Study of Voltage controlled oscillator for the applications in K-band and the proposal of a tunable VCO

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Abstract: The advances in wireless technology have made the transfer or sharing of information simple and efficient thereby maximizing its impact to society around the globe. Due to these advances more memory space is required to store such a large transfer of information. This can only be done by reducing the device size which means scaling of MOS transistor to deep submicron levels. The most important part of wireless technology is the wireless trans-receiver. Its role is to transmit or receive the information to (or from) the wireless device. In the wireless trans-receiver, the frequency synthesizer is responsible for generating a stable output frequency which is used further to mix the received signal down to lower frequencies and vice-versa. This stable output frequency is generated by using Phase Locked Loop (PLL). While working at high frequency at the range of 12GHz to 40 GHz, where the operation is carried out at a very high speed and the coverage is done with the multiple beams, the circuits used at high frequency should be compatible with high speed. So, in this paper one very basic component which is the heart of communication system i.e., VCO is studied and the design parameters has been listed in this paper.

Keywords: RFIC, VCO, Oscillators.

Received: April 15, 2022. Revised: June 6, 2023. Accepted: July 15, 2023. Published: August 2, 2023.

1. Introduction

With the advancement of wireless technology and number of users with a limited range of bandwidth unexpectedly increasing demands improved performance like high data rate with multimedia applications. This also leads the designers to design and fabricate the wireless components. With the technological advantages and automation algorithms in the past three decades, it is now viable to fabricate all the components of a transceiver in any wireless communication system on a single IC.

Because of the increased number of applications and demand in all the field of communication especially in the area of wireless communication where the high rate of data which is transmitted on daily basis results in the need of increase in bandwidth for the communication systems. This all is possible because of the advancement in VLSI technology and the automation industry. So, the range of frequencies from 12GHz to 40 GHz are the major area of interest in which carrier signals of very high frequency range are used. [1]. Where the applications are mainly focused for military arm forces, communication used in aircrafts and satellite, radio and radar communication. The range from 27GHz to 40 GHz is used in high throughput satellite applications and is widely available.

2. Voltage Controlled Oscillator Design

In any communication system whether it is a transmitter or a receiver; low noise amplifier (LNA), voltage-controlled oscillator (VCO) and phase lock loop (PLL) are the main part of the system. In those systems, voltage-controlled oscillator plays a very important part in any communication systems. The high frequency signals which are used as a carrier signal, these signals are obtained with the help of voltage-controlled oscillator circuits. These days with the advancement in CMOS technology where inductors can be realised using MOSFETs, so by using active inductors oscillators are designed which can be used to generate the signals up-to the range of GHz. [2][3].The traditional method used to design VCOsare either by using CMOS ring oscillator or by using Harley and Collpit's oscillator which uses LC as a tank circuit are described in [The advances in wireless technology have made the transfer or sharing of information simple and efficient thereby maximizing its impact to society around the globe. Due to these advances more memory space is required to store such a large transfer of information. This can only be done by reducing the device size which means scaling of MOS transistor to deep submicron levels. The most important part of wireless technology is the wireless trans-receiver. Its role is to transmit or receive the information to (or from) the wireless device. In the wireless trans-receiver, the frequency synthesizer is responsible for generating a stable output frequency which is used further to mix the received signal down to lower frequencies and vice-versa. This stable output frequency is generated by using Phase Locked Loop (PLL). While working at high frequency at the range of 12GHz to 40 GHz, where the operation is carried out at a very high speed and the coverage is done with the multiple beams, the circuits used at high frequency should be compatible with high speed. So, in this paper one very basic component which is the heart of communication system i.e., VCO is studied and the design parameters has been listed in this paper.4][5][6].

