Conception of Low Phase Noise RF-VCO Using MOS Varactor

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Summary
In this paper we propose new oscillator architecture (VCO2) and we compare it with a simple oscillator (VCO1). We describe the design and implementation of the differential LC-VCO for wireless applications. In this work we develop an analytical framework for determining the best VCO for a high-frequency synthesizer design based on the constraints of the application. We show methods for reducing the phase noise in LC-VCO. We describe the optimization of phase noise performance. We examine the effect of the choice of MOS varactor on the performance of a CMOS negative resistance oscillator. The three most common MOS varactor structures (inversion, accumulation, and gated varactor) are well studied. The design of both VCOs was implemented in a standard 0.35µm CMOS process. The VCO 2 is utilized in this study because of its low phase noise. It exhibits a 1.9 GHz frequency at 2 V supply voltage. Phase-noise measurements show a phase-noise of about -90 dBc/Hz at 1MHz from the carrier.

Key words:
VCO, RF, phase noise, varactor and inductance.

1. Introduction

Periodic oscillators perform a vital function in integrated circuits [1][3]. These ICs which combine RF, analog and digital functions on the same chip are required, rapidly approaching system-on-a-chip implementations [6][8]. One of the key building blocks of a CMOS integrated RF transceiver is the Phase Locked Loop (PLL), where its performance is strongly dependent on the characteristics of the Voltage-Controlled Oscillator (VCO) [18][19]. The relative stability of the VCO signals is of particular interest when designing the RF system [20][24]. Frequency instability can lead to serious performance degradation such as intermodulation distortion in RF [23]. The metrics commonly employed to describe this instability are phase noise [10][19]. Much RF work to date has focused on frequency domain simulation of phase noise [5][14]. The phase noise performance of integrated VCO's has improved rapidly over the recent years, and fully integrated VCO's start to appear in the marketplace [4][11][27]. A standard approach for differential VCOs is the use of cross-coupled transistors to generate a negative resistance sufficient to overcome the equivalent parallel resistance of the VCO tank circuit [10]. These VCO circuits are known as $-G_M$ LC-tank VCO [15][17]. Radio-frequency integrated circuits require high quality on-chip passive elements (inductors, varctors) [8][10][25].The phase noise of the harmonic oscillator is determined by the quality factor Q of the resonance tank. In integrated resonators, the overall tank Q is normally dominated by the Q of the inductors. Motivated by this fact, a significant amount of work on modeling the inductors and optimizing their Q-values has been published over the last couple of years [6][26]. Together with an integrated inductor, the varactor builds the core of the VCO. A varactor with high Q factor and large tuning range is a mandatory prerequisite for a current efficient LC-tank VCO designs [2][6].

In Section I, we begin by discussing various VCOs architectures and we indicate some of the challenges that are present in RF VCO at high frequency. Section II explains characteristics of LC-VCO. We then motivate the problem of performing noise analysis in VCO third section. Many articles exist on how to design an oscillator for low phase noise by selecting the appropriate topology, resonator and coupling network [26][27]. Finally Section III concludes this paper.

2. Topology selection of LC VCO:

2.1 RF VCO Fundamentals

An oscillator is a system which generates a periodic output signal. The VCO are oscillators in which the output frequency is proportional to an applied external voltage [1]. Thus, VCOs are found in telecommunication systems. Oscillators must have some sort of self-sustaining mechanism to ensure that they continue to generate these periodic signals for an indefinite period of time. Countless VCO designs have been published in the recent years [16][17][23]. A more detailed analysis of the VCO is beyond the scope of this work [26][27]. The intention of this section is to briefly show what kind of performance

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can be expected from a state-of-the-art integrated VCO [8][10]. Consider the simplified block diagram of a superheterodyne transceiver, shown in Fig.1 [14][22].

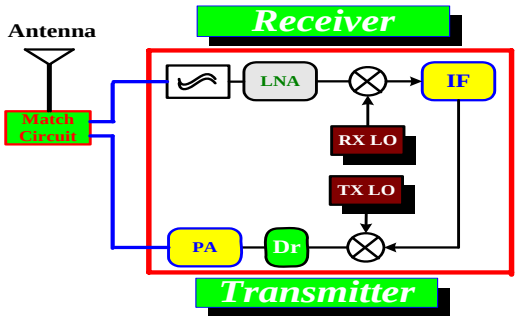

Fig. 1 Simplified block diagram of a superheterodyne transceiver.

