"Modelling of Low- Phase- Noise, LC Voltage Controlled Oscillator"

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***Abstract*— in this paper the Modelling of Low Phase Noise LC-VCO design issues have been discussed. The phase noise generated by the voltage controlled oscillator can be reduced by sizing the active devices, because the impact of physical parameter of device is large on the specification of any radio frequency integrated circuit.**

Several designs of voltage control oscillator circuits have been analyzed for a comparison and verify that the switched biasing does improve frequency and phase noise performance. The relative increase in voltage control oscillator's phase noise performance translates in higher modulation accuracy when used in a transceiver, therefore this increase can be regarded as significant.

***Keywords*-- VCO, LC, phase noise, LC-VCO, Tanner.**

INTRODUCTION

There are no. of techniques exist to improve phase noise performance in VCOs. One of the technique is to vary semiconductor process parameter, as the MOSFETs characteristic may have a large impact on the generation of phase noise.

No additional power is added to the system, ensuring low power operation at low noise levels. The increased oscillation amplitude will be required to maintain the oscillations.

A challenge that arises when designing an oscillator for low phase noise, is maintaining a reasonable tuning range to allow operation in the frequency bands adjacent to the Centre frequency. A large tuning range and a low available control voltage (limited by the supply voltage and device breakdown voltage) results in a large oscillator gain, which increases both intrinsic device noise and coupled spurious tones up-conversion around the Centre frequency [10]. Another concern is limiting the power dissipation of the oscillator, without compromising the output voltage amplitude, as a too low output signal might be overshadowed by noise.

SYSTEM MODEL

Figure 1.1 depicts the placement of a VCO in a communication system. The VCO is the primary tuning mechanism in any communication system, responsible for selecting the channel on which communication can commence, by generating an output signal from a synthesizer.

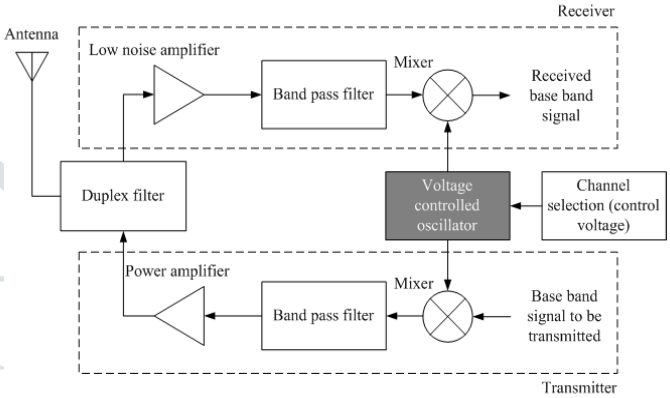

Figure 1(a). System Model illustrating the placement of the VCO.

Figure 1. illustrates how a signal passes through a communication system where a VCO is used. The signal is received by the antenna and passed through a duplex filter to distinguish between the input and output signal. If an input signal is received, it passes through a band pass filter to remove signal components outside the frequency band of interest. This signal is mixed with the signal generated by the VCO and the base band signal is extracted (down converted). If a signal is to be transmitted, the base band signal is up-converted in the mixer when modulated with the VCO signal. The signal passes through a narrow band-pass filter, is then amplified before transmission, distinguished as an output signal according to its frequency characteristics and transmitted by the antenna. The importance of the VCO in any transceiver system is evident, and low-noise operation enhances modulation accuracy.

A PLL is a control system, where phase is the variable of interest. The block diagram of a PLL is shown in Fig. 1.1. The circuit is called a phase-locked loop because the feedback operation in the loop automatically adjusts the phase of the output signal F_{out} to follow the phase of the reference signal F_{ref}. The prescaler (Frequency Divider in Fig.) divides the VCO frequency (and phase) by a division modulus of *N*.

