Low Phase Noise Performance of VCO Using MEMS

Khalid A. S. Al-Khateeb, M. Mu'adz Mohd Subki
Department of Electrical and Computer Engineering,
Kulliyyah of Engineering
International Islamic University Malaysia
khalid@iiu.edu.my

Abstract

The paper presents a monolithic voltage controlled oscillator (VCO) prototype designed with micro-electro-mechanical systems (MEMS) devices. It achieves the stringent performance requirements of various wireless communication applications such as GSM cellular telephony. The VCO meets the low phase noise requirement of -136 dBc/Hz at large offset frequency (3MHz) over the appropriate frequency range.

A model for the simulation of the monolithic VCO is proposed. A suitable topology for the model is the Colpitts Oscillator. It is relatively less complicated, which facilitates the practical integration of the LC components. The main components in the configuration are the MEMS variable capacitor and monolithic 3-D coil inductor. These components are suitable for low phase-noise and low power consumption at the application frequencies.

Key words: VCO, Colpitts oscillator, LC, MEMS, 3-D coil inductor, GSM, phase noise.

I. INTRODUCTION

Mobility and portability are features, which have a strong driving force in the miniaturization process of wireless communication interfaces, which have raised much interest in single-chip radios. The integration of passives devices such as variable capacitors and inductors, typically involves some trade-offs between noise, power consumption, linearity, frequency range, gain and supply voltage. Higher quality factors and lower insertion losses however, may mitigate some of the trade-offs. A low phase noise VCO operating at radio frequency (RF) can be designed by integrating a variety of components of high Q factors and low insertion loss.

Micro-electro-mechanical Systems (MEMS) can be used to achieve this purpose with variable capacitors (varicaps) and inductors. Both of these passive components can be fabricated on silicon substrates and thus are amenable to monolithic integration by standard IC process. The MEMS technology is attractive for the implementation of on-chip high-quality RF variable capacitors and inductors. The implementation of these devices is in low noise power amplifiers, matching networks, and monolithic low-noise VCO is an attractive proposition. In fact, the quality factor of these components ultimately determines the phase noise performance, which is critical in high performance communication systems [1]. The introduction of MEMS in RF systems increases the functionality and improves the performance. The challenge in VCO design is to minimize the phase noise while maintaining lowest possible power consumption.

II. THE PHASE NOISE

The main characteristics of a versatile VCO are; low phase noise, low power consumption, wide tuning range and a high output power. However, these are hard to achieve all at once, because of trade-offs. A significant amount of research is going on, and the phase noise is one of the most important targets. The phase noise is a rapid, short term random fluctuation, which can be expressed as signal to noise power ratio in unit bandwidth. The expression for calculation at an offset frequency f_m , from the carrier frequency, f_o from is the classical Leeson's model [2]:

$$PN(f_m) = \frac{2.k.T.F.R_p}{A_o^2}\left(\frac{f_o}{2.Q.f_m}\right)^2\left(1+\frac{\Delta f_{1/f^3}}{f_m}\right)^2$$

Where; F is the excess noise factor, k Boltzmann constant, T the absolute temperature, A_o is the amplitude of oscillation, Q is the resonator loaded quality factor, R_p is the parallel resistance to model

978-1-4244-1692-9/08/$25.00 ©2008 IEEE

losses in the resonator, $\Delta f_1 / f^3$ is $1/f^3$ corner frequency in the phase noise spectrum.

For an ideal oscillator, the shape of the spectrum is an impulse at a resonant frequency, ω_o. However, in actual oscillators, skirt shape is formed around ω_o. Figure 1(a) shows the single spike of energy at the center or carrier frequency, ω_o and Figure 1(b) shows the skirts around ω_o due to phase noise. Actually, the phase noise is expressed as the power at particular offset, ω_m from ω_o. The signal power is measured in a 1 Hz bandwidth at ω_m [3]. The unit of phase noise is dBc/Hz represented as decibels below the carrier per hertz.