The voltage controlled oscillator (VCO) is a key components of this transceiver as the VCO generates the ''local oscillator'' or LO frequency. The LO in turn drives the receive and transmit mixers, converting the received signal from RF to IF or baseband and similarly converting the baseband and IF signals to RF for transmission. This conversion process, or mixing, is achieved through multiplication of the sinusoidal output of the VCO with the modulated signal [18][22]. The LO signal is given by:

$$v_{LO}(t) = A.\cos(\omega_0 t + \varphi_n(t)) \quad (1)$$

Where A is the constant amplitude of the oscillator, ω_0 is the frequency of oscillation which can vary by application of the control voltage, and $\varphi_n(t)$ represents the random phase noise of the oscillator. The spurious components could be caused by known clock frequencies in the signal source, power line interference, and mixer products. The broadening caused by random noise fluctuation is due to phase noise [10]. It can be the result of thermal noise, shot noise and/or flicker noise in active and passive devices. The phase noise of an oscillator, quantified by its short term frequency stability, determines a system's ability to separate adjacent channels [5]. With the significant increase in portable, wireless traffic, better frequency stability is required. Phase noise becomes an important consideration. Choosing the appropriate topology for a low phase noise source is important, as is the choice of resonator and coupling network. An ideal VCO would have no phase noise. Its output would be a single spectral line. In practice, of course, this is not the case. There will be jitter on the output [17][19]. A noiseless oscillator is supposed to provide a perfect time reference to the circuit. However since the oscillator output is corrupted by noise, it is not perfectly periodic and it is said to have phase noise. Predicting phase noise in oscillators which are present in an RF system is extremely important because it critically affects the overall system noise performance. Fig.2 shows a typical spectrum, with random and discrete frequency components causing a broad skirt and spurious peaks [24].

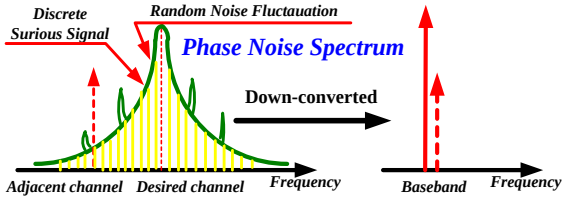

Fig. 2 Effect of phase noise in RF oscillator.

The desired channel that needs to be down-converted is showed as a solid arrow. Due to phase noise in the LO, the oscillator output spectrum is not a delta function, but is spread around the frequency of oscillation [18][23]. If an adjacent channel is also transmitting at the same time, since the noisy oscillator output power spectral density is nonzero at this adjacent channel frequency, the adjacent channel also gets down-converted to base band, thereby directly degrading the overall SNR of the system. Similarly in the transmit path, phase noise in LO output causes the up-converted signal to have finite energy outside the desired channel. Hence predicting oscillator output noise is an important problem in its own right [9][15].

2.2 Characteristics of RF-VCO circuits

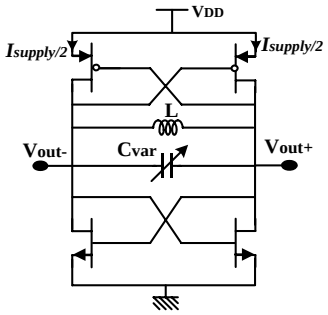

Fig. 3 CMOS architecture of the VCO1.

Practically all frequency synthesizers in communications applications employ some type of harmonic oscillator. After selecting a MOS topology, among the possible architectures that can be used in RF applications, is a differential cross-coupled with integrated LC tank. The cross-coupled CMOS was selected due to its best ratio between phase noise and power consumption [3][12]. A simple example of which is shown in Fig. 3 and 26 [15]. Due to its relative good phase noise performance, this differential LC-VCO type is a usually preferred topology for fully integrated VCO [5][9][11]. One complementary CMOS oscillator is preferred in RF applications despite

the added power consumption of the second active device. This because the two outputs of the VCO are differential, they can be subtracted to double their peak voltage output. The VCO core circuit is based on the principle of the capacity of the RLC circuit [2]. Fig.4. shows the schematic for a single-ended oscillator. The transistor (T_1) plays the role of an amplifier -G_M. It biased near the active region by a base voltage source and a current source [1]. The tank circuit consists of an inductor, a capacitor, and a parallel equivalent resistance that represents the loss (Q-factor) of the tank circuit. In this configuration, the impedance looking into the feedback loop from the tank circuit is approximately equal to $1/G_M$ (assuming that the current source presents very large output impedance). This resistance value is typically low compared to the parallel equivalent resistance of the tank circuit and will load the tank circuit, reducing its Q-factor. Since the Q-factor should be as high as possible, the tank can be buffered from the low input resistance using a buffer amplifier as shown in Fig.4.b.

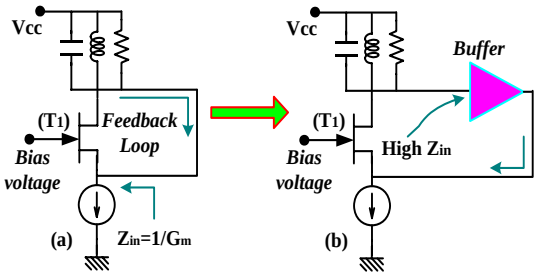

Fig. 4 Single-ended VCO model :(a) With direct feedback; (b) addition of high-impedance buffer to feedback

The buffer can be realized by a second transistor (T2) biased in a source (transistor NMOS) configuration as in fig. 5(a). This configuration is characterized by high input impedance, thus maximizing Q-factor of the tank circuit [1]. Adding a second, identical tank circuit to the drain of T_2 and connecting T_1 so that it too acts as a buffer for the second tank circuit leads to the differential implementation shown in fig.5.b.