2.1 VCO based on inductor capacitor pair

A very basic voltage-controlled oscillator with an inductor and capacitor is shown in Fig.1. The circuit contains inductor L and capacitor C which are parallel to each other. In the circuits parasitic components are shown as R_L and R_C for the inductor and capacitor respectively. The overcome the energy loss associated with these parasitic components MOSFETs or CMOS can be utilized to have the negative resistance. The energy which is lost in the tank circuit is given by the equation Eq.1.

$$P_{loss} = 4\pi^2 RC^2 fo^2 Vpeak^2 = \frac{R}{4\pi^2 L^2 fo^2} Vpeak^2 \qquad \text{Eq.1}$$

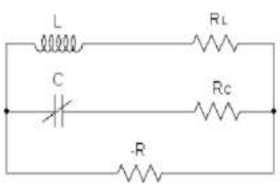

Fig. 1 VCO based on inductor capacitor pair

It can be observed from (1) that the power loss in the tank circuit is inversely proportional to the value of the inductance and the operating frequency. It can be seen that the power loss in the tank circuit decreases linearly if there is a decrease in the series resistance R as it is directly proportional to the loss, and it also decreases quadratically with an increase of the tank inductance. This energy loss due to the parasitic components should also be overcome by adding MOSFET to the circuit. To compensate the parasitic resistance, a negative resistance -R can be introduced to the circuit by using active devices so that both the unwanted stray elements can be cancelled out. This is done by using the transistors in cross-coupling topology in the tank circuit, this is shown in Fig.2.

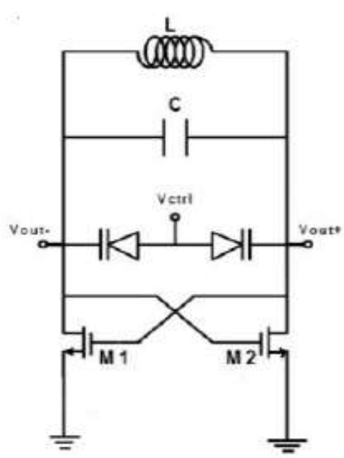

Fig. 2 Cross coupled oscillator

The idea behind using the cross coupled transistors is to have the same value of conductance (gm) as provided by the negative resistance from the oscillator. [7].

2.2 Ring VCO

A ring oscillator can be designed by using a number of buffer stages, in the basic approach the output of the last stage is connected back to the input of the initial stage. The criteria for the oscillation is that the circuit must give a phase shift of 2π or 0 and voltage gain should be greater that equal to 1 [8].

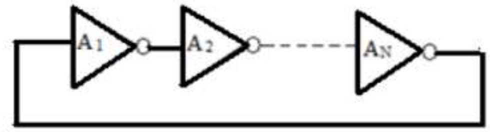

Fig.3Ring oscillator

In the circuit every stage is used to generate the delay and the phase shift of π=N, where N is used to define the number of delay stage. The another required phase shift is provided by a dc inversion [9].

2.3 Difference Between LC voltage-Controlled Oscillator and Ring VCO

The Voltage controlled oscillators as we know that it plays very important role in the design of Phase Lock Loop (PLL) circuit. In this study paper the most commonly used VCOs CMOS ring oscillator and LC tank oscillators are shown in the previous section. The LC oscillator circuits can be used as they have the advantage that they have better noise characteristics, but with the drawback that this approach may have the large dimensions, so cannot be used where the phase shift operation is required. Whereas, the ring voltage-controlled oscillator has the better performance parameters as compared to LC oscillator but they also have the demerit that these circuits have low power requirements and less area on the chip, so they can be prone to noise. So, because of these clear advantages of ring oscillators, ring oscillators are preferred over the LC oscillators [10] [11].

3. Design Topologies

The VCO is the only RF block in a PLL. Its basic function is to generate a constant RF frequency in wireless transceivers. Besides having a simple design architecture, it is the most challenging block to design because of its operation at high RF frequencies in which the phase noise becomes significant and its parameters gets deviated from desired values. When voltage at the input of VCO changes then frequency at the output is varied. The VCO can be realized either as a ring oscillator or as resonant oscillators.
As shown in Fig.4(a) an inductor L and capacitor C are parallel to each other. The resonance frequency of this LC circuit is given by Eq.2.

$$\omega_{res} = 1/\sqrt{LC} \qquad \text{Eq.2}$$

At the given resonant frequency, the impedance of the inductor and capacitor which are written as $jL\omega_{res}$, and $1/(jC\omega_{res})$ respectively , are opposite and equal to each other, thus resulting an infinite impedance. But in actual practical circuits these, passive components have stray impedance indicated as resistive components, as shown in Fig.4(b) and the quality factor for inductor is given as , Q as given in Eq.3

$$Q= L\omega/Rs \qquad \text{Eq.3}$$

Because the value of quality factor(Q) of the capacitor is much larger than the value of quality factor Q of the inductor, therefore the losses due to Rc are considered as negligible. The series model of the circuit is presented in the form of Fig.4(c)