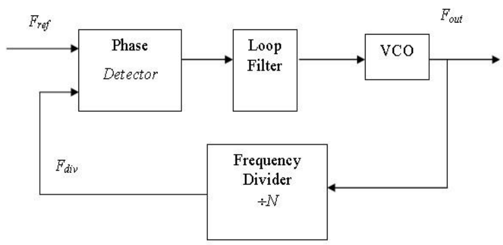

Fig 1(b). Phase Locked Loop

A. *Voltage Controlled Oscillator*

VCO is an electronic circuit designed to be controlled in oscillation frequency by a voltage input. The oscillator requires a tank circuit. A parallel resonance tank comprises of inductance (L) and capacitance (C). The principle operation of the VCO is by means of the controlled operation of the LC tank circuit. An oscillator can be described as a positive feedback system and it amplifies its own noise at a selected frequency $\omega 0$, as shown in Fig. 1.1.1.

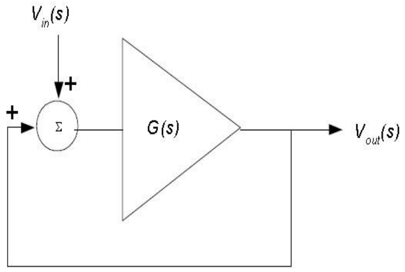

Fig. 2 Feedback diagram of an Oscillator

The transfer function of the oscillator is,

$$A_0 = \frac{V_{out}(s)}{V_{in}(s)} = \frac{G(s)}{1-G(s)} \quad \textbf{(1)}$$

From equation (1.1), it can be concluded that the closed loop gain will approach infinity under the following conditions: (1) the open loop gain is equal to unity, i.e. $G(S) = 1$, and (2) the total phase shift of the loop is equal to 0o, i.e. $\angle G(S) = 0o$, which are called the Barkhausen's Criteria. In an environment with the existence of noise at all frequencies, the Barkhausen's Criteria is satisfied only with the noise at a specific frequency $\omega 0$. When the oscillation is properly started, the noise signal at frequency ω_o is amplified and increased till the amplifying devices are saturated. Hence, the stable oscillation is maintained. In order to ensure the startup of the oscillation in presence of temperature and process variations, the small signal loop gain is typically chosen to be 2-3 times of the required value.

In most applications, it is required that the oscillator to be tunable, where the output frequency is a function of a control input. Thus, a VCO can be described by

Where, ω_{fr} is the free running frequency of the VCO, is the control voltage of the VCO and is the gain of the VCO specified in rad/s/V. A voltage signal with magnitude of V_m can be described as

$$\omega_{out} = \omega_{fr} + K_{vco} V_c \quad (2)$$

$$v_{out}(t) = v_m \cos(\theta(t)) \quad (3)$$

V_c K_{vco}

Where, $\theta(t) = \int \omega_{out}\, dt + \theta_0$. Substituting equation (2) into equation (1.3), the sinusoidal voltage output signal of a VCO is given by,

$$v_{out}(t) = v_m \cos(\omega_{fr} t + K_{vco} \int V_c\, dt + \theta_0)$$

Where, K_{vco} is assumed to be linear.

B. *Phase Noise*

Definition of Phase Noise

Phase noise is actually the change in frequency spectrum due to the deviation in the phase caused by the inherited defects in the device. If we see the output of an ideal oscillator may be expressed,

$$V_{out} = V_0(t)\cdot f[\omega_0 t + \phi_0(t)] \quad \textbf{(4)}$$

Where;

V0 = amplitude, ω0 = the frequency, φ0 = phase reference, V0 (t) and φ0 (t) are functions of time.