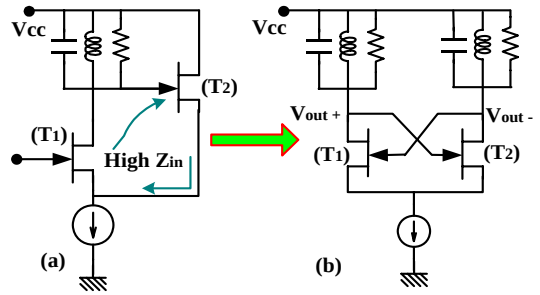

Fig. 5 Differential VCO model :(a) buffer implementation; (b) differential Implementation.

In the differential implementation, the oscillations are driven 180° out of phase with respect to each other, providing V_{out+} and V_{out-}, respectively, at the drain nodes of each transistor [1]. Differential oscillators have two distinct advantages over their single-ended counter-parts. First, the down-conversion mixers for which the VCO acts as the LO source are inherently differential. Second, differential circuits provide CMR that single-ended circuits cannot. Since the two outputs of the VCO are differential, they can be subtracted to double their peak voltage output. By subtracting them, noise signals that are common to both outputs are cancelled leading to a high CMRR (ratio). For these reasons, differential implementations are preferred in RF applications despite the added power consumption of the second active device. Different varactor-tuned negative-G_M oscillators are widely used in RF frequency synthesizer circuits, since they are suitable for full integration [10][12]. An ideal oscillator consists of an LC tank as shown in the fig.6 below. If we assume that the inductor and the capacitor are ideal the LC tank would oscillate if supplied with some initial energy.

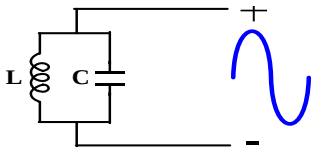

Fig. 6 Characteristics of ideal oscillator

The amplitude of the oscillations would depend on the initial energy injected into the tank:

$$Energy = \frac{1}{2} C_1 V_{pk,sug}^2 \qquad (2)$$

In an ideal LC-tank with no resistive losses, the inductor and capacitor oscillate indefinitely. Since in practice it is impossible to build a lossless passive circuit, active devices are used to produce a negative resistance to cancel out any parasitic losses in the tank [3][7]. The inductor is normally the greatest source of loss for the tank circuit and is responsible for a significant fraction of the total phase noise of the oscillator [1].

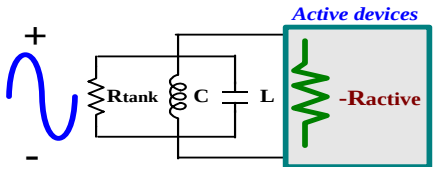

Fig. 7 Negative resistance model of real oscillator

Unfortunately, real oscillators have losses in the L and C elements and therefore the oscillations will die quickly. We need to inject energy in the tank circuit to sustain the

oscillations. The amount of energy injected in the tank should be equal to the energy lost due to the losses in the tank circuit. Injecting energy into the tank can be viewed as connecting negative resistance across the lossy tank circuit (fig.7).The frequency selective tank can be expressed or approximated by a simple parallel RLC circuit with equivalent parallel resistance, R. This is the resistance responsible for the loss in stored energy per cycle. The active circuit compensates for this loss by providing a negative resistance, -R, of equal amplitude to the equivalent parallel resistance of the resonator. Thus, from an operational point of view, the resistance of the resonator is cancelled out and it appears as a lossless network. The oscillator can now sustain an output signal of constant amplitude. The LC-oscillator oscillates at the resonant frequency of the inductor and capacitor,

$$\omega_0 = 1/\sqrt{LC} \qquad (3)$$

An LC-VCO generally consists of an LC tank and a circuit that generates a negative conductance for compensating the losses in the LC tank. For the start-up of oscillation, the following equation has to be fulfilled [10]:

$$-GM > \frac{1}{R_P} \qquad (4)$$

Where G_M is the negative conductance and Rp is the equivalent parallel resistance of the LC-tank. Fig. 8 shows this circuit redrawn as a pair of cross-coupled inverters shunted with a tank circuit [3][24].

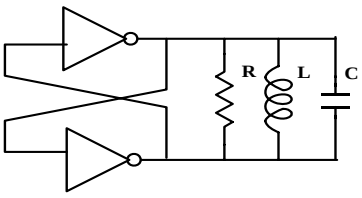

Fig. 8 Cross coupled inverters.

The cross-coupled NMOS transistors provide the negative resistance to cancel the losses presented by the parallel LC tank at resonance. Moreover, the PMOS devices allow better symmetry to be achieved on each of the resonant nodes by equating the positive and negative drive strength. It is this attention to symmetry on both the full circuit and each half circuit that reduces phase noise [1][15]. It turns out that the left and right sides of this complementary $-G_M$ oscillator, are identical to the structure of a CMOS inverter. This provides a very intuitive way to understand the operation of the complementary VCO.

