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# Design of a 2.4 GHz Low Phase Noise CMOS LC VCO for Wireless Applications

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**Abstract:** This paper presents the design of a 2.4 GHz CMOS LC voltage controlled oscillator (VCO) in TSMC 130 nm CMOS process. In this paper three different topologies of LC-tank VCO design for low phase noise and low power consumption are studied. Comparison is made between the VCO topologies considering their effect on the parameters such as phase noise, power dissipation, tuning range, tuning sensitivity. The effects of these parameters on the VCO performance are discussed. The proposed design is simulated using ADS Tool and operates from a supply voltage of 1.8 V. After simulating the proposed design the VCO shows a phase noise of -128.68 dBc/Hz at 1 MHz offset frequency from a 2.4 GHz carrier signal. The frequency of the VCO ranges from 2.36 GHz to 2.61 GHz when the control voltage is varried from 0 to 2 V. The FOM is obtained as -183.73 dBc/Hz.

**Keywords:** VCO, CMOS process, NMOS cross-coupled, LC tank, Phase noise, ADS (Advanced Design System), Figure of Merit.

## I. INTRODUCTION

With the tremendous growth of wireless communication technologies there is an increasing need for the bandwidth-efficient, low-power and low-cost transceiver design. The voltage-controlled oscillator (VCO) being an important component in the radio transceiver, its design is an attractive topic for the continued research and still is an active research area. VCO is one of the main building block in the RF communication systems such as Frequency Synthesizer and Phase-Locked Loop (PLL). VCO is an essential element to generate the local oscillation (LO) carrier frequency for up- and down-conversion mixing of the baseband and RF signal in a transceiver.

There are three different topologies for controlled oscillators on the integrated circuits (IC), namely, the ring oscillators, relaxation oscillators and tuned (LC) oscillators [1]. Ring oscillators consist of an odd number of single-ended inverters or an even/odd number of differential inverters with the appropriate connections. Relaxation oscillators alternately charge and discharge a capacitor with a constant current between two threshold levels. Tuned oscillators contain a passive resonator such as LC tank, transmission line resonator, crystal that serves as the frequency setting element. The relaxation and ring oscillator are very easy to integrate on a monolithic IC and are very compact. Their frequency is controlled by a current or voltage and it is possible to obtain linear frequency tuning characteristics over several orders of magnitude [2]. LC oscillators are difficult to integrate primarily because of the lack of high quality passive inductors in standard IC technologies and because of their large size. However, LC oscillators have a much higher frequency stability and spectral purity since it is set by the passive resonator. Relaxation and ring oscillators are typically very sensitive to noise in the switching thresholds and charging currents. Although the relaxation and ring oscillator can easily achieve wider tuning range, their poor phase noise performance makes them non-suitable for most of the wireless and wireline applications. For higher quality RF transceiver systems, a LC oscillator topology is chosen mainly because of its potential to achieve good phase noise performance, easier implementation, and differential operation than a relaxation or ring oscillator because the bandpass nature of the resonant tank in the LC oscillator provides the lowest phase noise for a given amount of power [3].

The performance metrics such as phase noise, power dissipation, tuning range and tuning sensitivity are most important parameters to consider in the VCO design that determines many of the basic performance characteristics of a transceiver. The VCO to be designed is such that it must be capable of achieving a low power consumption and low phase noise. Noise directly affects the information to be sent and received. The phase noise and power consumption are inversely proportional. That is in order to improve the power consumption performance, the phase noise must be increased and vice-versa. Therefore, a trade-off exist in the VCO circuit design between the phase noise and power dissipation. Thus the design of low power and low noise oscillator is significant. Multi-standard transceivers are needed to fulfil the ever increasing demands of the market due to the co-existence of the multiple communication standards. One of the design challenges for the multi-standard transceivers is a wide tuning range VCO that covers the bands of interest while meeting the requirements of each specific standard. The resonant frequency of the tank circuit decides centre frequency for a given topology, although the parasitic capacitances in the circuit causes the downward shift in the centre frequency. Since the inductor use is generally of fixed value, tuning range is provided by varactor and capacitance of the tank circuit. However the tuning range that can be achieved is limited by the parasitic capacitances of the active devices in the amplifier and of the inductor [4].