The output spectrum has power around ω0 if the waveform, f, is not sinusoidal, as shown in Figure 3.As a consequence of the random fluctuations represented by V0(t) and φ0(t), the spectrum will have sidebands close to the oscillation frequency, which is called phase noise, as shown in Figure 3.4. Hence Phase noise is measured in a 1Hz bandwidth at an offset Δω from the carrier, so the equation to calculate the phase noise is given by

$$L(\Delta\omega) = 10\cdot\log\left[\frac{\text{noise power in a 1Hz bandwidth at frequency } \omega_0+\Delta\omega}{\text{carrier power}}\right] \quad \textbf{(5)}$$

Here, Carrier power Spectral density is usually specified at one or a few offset frequencies and both the noise density and the offset frequency needed to be mentioned.

The figure 3.2 shows the description of phase noise in output spectrum

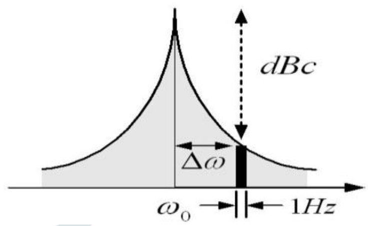

Figure 3 Phase noise in an oscillator output spectrum.

Phase Noise Models

Leeson's phase noise model, reported in 1966, is well known [7]. Leeson's model was extended in 1995 by J. Craninckx [19]. Even if Leeson's model has provides the physical information to improve phase noise. It predicts phase noise as

$$L(\Delta\omega) = 10\cdot\log\left[\frac{2FkT}{P_S}\cdot\left[1+\left(\frac{\omega_0}{2Q_L\cdot\Delta\omega}\right)^2\right]\cdot\left(1+\frac{\omega_{1/f^3}}{|\Delta\omega|}\right)\right] \quad \textbf{(6)}$$

Where :

F = Noise Factor,

k = Boltzmann's Constant,

T = the absolute Temperature,

Ps = average power dissipated in the resistive part of the tank,

ω0 = Oscillation frequency,

QL= Effective quality factor of the tank with all loading accounted for,

$\Delta\omega$ = the offset from the carrier,

1/f = Flicker Noise

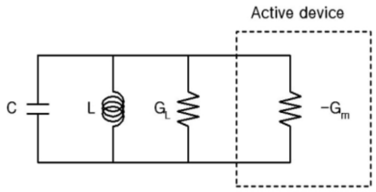

Figure 4 Equivalent one-port circuit for an LC oscillator.

The noise produced by an oscillator is important in practice because it may severely damage the performance of communication receiver sys- tem. Phase noise refers to the short term random fluctuation in the frequency (or phase) of an oscillator signal.

$$\mathcal{L}\{f_m\} = 10\log\left[\left[\left(\frac{f_0}{2Q_L f_m}\right)^2 + 1\right] \times \frac{FkT_0}{P} \times \left(\frac{f_c}{f_m} + 1\right)\right] \quad \textbf{(7)}$$

The above equation describes the dependence of phase noise on the noise factor which ultimately depends on output noise spectral density generated by circuit.

Overview of Oscillator Operation

An electrical oscillator generates a periodically time-varying signal when supplied with only DC power. An oscillator usually can be considered either as a two-port, feedback system or as two connected one-port circuits.

To generate a periodic output, the oscillator circuit must entail a self-sustaining mechanism that allows its own noise to grow and eventually become a periodic signal. Actually oscillators is a feedback system, as shown in Figure 3.1. Where the forward path is designed by an amplifier system and feedback system has a tuning section as shown in Figure 3.1, the overall transfer function from input to output is expressed as

$$\frac{y(s)}{X(s)} = 1 - \frac{A(s)}{1-A(s).F(s)} \quad \textbf{(8)}$$

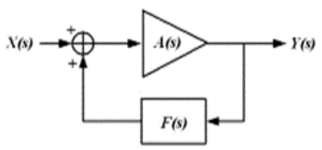

Figure 5 Positive feedback system with frequency-selective network

This feedback provides a periodic output at desired frequency so without any input as long as

$$A(s_0)\cdot F(s_0) = 1 \quad \textbf{(9)}$$

Which is known as the Barkhausen criterion. A(s)· F(s) is often called the loop gain.