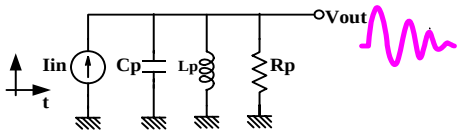

Fig. 9 oscillatory behavior Decay.

Oscillatory behavior is dilapidated because of lost energy in the form of heat in resistance (Fig. 9).

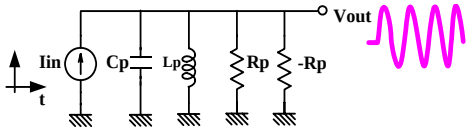

Fig. 12 –GM oscillator problems

$R_P//(-R_P)=\alpha$; It shows that the tank oscillates indefinitely. If a one-port circuit exhibiting a negative resistance is placed in parallel with a tank, the combination will oscillate. The response of a RLC tank with a negative resistance ($-R_P$) placed in parallel with RP as shown in the fig. 11.

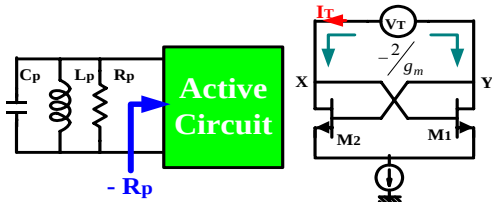

Fig. 11 representative Diagram of the oscillating circuit.

If the feedback is sufficiently positive (the loop gain is negative) a negative resistance is achieved. The cross-coupled pair can provide a negative resistance. Thus, the equivalent resistance is given by the following equation:

$$R_{eq} = \frac{V_T}{I_T} = -\left(\frac{1}{g_{m1}} + \frac{1}{g_{m2}}\right) = -\frac{2}{g_m} \qquad (5)$$

Viewing the negative resistances generated by the PMOS and NMOS devices in the manner discussed above, the total negative resistance of this circuit is the parallel combination of the two individual cross-coupled FET circuits [13][16]. Thus, the negative resistance is given by:

$$R_{n?ative} = \frac{2}{G_{Mn} + G_{Mp}} \qquad (6)$$

The linear oscillator that works based on generating a negative resistance has several problems:

- If $R_{tank} > R_{négative}$, oscillations will die

- If $R_{tank} < R_{négative}$, oscillations will grow
- Need $R_{tank} = R_{négative}$, to sustain fixed oscillation amplitude

Consequently, the oscillation condition is expressed by:

$$R_{\tan k} = R_{n?ative} \quad (7)$$

This effect is schematized by the fig. 12.

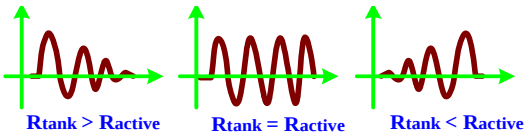

Fig. 12 –GM oscillator problems

To reduce VCO power consumption and phase noise the tank inductance should be minimized of the total tank capacitance. Therefore highly tunable varactors can be used to increase the VCO frequency tuning range, or to decrease power consumption and phase noise. In the following section, we study the design and modeling of a novel high-factor tunable capacitor implemented in CMOS technology. We present a simulation strategy to generate the capacitance, tuning range of MOS varactors and frequency of VCO. We characterize a method of adjusting the capacitance of the LC-tank to improve the performance in telecommunication application.

2. LC-VCO circuit design and measurements results:

2.1 Oscillator architectural Considerations

A VCO is an autonomous circuit with either feedback or negative resistance designed to cause periodic oscillation at one frequency; that frequency is set by an RC, RL, or resonant LC network (Fig. 13).

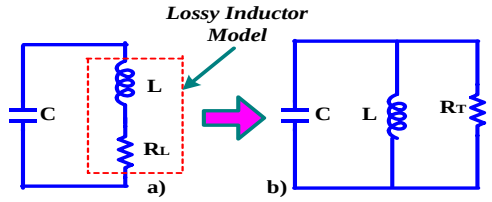

Fig. 13: a) Model for LC resonator with loss dominated by inductor, b) Parallel LC approximation with tank impedance RT at resonance.

The vast majority of VCO's designed for communication systems use a parallel LC resonator (or LC tank) to select the frequency of oscillation because of its potential for superior noise performance. The power requirements and noise performance of an LC VCO are largely determined by the impedance at resonance (R_T) and quality factor (Q_{tank}) of this resonant LC tank. Integrated circuit processes are inherently better suited to making capacitors than inductors and, for frequencies below about 10GHz, the value of Q_{tank} is usually limited by the losses in the inductor. The inductor quality factor (Q_L) is:

$$Q_L = \frac{\omega_0 . L}{R_L} \approx Q_{\tan k} \quad (8)$$

For the parallel LC tank in (Fig. 25.a), the approximate magnitude of the tank impedance at resonance (R_T) is given by:

$$R_T = \omega_0 . L Q_L \quad (9)$$

Some popular LC VCO topologies are shown in [1][2][8]. The circuit topology chosen for the LC oscillator was adapted from [27] and is shown in Fig. 26.