The VCO gain (KVCO) also called the tuning sensitivity of the oscillator determines the phase noise in the oscillator [5]. With the large KVCO, the noise coupling to the control node will be amplified and hence the phase noise performance will be degraded. This also makes the VCO very susceptible to the noise because of the AM to FM conversion. A VCO with small KVCO is desirable as it is less susceptible to the noise but it may cause the central frequency of the VCO to shift away from the desired frequency when the VCO suffers from the process and the temperature variations. Therefore, a trade-off exist in the VCO circuit design between the phase noise and tuning range.

This paper is organized as follows. Section II describes the performance metrics of VCO. Different VCO topologies and their comparison is studied in Section III and Section IV. Section V presents the proposed methodology and simulations results of the VCO. Finally, Section IV summarizes and concludes the paper.

## II. VCO PERFORMANCE METRICS

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### A. Phase Noise

Phase noise gives the measure of the spectral purity of the VCOs output signal. Phase noise is a critical and important parameter in RF wireless design. Phase noise of the VCO can be expressed as [6].

$$L(\Delta f) = 10log\left\{\left[1+\left(\frac{f0}{2\Delta fQ}\right)^2\right]\left(1+\frac{fc}{\Delta f}\right)\frac{FkT}{2Pav}+\frac{2kTRKvco^2}{\Delta f^2}\right\} \quad (1)$$

where L{Δf} is the phase noise at the frequency offset Δf from the carrier signal at fo, fo is the carrier signal frequency in Hz, Q is the quality factor of the tank circuit, F is the noise factor, T is the temperature in Kelvin, k is the Boltzmann's constant in J/K, R is the equivalent noise resistance of the varactor, Pav is the oscillator output average power, Kvco is the voltage gain of the VCO in Hz/V.

From (1), in the modified Lesson's formula Kvco dominates the phase noise performance, thus by reduction Kvco phase noise performance can be improved. Also it can be observed that the higher the Q-factor of the tank, the lower the noise factor (F), the phase noise performance of can be improved. However, the wide-tuning range design limits the quality factor. By fixing the channel widths of all transistors, the bias current can be increased to lower the phase noise; but this results in increased power consumption.

### B. Figure of Merit (FOM)

To compare the performance of the VCO with previously published literature a widely used figure of merit (FOM) parameter [7] can be stated by Eq. (2) as

$$FOM = L\{\Delta f\} - 20\log\left(\frac{fo}{\Delta f}\right) + 10\log\left(\frac{Pdc}{1mW}\right) \quad (2)$$

where the figure of merit in dBc/Hz, Pdc is the power consumption in mW and L{Δf} is the phase noise at the frequency offset Δf from the carrier signal at fo.

## III. LC-TANK VCO TOPOLOGIES

Differential cross-coupled topologies are generally preferred since they offer better power supply and substrate noise rejection over single-ended designs. Three different topologies of LC-tank VCOs for low power consumption and low phase noise are studied. The three different structures i) NMOS Cross-coupled ii) PMOS Cross-coupled iii) Complementary NMOS PMOS Cross-coupled are explained in details as follows:

### A. NMOS Cross-coupled

In Fig. 1 LC VCO using NMOS Cross-coupled transistors is shown. It consist of cross-coupled NMOS switches, two inductors, a varactor and a NMOS tail current source. The tail current source can be connected to either source or drain; in this structure it is shown to be connected to the source. A LC tank circuit is formed with the inductor and varactor. The transconductance of cross-coupled device gives the negative resistance required for the start-up of oscillations.