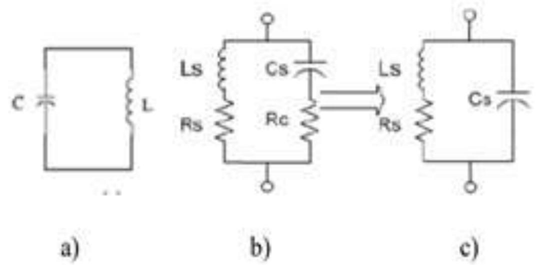

Fig.4: a) LC parallel circuit b) Oscillator Resonator with Series Resistance of the Inductor and Capacitor, c) series model of the circuit.

Now, converting the resistor (Rs) which in series with inductor (L) in Fig. 5(a) into the parallel form in Fig.5(b)
we get

$$L \approx L_p \qquad \text{Eq.4}$$
$$R \approx Q^2 Rs \qquad \text{Eq.5}$$

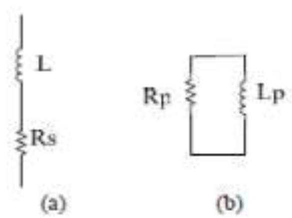

Fig.5: a) Inductor with Parasitic Series Resistance, b) Series Resistance Conversion into Parallel Resistance

It can be concluded from Eq.5; the quality factor of the inductor plays an important role in determining the amount of energy lost in the tank. Fig.6 shows a simple gain stage based on an LC tank.

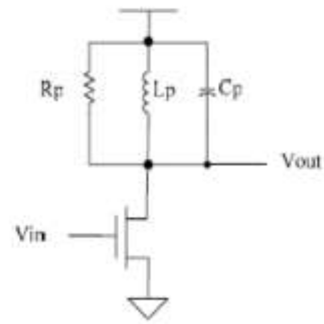

Fig.6: RLC Gain Stage used in the circuit

4. Design Parameters

Almost every trans-receiver which is designed for wireless applications requires a tunable reference frequency. Thus, an ideal VCO is required that will generate an output which is linearity proportional to the applied input voltage. And except from this linearity parameter some another parameteris also there which plays an important role in the designing of oscillators. Some of the parameters are discussed below:

4.1 Linearity

Linearity and the tuning of that linearity is the most important parameter of a VCO. Ideally, linear tuning is required, but in actual implementation the nonlinear behavior of VCO is observed as components used are also non-linear. Linearity is the required to have the VCO gain (KVCO) constant as given in Fig.7.

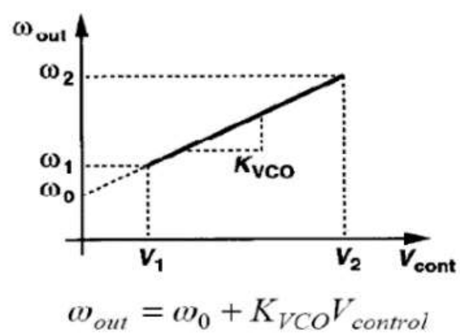

Fig.7: Ideal VCO Tuning Linearity

4.2 Range of Tuning

The range of tuning of voltage-controlled oscillator is based on the following two specifications:

(i) The center frequency of the tuning range must be remained constant with the frequency of oscillation.
(ii) Frequency deviation due to even slight variations in temperature results nonlinearities in VCO characteristics. To minimize the effect of these variations, so, a wide tuning range is selected. But these nonlinearities can be minimized by narrowing down the tuning range. Therefore, a tradeoff exists between nonlinearities and tuning range.

4.3 Power Consumption

In a PLL, most power is dissipated by the VCO as compared to other components. In this paper, VCO is studied for RF trans-receiver therefore; priority is given to the tuning range and phase noise as compared to power.