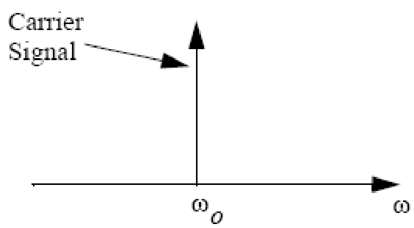

Figure 1. (a) Output spectra of ideal oscillator.

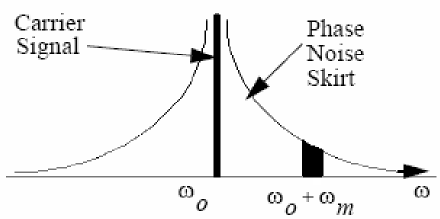

Figure 1. (b) Output spectra of practical noisy oscillator.

In the prototype MEMS oscillator, there is an additional noise source due to the mechanical thermal vibration is included instead of thermal and flicker noise. In practice, this kind of additional noise is due to the vibrations of the suspended plate which cause variation in the capacitance and affect the overall output of the phase noise [1].

III. MEMS PASSIVE DEVICES

There are two approaches to design and fabricate a VCO using MEMS passive devices. The first is to replace the MOS capacitors with MEMS, which is good for a wide tuning range. The second is to use a monolithic 3-D coil inductor. A high Q varicap is a key elements a low phase noise VCO. The high-Q MEMS varicap also enables a complete monolithic fabrication of RF VCO for on-chip IC compatible devices, with lower loss, larger tuning range and higher linearity [4]. The high-Q variable capacitor can be realized by a surface micro-machined all aluminum microstructure. The top and cross are shown in Figure 2. It consists of 1 µm-thick aluminum plate suspended in air 1.5 µm above the bottom layer and anchored with four folded beam suspensions acting as springs. Aluminum sheet resistance is low, which is critical to minimize the ohmic losses, and the fabrication temperature 150ºC [1] is also low. The plate size of 200 µm by 200 µm and 1.5 µm nominal air gap results in a nominal capacitance value of approximately 200 pF. Thus, large capacitance can be obtained by parallel connection [5]. In RF transceivers, the DC tuning voltage is typically limited to 3.3 V or less. Thus with a 1.5 µm air gap and a 200 µm square plate, require 3.8 N/m for a 3.3 V operation. This corresponds to a mechanical resonant frequency of 30 kHz [1]. The suspension consists of four folded beams 100 µm long and 20 µm wide as in Figure 2.

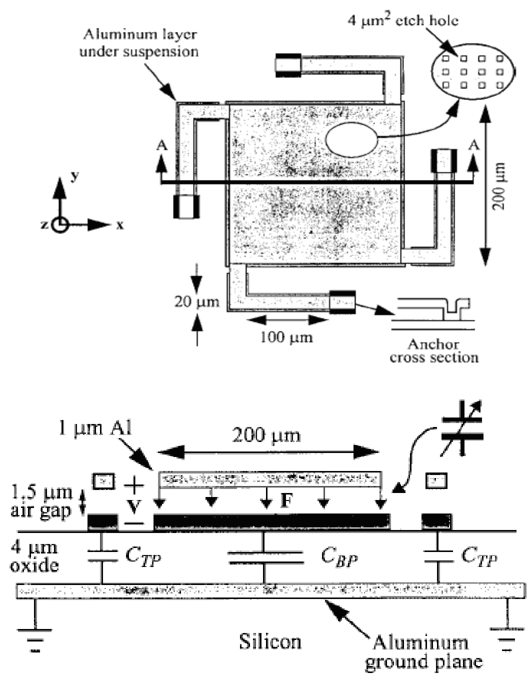

Figure 2. A micro-machined variable capacitor.