Typically, it has been defined that the magnitude of loop gain is designed to be greater than one to achieve oscillation. Then, as the magnitude of the periodic signal increases, the magnitude of the loop gain is reduced to one by non- linearity in the amplifier in its steady-state operation.

Resonating section design

To design resonator of a voltage controlled oscillator it is needed to keep in mind that for what fundamental frequency it is going to be designed that is called a resonance frequency.

The resonance frequency is defined as

$$\omega_r = 1/\sqrt{L_{eq}\cdot C_{eq}} \quad \textbf{(10)}$$

Where :

Leq = Equivalent inductance in the resonating network,

C_{eq} = Equivalent Capacitance in resonating network.

To decrease the phase noise value of the voltage control oscillator the equivalent inductance and capacitance because the quality factor of the tank circuit depends on the value of these equivalent parameter values.

Literature Review

Seyed Reza Hadianamrei et al. [1] have discussed a quadrature VCO (voltage control oscillator) which applies super harmonic coupling. The presented quadrature VCO is suitable to be used, both with 2 × sub harmonic mixers, as well as 4× sub harmonic mixers. It would be impossible to avoid the presence of harmonics in CMOS VCO circuits. These harmonics are in general, undesirable signals which tend to accompany the desired fundamental signal. There are common-mode nodes (similar to those in the two source nodes in a cross-coupled VCO) in defer-entail VCO at which higher-order harmonics are present while the fundamental is absent in essence. We can make use of these second-order harmonics which are present at the common-mode nodes of two VCO in or-der to implement a quadrature connection between the fundamental outputs. The technique through which this is done is called super harmonic coupling. This CMOS quadrature VCO which applies active super harmonic coupling puts an excellent performance in show, with an output power –0.942 dBm for fundamental and –9.751 dBm for sub-harmonic, phase noise –107.2 dBc/Hz for fundamental and –114.8 dBc/Hz at a 1MHz offset.

Nisha Gupta [2] have discussed A design for a voltage-controlled ring oscillator (VCO) is Presented. The design allows an implementation of low frequency ring oscillator using relatively small devices and less stage. It is implemented using .18um technology provided by TSMC technology using 3.3V power supply. The VCO topology exhibits a very wide tuning range from few Hz to 368.9 MHz it also features the rapid voltage swing and the 48% duty cycle with good transient characteristics which is difficult to get from the conventional oscillator. Its power dissipation at the maximum oscillation frequency is 35.05 mW. Phase noise for simulated circuit is -88dbc when offset frequency is 105 HZ.

Lu Peiming et al. [3] have discussed a design of integrated LC-VCO which is used in the phase-locked loop frequency synthesizer is presented. We reduce the phase noise effectively presupposes the tuning range. The VCO is realized by using the technology of tsmc CMOS 0.18um. The whole circuit is completed under the environment of CANDENCE, the result shows that the phase noise is -108dbc/Hz @100KHz and - 131.9dbc/Hz@1MHz.

Hye-Ryoung Kim et al. [4] have discussed a new quadrature VCO (QVCO) is proposed with the NMOS back-gate as a coupling transistors. The advantage of proposed QVCO is analyzed in terms of power consumption and phase noise. Additional design techniques are applied to improve the symmetry of the complimentary VCO and to suppress the tail current noise contribution. The very low power QVCO has been fabricated in 0.18um CMOS technology for 1GHz band operation and obtained phase noise of -120 dBc/Hz at 1MHz offset.