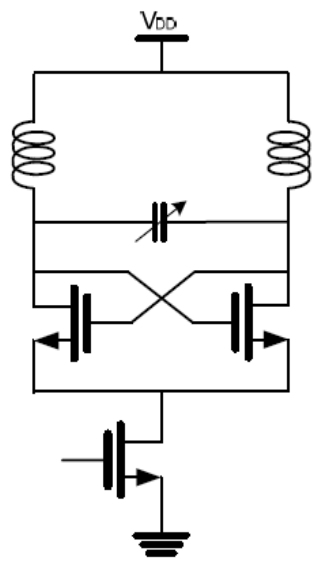


Fig. 1. NMOS Cross-coupled LC VCO

The cross-coupled NMOS structure injects energy to compensate for the losses of the tank and maintain the oscillation as per Barkhausen criterion. The inductor separates the varactor from the supply and the cross coupled NMOS pair and the tail current source separates it from the ground. With the direct connection of inductors to the supply, the oscillator becomes more sensitive to disturbances from the supply. However, due to the tail current source, the LC tank is well guarded against the disturbances caused by the ground. A symmetrical differential pair formed with the implementation of the switching transistors and the tail current source bias causes


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a lower harmonic distortion. The tuning voltage controls capacitance of the varactor. The available headroom enables a maximum tuning range, although the oscillator operates under low voltage condition. If the bulk voltage is tied to the supply voltage, the varactor works from the depletion – to the weak inversion region, where the capacitance tuning voltage characteristic achieves its best linearity. Depending on nonlinear behaviour of the tuning capacitance the varactor also up convertes noise. The quality factor of the inductor and varactor determines the phase noise performance. The phase noise performance is affected additionally by the current source and voltage across the LC tank apart from the quality factor.

B. PMOS Cross-coupled

In Fig. 2 LC VCO using PMOS cross-coupled transistors is shown. The PMOS structure is fully complimentary to NMOS LC VCO (Fig. 1). However, in order to achieve the same transconductance and to provide the same negative resistance; the PMOS transistor is sized about three times larger compared to the NMOS counterpart. This is due to the fact that reduced mobility of holes (μp) in the PMOS transistor as compared to the NMOS. PMOS cross-coupled structure shows a better phase noise performance as the noise factor is lower for PMOS compared to NMOS based VCO structure.

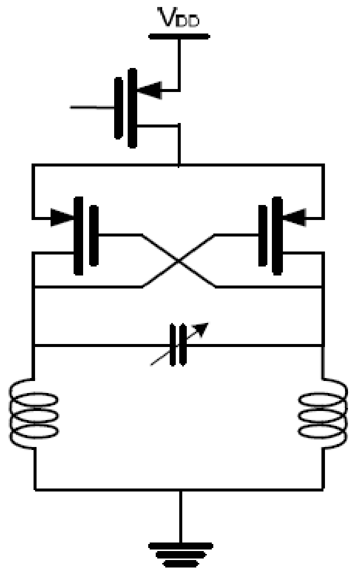


Fig. 2. PMOS Cross-coupled LC VCO

C. Complementary NMOS PMOS Cross-coupled

In Fig. 3 Complementary NMOS PMOS Cross-coupled LC VCO is shown. This structure employs both the NMOS and PMOS cross-coupled pairs. The negative resistance provided is two times larger for the same power consumption as the same bias current flows through both NMOS and PMOS devices. The total negative resistance of NMOS PMOS cross-coupled structure can be expressed as a parallel combination of the NMOS and PMOS negative resistance, Rinn and Rinp , respectively, as:

$$R_{Negative} = Rinn \,||\, Rinp = -\frac{2}{Gmn+Gmp} \quad (3)$$

where Gmn and Gmp are the transconductances of the NMOS and PMOS cross-coupled, respectively.

The amplitude of the voltage across the LC tank is increased in this structure as the NMOS and PMOS transistors are operating in a mutual switching scheme during one half period. Finally due to the presence of both PMOS and NMOS cross-coupled pairs complementary structure exhibits immunity against process variations. This makes it more attractive choice for deep submicron CMOS technologies.