A high Q inductor is another key element in low phase noise VCO, since the inductors produced by silicon processes cannot provide high Q factors, due to ohmic loss in the thin metal layers and eddy-currents [6]. Several methods have been proposed. However, bond-wires are been chosen as an attractive alternative because their Q values at least an order of magnitude higher than on-chip spiral inductors. They have been implemented in RF VCOs and high efficiency power amplifiers. The 3-D microstructure also minimizes the capacitive coupling and eddy current loss, leading to larger Q-factor at higher frequencies. This bigger inductors and smaller capacitors, allow operation with less power [6].

In a high Q inductor every mm of bond-wire contributes about 1 nH. Therefore, a few nH requirement for a wireless applications can be provided readily, with a lead frame of a standard IC package [1].

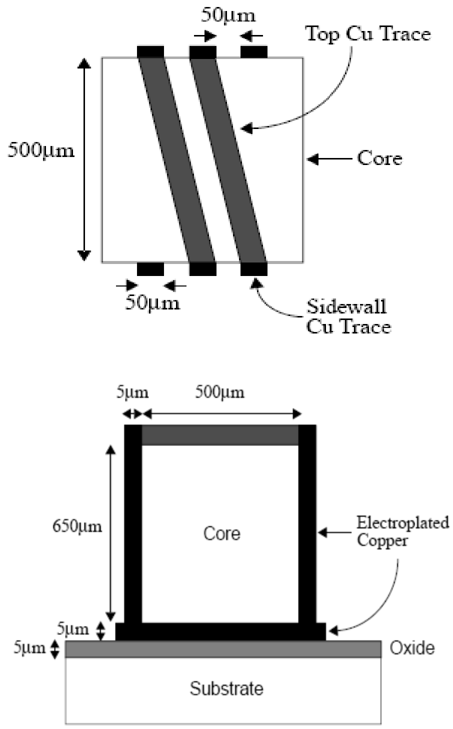

Figure 3. A 3-D coil inductor.

The 3-D coil inductor, shown in Figure 3, consists of two 5µm thick turns, 50µm wide copper traces electroplated around an insulating core with a 650µm by 500µm cross-section. The core is alumina, which has negligible loss tangent, another key parameter to ensure high Q. A core width of 500µm is found experimentally to be the minimum that avoids tilting during attachment. The fabrication process is described in details elsewhere [8].

IV. IV. VCO DESIGN

There are many types of oscillator topologies which can be used to construct an RF VCO for frequencies below 1 MHz. For frequencies above 1 MHz however, LC feedback oscillators are normally used. Due to the frequency limitations of most op-amps, transistor amplifiers are used as the gain elements. Thus, a popular topology, which proved successful in many commercial modules is the Colpitts oscillator, due to its simplicity, robustness and wide range of operating frequencies, from IF to RF [8].

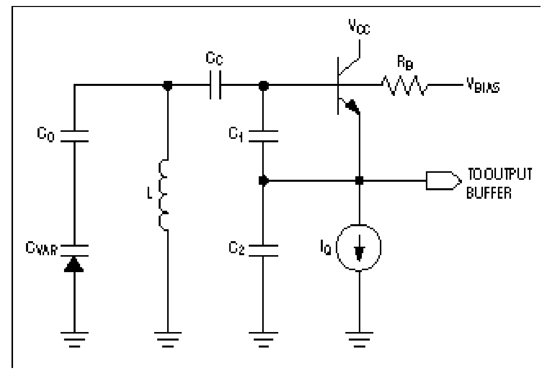

Figure 4. Colpitts topology in a VCO.

The frequency is determined by the resonant frequency of the feedback network, which is a parallel resonant tank circuit, in which any change in the inductor or capacitor will change the oscillation frequency, f_0 given by:

$$f_o = \frac{1}{2\pi\sqrt{LC_T}}$$

Where $C_T = C_v + C_{12}$, $C_v = (C_{var} \times C_o)/(C_{var} + C_o)$

and $C_{12} = (C_1 \times C_2) / (C_1 + C_2)$

Note: The above equation is accurate only if the LC circuit has a high Q.