To-Po Wang et al. [5] have discussed a low-phase-noise wide-tuning-range K-band voltage-controlled oscillator (VCO) is presented in this paper. By employing accumulation MOS (AMOS) varactors deposited between drain and source terminations of the cross-coupled pair, the tuning mechanism are enhanced, leading to a boosted VCO tuning range. Moreover, the phase noise can be improved due to the better cyclo-stationary noise property. Based on this architecture, the fabricated VCO in 0.18-μm CMOS exhibits a measured 18.2% tuning range. Operating at 0.6-V supply voltage, the VCO consumes 2.28-mW dc power excluding the buffers. The measured phase noise is −112.53dBc/Hz at 1-MHz offset from 24.68-GHz oscillation frequency. Compared to the recently published K-band 0.18-μmCMOS VCOs, it is observed that the proposed VCO can simultaneously achieve low phase noise, wide tuning range, and low dc-power dissipation.

Chunhua Wang et al. [6] have discussed a new quadrature voltage controlled oscillator (QVCO) circuit topology is proposed for low-voltage and low-power applications. In the proposed circuit, two oscillators with current-reused structure are coupled to each other by two P&N-MOS pairs. In this way, low phase noise quadrature signals are generated with low-voltage and low-power. The simulation is made by Cadence in chartered 0.18 μm CMOS process. The simulation result shows that the QVCO phase noise is approximately - 117.1 dBc/Hz at 1MHz offset from 1.8 GHz operation frequency. The QVCO dissipates 1.92 mW with a 1.1 V supply voltage.

Rui Murakami et al. [7] have discussed an ultra-compact LC-VCO. Due to the speed-up of CMOS digital circuits, jitter of ring oscillators is becoming a critical problem. Even though an LC-VCO has a better phase noise, a layout size of on-chip inductor is a problem as a clock generator. Thus, the proposed LC-VCO consists of a very compact stacked-spiral inductor and active components placed are beneath the inductor. The VCO is implemented by a 65-nm CMOS process, and the chip area is only 594 μm2. This VCO achieves a phase noise of 93dBc/Hz@1MHz, power consumption of 0.36mW, and FOMA of 210dBc/Hz.

Emad Ebrahimi et al. [8] have discussed a study of some reported LC quadrature voltage- controlled oscillators (LC-QVCO) is performed in which it is shown that robustness of the quadrature oscillation varies depending on the coupling configuration. Next, a new superharmonic LC-QVCO is pro- posed in which the common source node in either of two identical cross- connected LC-VCOs is coupled via a capacitor to the node common between the two varactors in the LC tank of the other LC-VCO. In the proposed coupling configuration there exists a *closed loop* through which the second harmonic signals circulate. A qualitative argument is presented to justify the robustness of the quadrature nature of the proposed QVCO by applying the Barkhausen phase criterion to the second harmonic signals in the loop. Since the coupling devices are only two capacitors, no extra noise sources and power consumption are added to the core VCOs. A Monte Carlo simulation showed that the phase error of the proposed QVCO is no more than 10. Also, generalizing this method to several numbers of VCOs in a loop, multiphase signals can be generated.

Chiung-FengTai et al. [9] have discussed An extended-resonant output matching circuit was proposed to enhance the negative conductance, output power and phase noise of a 24GHz transformer coupled voltage controlled oscillator (VCO). The circuit was realized by a capacitive stub-loaded resonator in a voltage boosted scheme to steepen the phase slope of the oscillator. The designed VCO shows phase noise of -117dBc/Hz at 1MHz offset frequency.

Specifications of VCO

As any electronic circuit of the electronic system works under some parameter values limitations and these limitation of values are defined as specification of circuit and system. Same way Voltage control oscillator has number of specifications that describes its performance and these are:

- Oscillation frequency
- frequency tuning range,
- phase noise
- Power consumption.

Among all the specification mentioned above phase noise is the most critical among the specifications for a VCO. Power consumption is the second most important consideration as it required to have a long battery backup is expected from a mobile device. However, a trade-off exists between power consumption and phase noise. The semi-empirical phase noise model, known as the Leeson model, is given by [7] s

$$L(\Delta\omega) \propto \frac{N}{P_S \cdot Q_L} \cdot \left(\frac{\omega_o}{\Delta\omega}\right)^2. \qquad \textbf{(11)}$$

Where

N = noise factor,

P_S = the signal power at the resonator,

Q_L = the effective quality factor of the resonator

ω_o = the oscillation frequency, and $\Delta\omega$ is an offset frequency from the carrier.