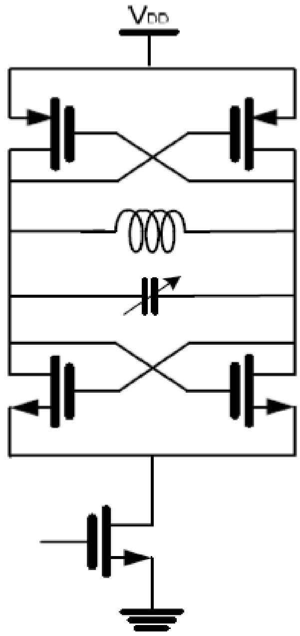


Fig. 3. Complementary Cross-coupled LC VCO

The current mirror is employed in the VCO circuit, since, the transconductance is controlled solely by the size of the device, thereby lacking a flexible approach in establishing control of the transconductance. Therefore, a current mirror is generally adopted to limit the supply current, in order to achieve a desirable control over the negative resistance and evidently, the oscillation amplitude. However, it has been observed that, it may be beneficial to entirely eliminate the tail current source under certain conditions, to achieve better phase noise performance.
For example, under low supply voltage condition, lower than 0.5 V, the tail current source can be eliminated to improve the transconductance and the voltage swing of the cross-coupled PMOS pair. Thus the tail current source aids a designer in achieving a compromise between phase noise performance and power dissipation.

## IV. COMPARISON OF VCO TOPOLOGIES

The comparison of the PMOS cross-coupled with NMOS cross-coupled and of PMOS- or NMOS-only cross-coupled with complementary cross-coupled is discussed in detail as follows:

A. PMOS cross-coupled Vs NMOS cross-coupled

PMOS cross-coupled pair has low noise characteristics compared to NMOS. PMOS structure has a lower flicker noise of about 10 times smaller than its NMOS counterpart of similar dimensions and thus is more suitable for low phase noise operation than NMOS. Further PMOS

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transistor has lower current density compared to the NMOS transistor, which results in inherent less thermal and flicker noise contribution. However, since the mobility of holes (µp) is lower than mobility of electrons (µn), PMOS devices have to be twice the size of NMOS devices to achieve a similar transconductance performance.

B. PMOS- or NMOS only cross-coupled Vs Complementary cross-coupled

An important difference between the complementary cross-coupled and its NMOS- or PMOS-only cross-coupled is in limiting the differential voltage swing. In NMOS- or PMOS-only versions, the voltage swing is limited only by the bias current, while, in complementary cross-coupled oscillators, the voltage swing is essentially limited by the supply voltage and the bias current. NMOS- or PMOS-only cross-coupled circuits exhibit AC voltage swings that exceed VDD. When designed for the same supply voltage and bias current and when operated in the same current-limited regime, the complementary cross-coupled oscillator shows a better phase noise performance compared to the NMOS- or PMOS-only cross-coupled oscillators. The important drawback of complementary cross-coupled structure is its sensitivity to supply noise.

Due to the higher harmonic distortion the thermal – and flicker – noise will be up converted. Although a complementary cross-coupled topology allows for its higher tank voltage amplitude for a given bias current and LC tank configuration, but at the cost of reduced headroom, increased parasitics, and additional noise sources. Also, the use of more than two active devices other than only the NMOS or PMOS pairs increases the number of noise sources and the parasitics, thereby resulting in harmful effects on the phase noise and frequency performance tuning characteristics.

## V. PROPOSED METHODOLOGY

The proposed design uses a NMOS cross-coupled structure for the design of VCO as shown in Fig. 4. The VCO is designed with a centre frequency of 2.4 GHz and covers a wide frequency range from 2.36 GHz to 2.6 GHz. The proposed VCO shows an excellent phase noise performance of -128.68 dBc/Hz at 1 MHz offset frequency from a 2.4 GHz carrier signal. The NMOS cross-coupled topology has been chosen because it shows the higher transconductance per unit area, and hence smaller transistor capacitances will contribute to the total parasitic capacitance of the resonant tank circuit. Also it gives the best overall performance in terms output voltage swing, bias current, phase noise, power dissipation, and total chip area required.