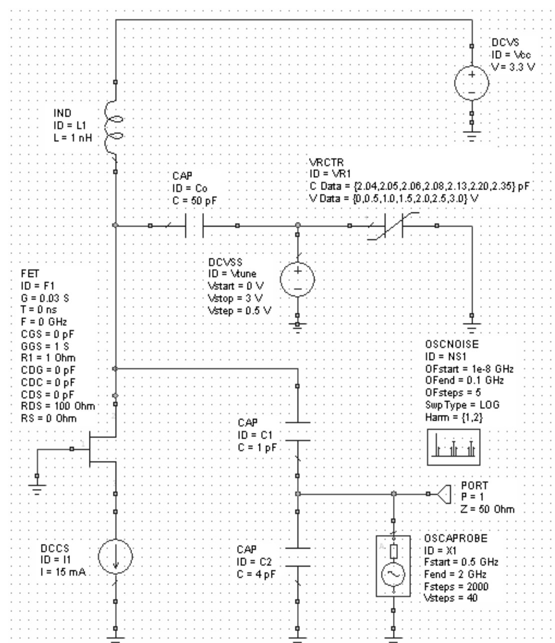

Figure 5. A circuit design of VCO.

Considering the Colpitts VCO, Figure 5, which uses parallel-mode LC tank configuration, The analysis is straightforward analysis. The FET is a medium power amplifier as compared to a bipolar transistor. It may provide double the power for a given frequency or double frequency for a given power. In fact, FET can be used up to 30GHz. At 10GHz, the FET itself may actually provide several watts of output power [9]. In the simulation model however, the VCO operates at a frequency f_0 approximately 1 GHz.

The model for phase noise performance analysis is to reconfigure the Colpitts oscillator as amplifier with positive LC feedback, Figure 5. Hence a readily available set of design equations can be used, which are insightful, clear and convenient. Instead of only analyzing the phase noise, this model is also useful in calculating the loop gain as well as oscillation amplitude [9].

There are many factors that affect the accuracy of phase noise simulation and measurement. Possibly, these factors can be accurately addressed through the use of phase noise simulation along with prudent passive component selection and resonator modeling. In assessing an acceptable level of simulation accuracy for a VCO that operates at RF frequencies and above, every component in the linear network such as transmission lines and discontinuities must be accurately characterized to several harmonics of the fundamental oscillation frequency. It is important because the accuracy of the oscillation signal affects the noise analysis, and the noise analysis itself depends on the linear network. This means that any inaccuracy in the network characterization will affect the quality of the phase noise simulation. The simulation accurately of the VCO will ultimately determine what will be fabricated, including circuit board dimensions, material properties, and component models of any parasitic behavior [10].

V. RESULTS AND ANALYSIS

Microwave Office is software useful in simulating any circuit design. It is suitable for the circuit simulation of the VCO, and can predict the performance characteristics. The behavior of the oscillators can be analyzed either in the frequency domain using the harmonic balance technique, or in the time domain using transient simulators such as SPICE and Spectre.

The simulation method involves three main steps when performing oscillator analysis. First, the simulator will attempt to locate the start-up frequency with respect to the well-known loop gain criterion. When the loop gain saturates to magnitude 1 in the large-signal steady state, the simulator will step the probe voltage in an attempt to detect loop gain saturation. Then, the neighborhood of gain saturation is used as the starting point for the analysis, whereby the voltage and frequency of the probe are adjusted in a way that results in zero probe-current. After all the requirements (as in Figure 6) had been followed, the simulation is then executed and automatically performs oscillator analysis.

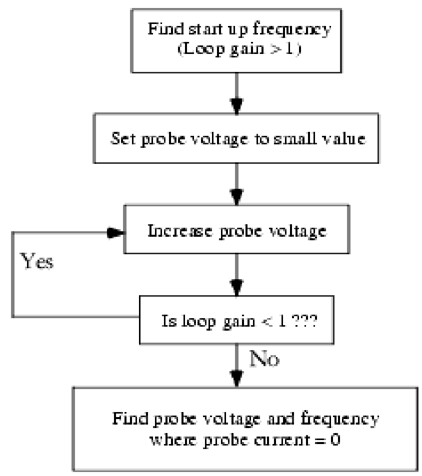

Figure 6. Analysis flow of oscillator.