4.4 Phase Noise

The sidebands present around the central frequency in frequency domain system is called the phase noise and the same sidebands in time-domain system is called jitter. Linear time-invariant model of phase noise given by Leeson is represented in Eq.6.

$$L(f_m) = 10\log[\frac{2FkT}{Ps}(\frac{f_o}{2Q_l f_m})^2\left(1+\frac{f_k}{f_m}\right)+\frac{|K_{VCO}|^2}{2f_m^2}S_{VCNT}+\frac{|K_{VDD}|^2}{2f_m^2}S_{VDD}+\frac{|K_{IB}|^2}{2f_m^2}S_{IB} \quad \text{Eq.6}$$

Q_L = loaded quality factor
fo = oscillation frequency
Ps = signal power of oscillation
fm = offset frequency
F = noise factor of active devices
k = Boltzman's constant
T = temperature (Kelvin)
f_k = flicker noise corner frequency in the phase noise

$\frac{|K_{VCO}|^2}{2f_m^2}S_{VCNT}$, $\frac{|K_{VDD}|^2}{2f_m^2}S_{VDD}$ and $\frac{|K_{IB}|^2}{2f_m^2}S_{IB}$

are the sensitivity of the VCO to the control voltage, supply, and bias current respectively.

We observe that amongst various factors that can reduce phase noise, the circuit designer can control only three factors namely, loaded quality factor, noise factor of active device and signal power of oscillations.

(i) The loaded quality factor of the device (QL) is extracted by the amount of series resistance in the LC tank.

(ii) Therefore, high quality factor resonators inherently have lower phase noise.

(iii) The output power (Ps) is inversely proportional to phase noise. But output power must be minimized. So, we have a tradeoff between power and phase noise.

(iv) The noise factor (F) is directly proportional to phase noise. Lowering the noise factor is directly related to the active components used in the VCO. Therefore, devices with lower flicker noise are better for this application.

5. Performance Comparison of VCO Designs

Various VCO structures has been studied and their performance parameters has been compared. The comparison of performance parameters has been done for the designs which are designed for the frequency range between 24GHz to 40GHz i.e., suitable for the application of 5G circuits.
The circuit presented [12] is used for the generation of a 24GHz oscillatory signal. This signal has been generated using a 12GHz voltage-controlled oscillator indirectly cascaded with passive mixer. The circuit has been implemented in 0.18um CMOS technology, the advantage of using the passive mixer reduces the power consumption and also increases the tuning range of the device.

6. Varrious Vco Designs Used in the Frequency Range of 24Ghz to 40Ghz

As it has been studied that the VCO is one of the important blocks in the communication system. For the application of VCOs in Radar, it is used to find the highest frequency range of the system. In VCOs varactor diodes are used to tune the frequency of the device. A complementary Cross – coupled LC VCO presented in [13] that uses the MOSFET in accumulation mode for the tuning of the device. The LC tank resonator is used in the circuit contains on-chip differential inductor and a pair of MOSFET that is used in accumulation mode for a good linearity. As another application of VCO an integrated PLL has been shown [14] with low phase noise. The circuit can be used for wireless high quality video streaming. The circuit also uses the cross-coupled VCO used with varactor capacitance. The circuit provides the wide tuning range, less power consumption as well as low phase noise. Next approach that can be used and indicated [15] that uses the tunable active inductor approach. This circuit presented in [15] is also designed for the radar application and for the K and Ku band of applications. The circuit indicates the high value of Q-factor and low phase noise. VCO indicted in [16] [DTMOS] provides high transconductance gm. In the given circuit two N-type MOS are connected in parallel with the conventional VCO circuit.Capacitive division technique is used to increase the voltage swing and to lower the phase noise value.

The design of cross coupled VCO is presented in Fig.8 and has been simulated at 90nm technology using BSIM4 MOSFETs and the operation is carried out by the charging and discharging of inductor and capacitor. There will be the die down wave in the frequency of oscillations because of the lose of energy. This lose of energy can by represented by adding the Rp resistance in parallel to L and C.