To tune the output frequency of the VCO, a varactor circuit implemented with the help of four transistors structure as shown in Fig. 4, is applied to vary the capacitance. The varactors are implemented with the help of MOSFETs by shorting its drain and source terminals and applying voltage between its gate and the short terminal. The VCO can be made oscillating more easily by increasing the fingers of MOSFETs but this will lead to a

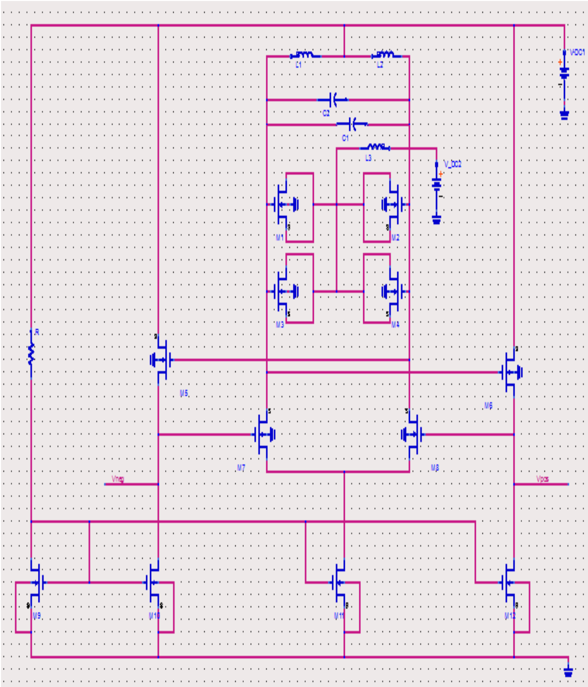

Fig4 Schematic of NMOS Cross-coupled VCO

bigger parasitic capacitance. The fixed capacitance, a varactor capacitance provided by four transistor structure and the parasitic capacitance gives the total capacitance of the circuit. To make sure a wide output frequency range, the tuning range of varactors Cmax/Cmin should be as large as possible. The effect of adding a fixed capacitance in parallel with the LC tank is such that it adjusts the resonance frequency of the tank circuit and lowers the gain of the varactor. The proposed VCO is designed using the TSMC 130nm CMOS process and simulations are carried out using the ADS Tool produced by the Agilent Technologies Inc. The simulated phase noise performance of the VCO is shown in Fig. 5. It can be seen that the VCO has a phase noise of -128.68 dBc/Hz at 1 MHz offset frequency from a 2.4 GHz carrier signal. The total DC power consumption of the VCO is about 18mW. As the KVCO is relatively high, the phase noise performance can be further improved without sacrificing the tuning range, by reducing the gain of the varactors which reduces the KVCO.

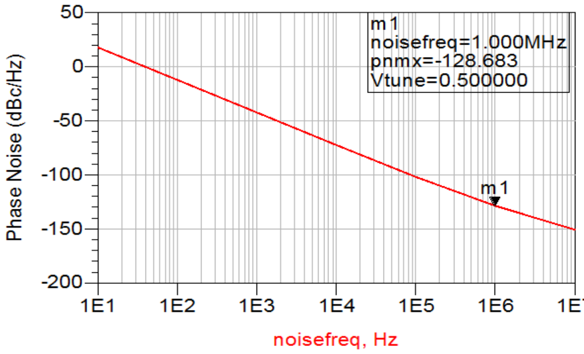


Fig. 5. Phase Noise at 1 MHz Offset

When the control voltage changes from 0 to 2 V, the frequency of VCO varies from 2.36 GHz to 2.61 GHz, which corresponds to tuning range of 250 MHz. Thus the

VCO gain, KVCO, can be calculated as 125 MHz/V. The tuning range of the VCO is shown Fig. 6.