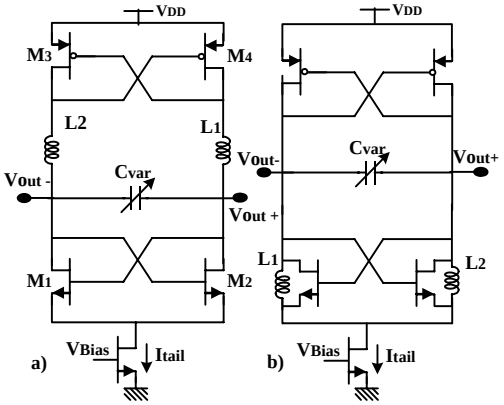

Fig. 14 Complementary CMOS oscillators Topologies: a) VCO1, b) VCO2.

This one shows the CMOS version of this circuit with a current mirror that can be used to control the bias current, and therefore the negative resistance of the circuit. However, the ideas presented apply to most differential LC tank tuned oscillator circuits [4][5]. The cross-coupled NMOS devices (M1 and M2) form the negative resistance and the PMOS devices (M3 and M4) create a positive feedback load. Cvar is perhaps the most important element of the LC oscillator circuit besides the inductor itself. This is tunable capacitor that provides for the tuning range of the oscillators. Generally, the tuning range, of LC-oscillators is very limited. As well as, tuning is accomplished using a varactor which is regarded as capacitance in the tank. Since integrated varactors have limited tuning range, LC-oscillators cannot compare with ring oscillators in this regard [6]. The VCOs designed for

this paper can be categorized as negative transconductance ($-G_M$) oscillators. Fig. 14 b) shows a switched resonator that is composed of a spiral inductor and a switching transistor connected in parallel with an inductor. The inductance of the resonator is largely determined by the inductor while the capacitance is determined by the parasitic capacitance of the inductors and the capacitance between drain and ground of the switching transistors. A certain amount of current is needed for oscillation to begin, but the current required to meet output swing requirements is usually much greater. The bias current I_{tail} that flows through the mirror device is referred to as the tail current [4][9]. However in some cases it may be advantageous to eliminate the tail current source entirely since it will contribute device noise to the circuit. Typically, output voltage V_{out} must be at least a few hundred mill Volts. V_{out} can be expressed as a constant times the product of the bias current and R_T for the proposed VCO. Hence, R_T must be maximized to minimize current, making high value, high-Q inductors critical to reducing power in the VCO [17]. The choice of VCO topology is also an important consideration for minimizing power. For instance, V_{out} as a function of I_{tail} and R_T for the NMOS only circuit is [9]:

$$V_{Out} \approx \frac{2}{\pi}.I_{tail}.R_T \tag{10}$$

Whereas, V_{out} for the complementary (CMOS) VCO is:

$$V_{Out} \approx \frac{4}{\pi}.I_{tail}.R_T \tag{11}$$

The CMOS VCO will deliver twice the output swing for a given current, but can only generate half the maximum swing of the NMOS only device, which swings about the supply rail. Thus, the CMOS would be the preferred choice unless it can't generate sufficient swing. For a given bias current, the CMOS VCO provides twice the voltage swing because the commutating current I_{tail} flows through a parallel impedance of $2R_T$, whereas the impedance seen by I_{tail} in the NMOS VCO is only R_T. The CMOS VCO can also be seen as a vertical stack of two VCO's sharing the same bias current. As we'll see below, stacking RF circuits to reuse bias current is a powerful tool for improving system efficiency. In reality the L is not ideal and there is always serial resistance associated with the actual inductor. This resistance needs to be cancelled by the active device which provides negative resistance. The capacitor C can be implemented using a MOS varactor. The total parallel capacitance includes the parasitic capacitance from the inductor, the capacitance from the MOS varactor, and the drain capacitance of the active device M1 or M2 (consider the VCO in fig. 26 for example).

2.2 Analytical study of oscillator phase noise

The LC-tank inherently filters out frequencies away from the resonant peak, which improves the phase noise performance, particularly with a high-Q tank. In addition, the energy storage of the inductor and capacitor mean that only a minimum of energy must be added by the active devices, further helping phase noise performance. Using the one port model of an oscillator we can understand the origin of phase noise in an oscillator and derive expression that would allow us to quantify the phase noise of oscillators. We will assume that the active circuit that generates the negative resistance is noiseless. In this section we will derive an expression for phase noise of an oscillator assuming that the active circuit contributes a finite amount of noise to the circuit. That is to say:

- Active circuit does not add noise
- Active circuit acts as $R_{active}= R_{tank}$ only at resonance and $R_{active}=$ infinite at all other frequencies

An equivalent one-port model of an LC oscillator is shown in Fig. 15. All noise sources in the circuit are combined into a single current source $\overline{I^2_{R\tan k}}$.