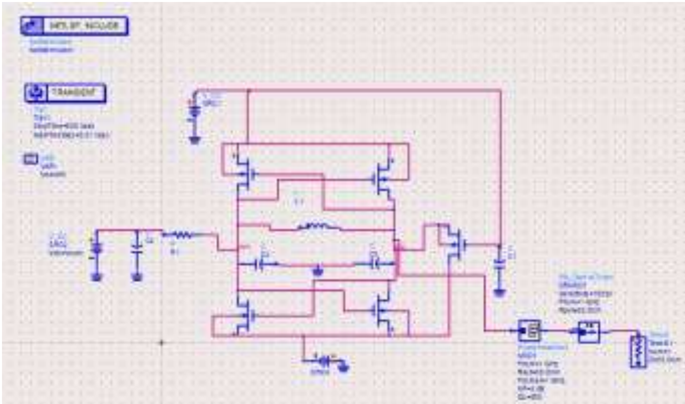

Fig.8: Cross-Coupled Voltage Controlled Oscillator

The circuit has been designed on ADS design tool and the simulation is done at 90nm technology. The output has been plotted differentially between Vop and Vom nodes. To avoid the degradation of VCO tuning range the capacitively loading on the output nodes should be avoided. The device size is decided by considering the loss in the circuit. When the net currents are balanced, net voltage across the LC tank circuit is zero and at that point the noise will affect the circuit performance. The tuning of the VCO can be done by unis the tunable active inductor. The oscillation produced are shown in the Fig.9. and the frequency of oscillations can be calculated by taking the fourier transform of the (Vop-Vom). The tuning of the circuit is proposed by replacing the inductor L by gyrator-C based inductor in which the direct tuning can be done by the biasing applied at the feedback MOSFET as shown in Fig.10.

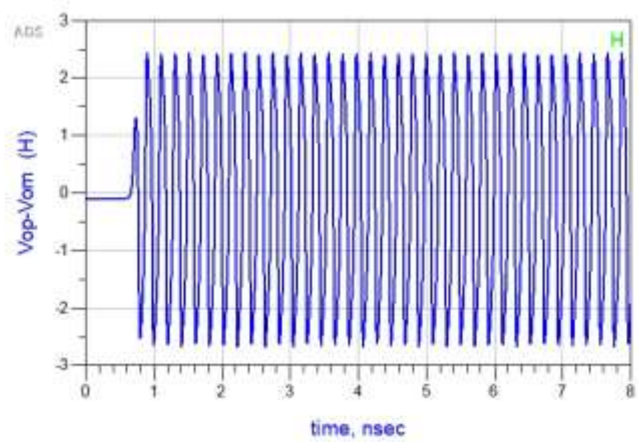

Fig.8: Frequency of oscillations of Cross-Coupled VCO

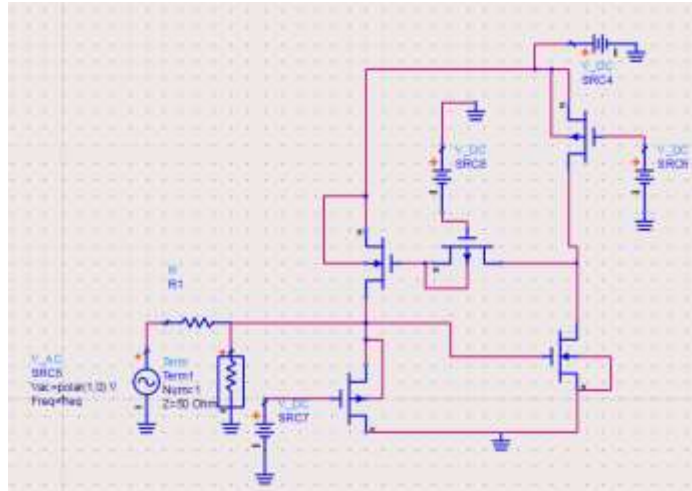

Fig.10: Tunable Active inductor design

7. Conclusion

The role of voltage-controlled oscillator in the field of wireless communication and other area of application has been studied. The design parameters which should be kept in mind to while designing the VCO has been presented in the paper. And as an application in the field of radar and another wireless communication system has been seen. Some of the designs used the tunable active inductor approach, which can be further improved by changing the design technology. A simple approach where a inductor L is replaced by single ended inductor is proposed in this study paper. The further modification can be done by using the varactor diodes for the charge storage in the tank circuit.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The author has no conflict of interest to declare that is relevant to the content of this article.