In oscillator analysis, a special device called oscillator probe is used to allow for fast and robust oscillator simulations, even for the case of extremely high resonator Q. The oscillator probe is referred to the combination of the source and the ideal impedance element. In Microwave Office simulator, the oscillator probe is denoted as *OSCAPROBE*, as in Figure 7.

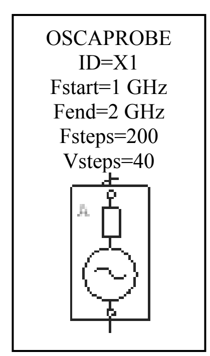

Figure 7. A schematic symbol of *OSCAPROBE*

The most significant probe parameters are *Fstart* and *Fend*. These parameters indicate the range of search for start-up frequency. Another parameter is the *Fsteps*, which refers to the number of steps used in the search for start-up frequency and rarely needs to be changed from default. However, in extremely high-Q cases, *Fsteps* may be increased or the frequency range narrowed. The recommended location of the oscillation probe is at a node connecting the resonator and the active device.

The main objective of simulating the VCO is to measure the phase noise performance, then to compare it with the values of a real prototype VCO at the offset frequency, 3MHz.

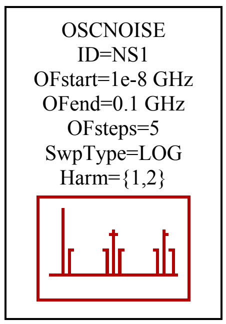

Figure 8. A schematic symbol of *OSCNOISE*.

Using the *OSCNOISE* simulator of Fig 8, the phase noise performance of the VCO is shown in Figure 9. The phase noise is measured in dB/Hz offset from the carrier and is plotted on a log frequency scale. For this simulation, the *OFstart* and *OFend* parameters are set to 1e-008 GHz and 0.1GHz respectively

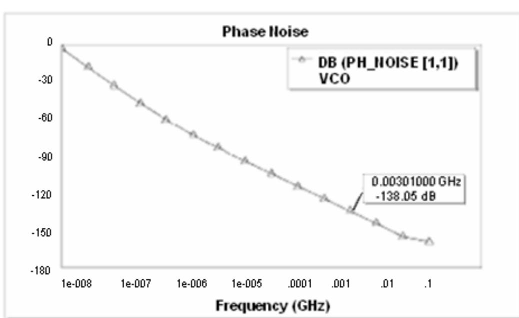

Figure 9. The simulated phase noise plot.

The graph shows that at the offset frequency of approximately 3MHz, the value of phase noise is -138.05 dBc/Hz. It is in good agreement with the actual value for the prototype -136 dBc/Hz.

Noise components in conventional LC tuned oscillators are; electrical thermal noise, flicker noise (l/f noise), supply voltage noise, and the noise contribution from the substrate. In practical MEMS based LC tuned oscillators however, additional phase noise is introduced due to the mechanical thermal vibration of the variable capacitors. The vibration of the suspended plates causes variation in the capacitance value, which results in phase noise or jitters in the output frequency [1]. The noise power spectral density due to plate displacement can be expressed as follows:

$$\overline{X_n^2(\omega)} = \frac{4.k.T.b}{k_m^2\left[\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \frac{1}{Q_M^2}\frac{\omega^2}{\omega_n^2}\right]}$$

where k is Boltzmann constant, T is the absolute temperature, b is damping coefficient due to the surrounding gas ambient and internal dissipation of the system, ω_n is the mechanical resonant frequency of the capacitor, k_m is the structure compliance and Q_M is the mechanical quality factor.