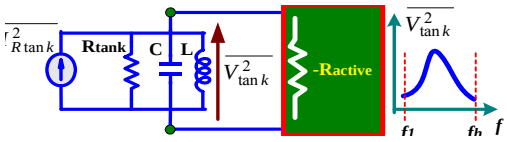

Fig. 15 One-port model of an LC oscillator

Let us qualitatively understand the impact of noise generated by the loss of the tank on the phase noise of the oscillator. We are ready to determine the tank Voltage

$$\overline{V_{\tan\ k}(\omega)} = \left[\frac{1}{\frac{1}{R}+\frac{1}{j\omega L}+j\omega C}\right].\overline{i_{R\tan\ k}(\omega)} \tag{12}$$

The total output voltage is defined by

$$\begin{aligned}\overline{V^2_{total}} &= \int_0^{\alpha}\overline{V_{\tan\ k}(\omega)}.d\omega \\ &= \int_0^{\alpha}\left[\frac{1}{\left(\frac{1}{R}\right)^2+\left(\frac{1}{j\omega L}+j\omega C\right)^2}\right].4\,KTRdf \\ &= \frac{KT}{C}\end{aligned} \tag{13}$$

Phase perturbations due to random noise in the oscillator result in a random shift of the oscillator frequency. These random frequency variations are caused by thermal noise, shot noise, and flicker noise. Thermal noise is a function

of the temperature, bandwidth and resistance, shot noise is a function of the DC bias current, and flicker noise is a function of the active device characteristics. Single sideband phase noise is defined as the noise power in a 1-Hz bandwidth at some offset frequency from the carrier, oscillation frequency, and has the units of dBc/Hz (Fig. 16). In general phase noise can be defined as (47)

$$L(\Delta\omega)\{dBc/Hz\} = 10.\log\left[\frac{P_{sideband}\ (\omega_0+\Delta\omega,1Hz)}{P_{carrier}}\right] \quad (14)$$

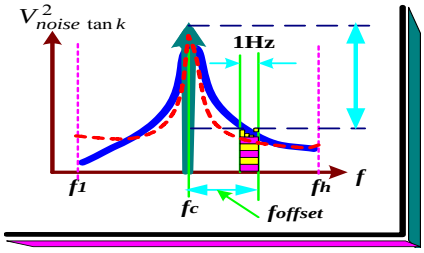

Fig. 16 Characterization of noise sideband in frequency domains

In (14), $P_{sideband}(\omega_0 + \Delta\omega, 1Hz)$ represents the single sideband power at a frequency offset ($\Delta\omega$), and $P_{carrier}$ represents the total power under the spectrum. It should be noted that (14) includes both amplitude and phase fluctuations. Otherwise, we definite (14) by:

$$L(\omega_0+\Delta\omega) = \frac{\overline{V^2_{noise,tank}(\Delta\omega)}/1Hz}{V^2_{rms,sig}} \quad (15)$$

The noise voltage the output can be expressed as follows:

$$\overline{V_{noise,tank}(\omega_0+\Delta\omega)} = \left(\frac{1}{\frac{1}{R}+\frac{1}{j(\omega_0+\Delta\omega)L}+j(\omega_0+\Delta\omega)C}\right)\overline{i_{R\,tank}(\omega_0+\Delta\omega)} \quad (16)$$

This enables us to find the following formula

$$\overline{V^2_{noise\ ,tan\ k}(\omega_0+\Delta\omega)} \approx 4KTR.\left(\frac{\omega_0}{2Q.\Delta\omega}\right)^2 \quad (17)$$

Where ω_0 is the oscillation frequency, Q is the quality factor in LC tank, $\Delta\omega$ or ω_m is offset frequency We definite the factor of quality of inductors by a limiting factor and mainly determines the total Q of an LC tank. The quality factor is defined as [1][6]:

$$Q = 2\pi\frac{maximum\ \ energy\ stored}{energy\ dissipated\ \ per\ cycle} = \frac{\omega_0}{\Delta\omega} \quad (18)$$

Where $\Delta\omega$ is the 3-dB bandwidth of the system and ω_0 is the resonant frequency of the system. The resonator Q will strongly influence both the phase noise and the power consumption of an oscillator. The inductor in an LC VCO is usually the most critical circuit element in the design-typically; the Q of the inductor dominates the total Q of the tank circuit. In addition, the tuning range of a VCO is strongly affected by the inductor.

$$L(\Delta\omega)\{cdB/Hz\} = 10*\left\{\frac{\overline{V^2_{noise,\tan k}[@(\omega+\omega_m)]/1Hz}}{V^2_{sig}}\right\} \quad (19)$$

$$\approx 10.\frac{4.K.T.R\left(\frac{\omega_0}{2.Q.\Delta\omega}\right)^2}{V^2_{sig}}$$

As mentioned before the phase noise occurs due to the device and component noise, and interference. The contributions of various noises to phase noise have been studied [5][9][11] and can be identified by plotting L{Δω} as a function of Δω on logarithmic scales.