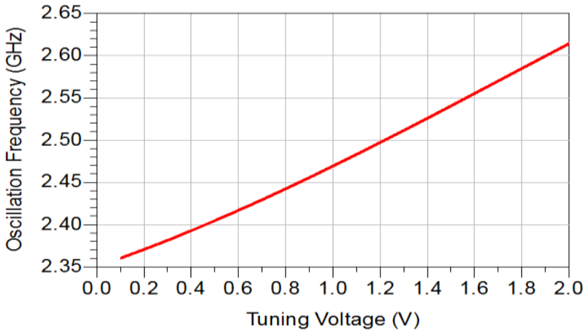


Fig. 6. Tuning Range of VCO

The circuit generates stable periodic oscillations with harmonic index as shown in Fig.7. Harmonic balance simulation simulates the circuit multiple input frequencies and calculates the steady state response of the circuit.

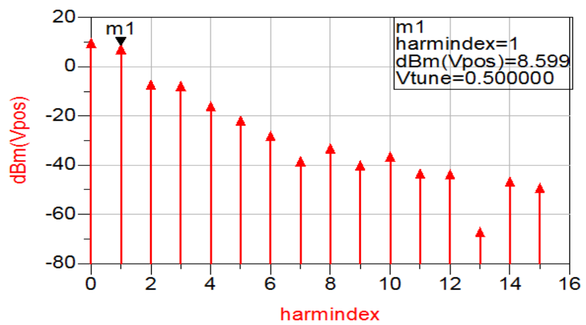


Fig 7Harmonic Index of the VCO

The FOM of the VCO is calculated to be -183.73 dBc/Hz at the centre frequency of 2.4 GHz according to the Eq. (2). The proposed VCO gives a power dissipation of 18mW and operates from a supply voltage of 1.8 V.

TABLE I gives a brief description of the performance comparison of the proposed VCO with the previously published works. It can be determined from TABLE I that our proposed design shows superior performance when compared with previous works.

TABLE I. PERFORMANCE COMPARISON OF VCO WITH PREVIOUS WORKS

| **Parameters** | **This work** | **[7]** | **[8]** | **[9]** |
|---|---|---|---|---|
| Technology (nm) | 130 | 180 | 180 | 250 |
| Supply Voltage (V) | 1.8 | 1.8 | 0.25-0.5 | 2.5 |
| Power Dissipation (mW) | 18 | 3.1 | 2.82 | 15 |
| Tuning Range (MHz) | 250 | 330 | 260 | 390 |
| Frequency (GHz) | 2.4 | 2.4 | 2.29 | 2.4 |
| Phase Noise (dBc/Hz) | -128.63 @1M | -126.1 @1M | -118.9 @1M | -115.7 @600K |
| FOM (dBc/Hz) | -183.73 | -188.8 | -181.6 | -175.98 |

## VI. CONCLUSION

The design of a 2.4 GHz LC voltage controlled oscillator based on NMOS cross-coupled structure which is implemented using TSMC 130nm CMOS technology is presented. The main parameters such as phase noise, power dissipation, tuning range and tuning sensitivity and their effects on the VCO performance are discussed. The paper explains in detail the three different topologies of LC-tank VCO design for low power consumption and low phase noise. Comparison between the VCO topologies considering their effect on the performance parameters is done. The VCO simulations and design of the layout are carried out using ADS Tool. The VCO shows a frequency tuning range of the VCO is from 2.36 GHz to 2.61 GHz when the control voltage changes from 0 to 2 V which corresponds to a 10%. The simulated phase noise of -128.68 dBc/Hz at 1 MHz offset frequency from a 2.4 GHz carrier signal. The figure of merit value is calculated to be -183.73 dBc/Hz. This design finds its applications in RF wireless communication applications because it offers low power, high performance (low phase noise), wide tuning range and small size (low cost).

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