In sequence, this additional phase noise can be further expressed as given below:-

$$S_\theta(f_m)_{Brownian} = \frac{\overline{X_n^2(f_m)}}{8\left(\frac{1+\alpha}{\alpha}\right)^2 N x_o^2}\left(\frac{f_0}{f_m}\right)^2$$

where x_o is the nominal air gap of the capacitor, N is the number of parallel-connected devices and α is the ratio between the nominal tank tunable capacitance and its parasitics, f_o and fm are the oscillation frequency and the offset frequency, respectively.

By referring to the previous two equations, the Brownian motion induced phase noise can be determined at various offset frequencies. For a typical design condition of $x_o = 1.5\mu m$, $Q_M \cong 1$ at 1 atm, $\omega_n = 2\pi$ (30 kHz), N = 4, $\alpha \cong 0.5$, and f_o = 1GHz, the phase noise at offset frequencies f_m of 10KHz, 100KHz, and 3 MHz are respectively [1] 64dBc/Hz, -105dBc/Hz, and -136dBc/Hz, The typical wireless communication applications specify low phase noise requirement at relatively large offset frequency, for example –136 dBc/Hz at 3 MHz offset for GSM. In order to fulfill the GSM norms, the VCO must maintain a phase noise better than –135 dBc/Hz at 3 MHz offset over the appropriate frequency range of 855 MHz to 863 MHz.

VI. CONCLUSION

A MEMS tunable VCO has been designed using Microwave Office software tool, and the phase noise was analyzed by simulation and described explicitly. The Microwave Office simulator is a powerful tool for simulating and analyzing any linear or nonlinear design and measurement including oscillator analysis. In practical application, the VCO simulation model can be fabricated using real MEMS passive devices as high-Q variable capacitors and 3-D coil inductors. The real VCO prototype in which MEMS devices constitute frequency determining components of low phase-noise with low-power consumption, may prove to be a commercially attractive proposition for GSM telephony. It meets the stringent performance requirements at the application frequencies.

REFERENCES

[1] D. J. Young, V. Malba, A. F. Bemhardt, and B. E. Boser, "A Micromachined RF Low Phase Noise Voltage-Controlled Oscillator for Wireless Communications", *IEDM Dig. Tech. Papers*, pp. 285-300, 24 April 2001.

[2] D.B. Lesson, "A Simple Model of Feedback Oscillator Noise Spectrum", *Proc. IEEE*, 54 (2), pp. 329-330, 1996.

[3] V. K. Saraf, "Low Power Wide Tuning Range LC-VCO using RF MEMS Passives", *Master thesis*, Univ. of Carnegie Mellon, Pittsburgh, PA, August 2004.

[4] B. S. Darade and T. A. Parmar, "Low Phase Noise Fully Integrated VCO", *18th Intl. Conference on VLSI Design*, Jan 2005.

[5] D. J. Young and B. E. Boser, "A Micromachined Variable Capacitor for Monolithic Low-Noise VCOS", *Solid-State Sensor and Actuator Workshop, Dig. Tech. Papers*, pp. 86-89, June 1996.

[6] E. C. Park, Y. S. Choi, J. Yoon, S. Hong and E. Yoon, "Fully Integrated Low Phase-Noise VCOs With On-Chip MEMS Inductors", *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 1, January 2003.

[7] D. J. Young, V. Malba, J. J. Ou, A. F. Bemhardt and B. E. Baser, "Monolithic High-Performance Three-Dimensional Coil Inductors for Wireless Communication Applications", *IEDM Dig. Tech. Papers*, pp. 67-70, December 1997.

[8] R. H. Berube, "Computer Simulated Experiments for Electronic Devices Using Electronic Workbench", *Prentice-Hall*, Inc., 2000.

[9] C.O'Connor, "Develop A Trimless Voltage-Controlled Oscillator", *Microwaves & RF Magazine*, pp. 94-105, 2000.

[10] D.Vye, "*Improving VCO Phase Noise Performance Through Enhanced Characterization", High Frequency Electronics Magazine*, pp. 56-60, 2004.