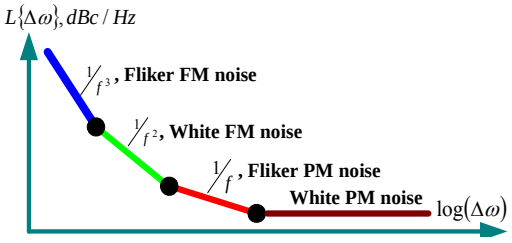

Figure 17 A typical phase noise plot for a free running oscillator.

Fig.17 shows an asymptotic plot of single sideband noise as a function of offset frequency from the carrier for a free-running oscillator. The different regions are identified based on the roll-off in carrier power with frequency. The phase noise plot has been effectively split into four different regions. The noise power in the three regions close to the carrier has cubic ($1/f^3$), quadratic ($1/f^2$), and linear (1/f) dependence with frequency. At large offset frequencies the spectrum becomes flat. The regions are named considering the noise source contributing to the phase noise. The simplified model of an LC oscillator is a lossy LC tank combined with a noiseless energy restorer that keeps constant oscillation amplitude. The phase noise for this model can be analytically calculated, it is [14][15]:

$$L\ \{\Delta\omega\} = 10\log\left\{\frac{2\ KT}{P_{diss\ ,\tan k}}\left[\frac{f_0}{2\,Q_L\ \Delta f}\right]\right\} \quad (20)$$

This is the theoretical limit for an LC oscillator (flicker noise being neglected). There will be further noise contributions that usually dominate the oscillator phase noise. The goal for the LC-VCO design is to reduce these contributions and approach the limit as close as possible. The phase noise of the VCO is determined primarily by the overall Q of the circuit. In order to design a circuit with high Q, the tuning bandwidth must be made small.

Therefore, a VCO designed for low phase noise performance will have a smaller tuning range. The spectral density of phase fluctuation, due to phase modulation of the carrier signal, is represented by Lesson's Phase Noise Model [1]:

$$L\{\Delta\omega\} = 10\log\left\{\frac{2FKT}{Ps}\left[1+\left(\frac{\omega_0}{2Q_L\Delta\omega}\right)^2\right]\left(1+\frac{\Delta\omega_{1/f^3}}{|\Delta\omega|}\right)\right\} \quad (21)$$

Where F is an empirical parameter, k is the Boltzmann constant, T is an absolute temperature, PS is signal power, ω_0 is the oscillation frequency, Q_L is the loaded Q of an LC tank, $\Delta\omega$is offset frequency, and ω_{1/f^3} is corner frequency. It is well known that phase noise decreases inversely proportional to the square of the quality factor Q in an LC tank. Note that the impact of phase noise on the performance of a receive chain depends critically on the nature of the phase noise energy as we move away from the carrier. The energy injected into tank is defined by the following equation:

$$Energy = \frac{1}{2}C_1V_{pk,sug}^2 \quad (22)$$

This gives

$$\overline{V_{trms,sig}^2} = \frac{Energy}{C} \quad (23)$$

Recalling (46), we can now determine the signal to noise ratio of The VCO:

$$\frac{Signal-Power}{Noise-Power} = \frac{\overline{V_{trms,sig}^2}}{V_{total}^2} = \frac{Energy}{KT} \quad (24)$$

2.3 Practical results

The topic of analyzing and determining phase noise is vast and very interesting. Hence, this sub-section reviews the phase noise of the proposed VCOs. Simulations show VCO2 (Fig. 14.b) operate at 1.87 GHz under 1 V control voltage. Fig. 18 shows the SPICE simulated results. The simple equation governing the frequency of oscillation was discussed in the equation (15) (in second section).

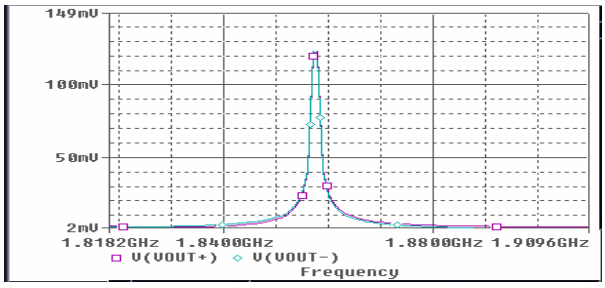

Fig. 18 Frequency spectrum of VCO2

In order to obtain a high Q inductor shortly, we need to estimate the inductor characteristics quickly and accurately against various physical parameters of inductor structures. We usually optimize the inductor structure to maximize the Q value of inductor, under the constraints of the demanded inductance value. We can naively optimize the structure with a lot of simulations by trial and error. Looking more into how the VCO2 circuit design functions, Fig.32 shows the voltage output waveforms.

