limits the selectivity of a radio system, the ability to receive a desired signal in the presence of strong interferers

With an increasing number of wireless users and ensuing demand for more efficient usage of frequency resources, the frequency spectrum has become the most important resource in wireless communications. Because wireless transceivers rely heavily on frequency conversion by the oscillators, the spectral purity of both the receiver and transmitter of the VCO affects the maximum number of available channels and users. In the receiver, the phase noise of the VCO limits its ability to detect a weak signal when there is a strong signal in an adjacent channel. Similarly, in a transmitter, oscillators phase noise is modulated onto the desired signal, resulting in unwanted energy being transmitted outside of the desired band. It affects not only selectivity, but also the sensitivity and dynamic range of the wireless receiver system. In a RF system, mixing a clean low phase noise radio frequency signal, with a poor phase noise local oscillator, it will turn into a noisy intermediate frequency as in figure9:

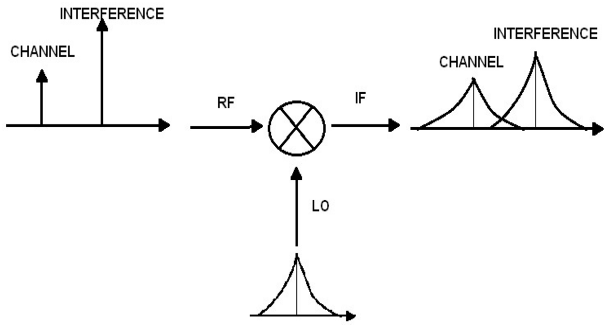
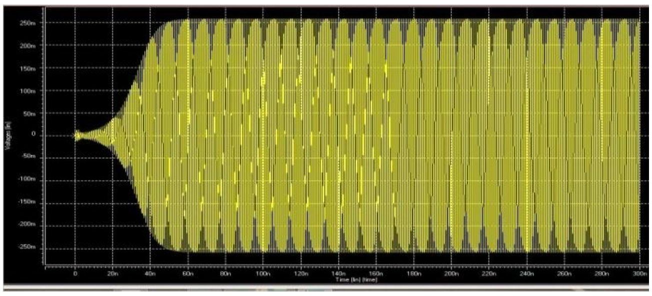
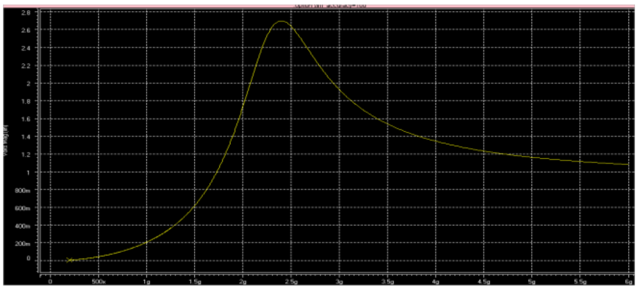


Fig9: Effect Of Phase Noise

4. RESULTS AND DISCUSSION



Transient Response



Ac Analysis

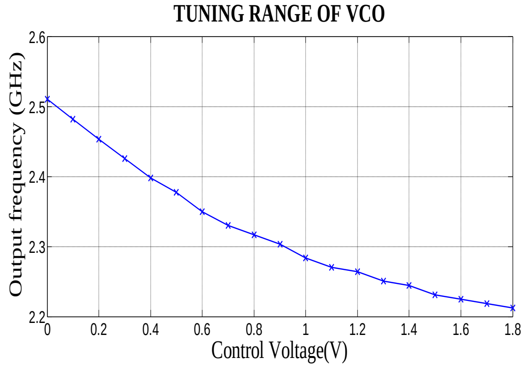
TUNING RANGE OF DESIGNED VCO:

Table1: Frequency variation by varying capacitance through control voltage

Control Voltage(V)	Capacitance (fF)	Frequency (G Hz)
0	186.91	2.51061
0.3	200.28	2.42538
0.6	213.37	2.34980
0.9	222.14	2.30293
1.2	229.95	2.26350
1.5	236.66	2.23116
1.8	240.79	2.21197

Frequency tuning is done by varying MOS-varactor capacitance through control voltage. In the designed LC-VCO, control voltage is varied from 0 V to 1.8 V across varactors to vary frequency from 2.21197 GHz to 2.51061 GHz. Table 1 represents variation of capacitance and frequency with variation in the control voltage. The obtained tuning range of VCO is 300 MHz.

TUNING CURVE OF LC-VCO



RESULTS

Table2: LC-VCO results summarized

PARAMETERS	VALUES
Technology	180 nm
Supply voltage	1.8 V
Oscillation frequency	2.4 GHz
Tuning range	300 MHz
Phase noise	-91 dBc/Hz
Power	0.9 m W
Output amplitude	550mV

COMPARISION WITH PUBLISHED WORKS

Table3: VCO Performance Summary in comparison with published works

Ref. paper	2	3	4	5	6	7	This work
Technology [nm]	180	350	180	350	180	180	**180**
Frequency [G Hz]	2.4	2.4	2.41	2.4	2.4	2.2	**2.4**
Voltage Supply[V]	1.2	1	1	2.5	1.2	1.8	**1.8**
Tuning Range[M Hz]	210	128	40	250	270	130	**300**
Power [mW]	1.8	5.5	2.8	22.5	0.67	1.8	**0.9**
Phase noise [dBC/Hz]	-122	-107	-124	-118	-121	-110	**-91**

5. CONCLUSION & FUTURE SCOPE

A completely integrated LC-VCO compatible with the 2.4 GHz ISM band applications is designed using a 180nm CMOS technology and with supply voltage of 1.8 V. Simulation is done using HSPICE and performance results are reported as in the table2. All the simulation results show the well optimized performance of designed LC-VCO compared with other publications as shown in table3.

The designed VCO showed a phase noise of 91dBc/Hz. The performance of the proposed VCO shows the excellent optimization for low power as low as 0.9 mW. Varying control voltage from 0 V to 1.8 V across varactors results in the frequency tuning from 2.21197 GHz to 2.51061 GHz. The tuning range obtained is 300 MHz which can be expressed as 12.5%. With improved performance parameters, the LC-VCO is compatible for the industrial, scientific and medical (ISM) band 2.4 GHz wireless applications such as bluetooth, Wi-Fi, Zigbee. The scope of future work is to design frequency mixer and IF amplifier. Integration of voltage controlled oscillator with mixer and LNA(low noise amplifer) constitutes RF transceiver.

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