From equation (11) we can see that as large signal power will be as better will be the phase noise performance. And other parameter like Oscillation frequency and frequency tuning depend on the application. The frequency tuning range tends to be wider to cover multiband. The frequency tuning range also is related to phase noise. Usually frequency tuning is achieved by a variable capacitor that can be achieved by using a capacitive network.

Amplifier Section Design

To design the amplifier for voltage control oscillator number of things are kept in mind,

First is to maintain the amplitude at the output of the circuit.

Second is to make active devices work in a non-linear region because only in nonlinear region active devices can produce oscillations.

Third is to select active device technology, as there are number of active devices available that can produce oscillation in its nonlinear region but as every device has different physical characteristics that need specific external and device parametrical values.

Amplifying section of voltage controlled oscillator can be designed with single transistor and with multiple transistors.

The examples of single transistor oscillators are Hartley oscillator and collpits oscillator.

While designing a multiple transistor voltage control oscillator it is important to consider how they will be connected because mismatching may occur between them. Hence the topology would be an important consideration here.

Voltage-Controlled Frequency Tuning

If you see each and every communication device uses single or multiple voltage controlled oscillator, as it deals with number of frequencies it has to generate all that frequencies and it has to be designed to cover all those frequency that means its bandwidth should be large enough to accommodate and the range that it can accommodate is called the frequency tuning range.

An ideal VCO is a circuit whose output frequency is a linear function of its control voltage (*Vcon), as shown in* Figure 6.

$$f_{out} = f_o + K_{VCO} \cdot V_{con} \quad \textbf{(12)}$$

Where,

F_0 = the oscillation frequency at $V_{con} = 0$

K_{VCO} = sensitivity of the circuit

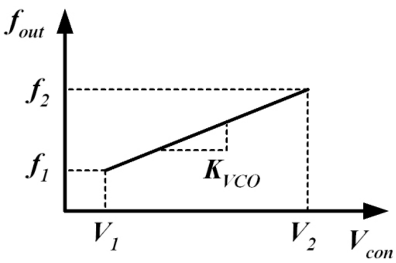

Figure 6 Definition of K_{VCO}

Frequency tuning is required not only to cover the whole application bandwidth but also to compensate for variations of the center frequency of the VCO that are caused by the process and by temperature. The oscillation frequency of an LC-tank VCO is approximately equal to

$$f_{osc} = 1/\left(2\pi\sqrt{LC}\right) \quad \textbf{(13)}$$

Power Consumption

Power consumption is one of the important specification of voltage control oscillator as the most electronic devices are hand held that require longer battery backup.. In a VCO design, it is difficult to have low phase noise with low power consumption simultaneously because the tank voltage amplitude is proportional to the current flowing. Therefore, there is a trade-off between phase noise and power consumption.

The voltage amplitude of the tank for the CMOS cross-coupled differential topology shown in Figure 3.7 (d) can be expressed by assuming that the differential stage switched from one side to the other. As the tank voltage changes, the direction of the current flow through the tank reverses. The differential pair can be modeled as a current source switching between I_{total} *and* $-I_{total}$ *in* parallel with an RLC tank. R_{eq} *is the equivalent* parallel resistance of the tank. The tank amplitude can be approximated as

$$\boldsymbol{V \approx I_{total} R} \quad \textbf{(14)}$$

This current I_{total} is responsible for the power loss in voltage control oscillators. Hence to reduce the power consumption level the total current has to be maintained.

Conclusion

In this paper various design issues for modelling of VCO for phase noise correction has been discussed. Phase noise can be modelled using parametric equations for VCO design. Some design issues for phase noise removal are taken in account for modelling. Also thermal noise reduction techniques will be applied while designing using inductors.

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