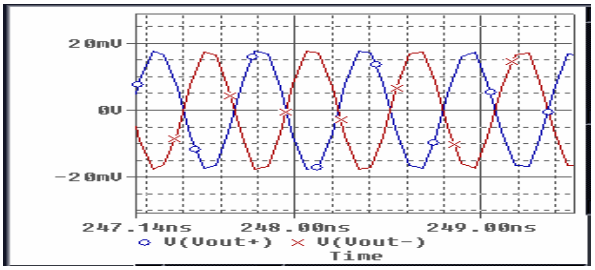

Fig. 32 Output waveform of Modified VCO.

The inductor Q is limited by physical phenomena that convert electromagnetic energy into heat or radiation. If the substrate is sufficiently conductive, magnetically induced currents, or bulk eddy currents, flow in the substrate and act as a possibly dominant form of loss. In the case of highly conductive substrates, eddy current losses indeed severely limit the Q. For all measurements, the supply voltage and control voltage were set to the nominal values of 2V and 1V, respectively.

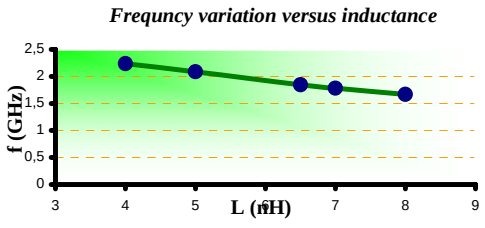

Fig. 19 Oscillation frequency versus inductance

The simulation shows that the main noise contributors of the VCO circuit are the losses of the LC tank and the active elements of the VCO core circuit.

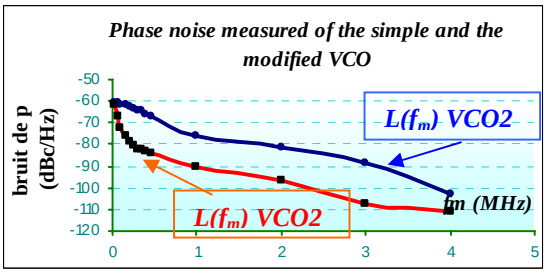

Fig. 20 Phase noise spectral density results for each VCO

This degradation of phase noise is explained by the increasing inductance driving the oscillator into the saturation region as illustrated in Fig. 21.

Here we observe upconverted flicker noise close to the fundamental. The corner frequency is near 1MHz for the VCO_2 configurations. The VCO_1 configuration exhibits substantially more flicker noise upconversion and it is observed over a much wider bandwidth. A gain of over 15dB is achieved in the device polarity change from VCO1 to VCO2. The phase noise of VCO_1 and VCO_2 displays little dependence on the frequency tuning; the small difference is likely due to the small change in tank quality factor with frequency. In order to compare VCO_2 performance to VCO1, it is useful to employ a figure-of-merit (FOM) that captures two important performance parameters for oscillators: phase noise and power consumption. The formula (25) is presented in [26], is repeated here for convenience:

$$FOM = 10\log\left\{\left(\frac{f_0}{\Delta f}\right)^2 \frac{1}{L\{\Delta f\}.V_{DD}.I_{DD}}\right\} \qquad (25)$$

The calculated FOM for VCO2 is 158 dB, which compares favorably with VCO1.

Table 1: Margin specifications Summary of simulated and calculated phase noise for each oscillator configuration, f_0 = 1.865GHz

	VCO1	*VCO2*
Technology	0.35µm CMOS	0.35µm CMOS
Supply Voltage	2V	2V
Center frequency	1.858 GHz	1.889 GHz
Tuning Range	1.511 MHz	1.423 MHz
Phase Noise @1MHz	-75 dBc/Hz (from 1.9 GHz carier)	-90 dBc/Hz (from 1.9 GHz carier)
quality factor	1230	1328

7. Conclusion

This paper has presented studies and simulation results of different approaches to phase noise reduction in RF VCO using varactor MOS. We develop an analytical framework for determining the best VCO for a high-frequency synthesizer. We describe the optimization of phase noise performance in LC-VCO.

The C-V characteristics of MOS Varactor contain a wealth of information about the semiconductor characteristics, which extend to oscillator performance. VCO design presented in this work is characterized by frequency tuning performed by voltage control on chip capacitances. We examine the effect of the choice of MOS varactor on the performance of a CMOS negative resistance oscillator.

The three most common MOS varactor structures (inversion, accumulation, and gated varactor) are well studied. Low noise fully integrated VCO was presented in this paper. Design equations are provided that give reasonable prediction of phase noise as verified by simulation.

An efficient and robust method based on the passive elements used to compare the phase noise of two VCOs. We present a simple oscillator (VCO_1) compared to modified oscillator ($VCO_{2)}$. Simulation results show that VCO_2 clearly displays the lowest phase noise at large offset frequencies from carrier is about -90 dBc/Hz at 1 MHz, and the lowest tuning range and the most quality. The design of both VCOs was implemented in a standard 0.35µm CMOS process, under 2V and 1V voltage supply and tuning voltage, respectively.

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