Micromachined RF Voltage-Controlled Oscillator with Phase Noise Characterization

Darrin J. Young
EECS Department, Case Western Reserve University, Cleveland, Ohio, USA

ABSTRACT

An RF voltage-controlled oscillator (VCO) is implemented employing an on-chip, high-Q micromachined variable capacitor and three-dimensional (3-D) coil inductor. The micromachined variable capacitor achieves a 15 % tuning range with a nominal 2pF capacitance and a Q value above 60 at 1 GHz. The 3-D inductor minimizes the substrate loss and achieves a Q of 16 at 1 GHz. Both passive components are fabricated on silicon substrates and thus amenable to monolithic integration with standard IC processes. The prototype VCO exhibits a phase noise of –136 dBc/Hz at 3 MHz offset frequency from the carrier, suitable for various wireless communication applications, in particular GSM. The VCO is tunable from 855 MHz to 863 MHz under 3V, limited by the test setup. The micromachined VCO exhibits an additional phase noise caused by mechanical-thermal vibration of the suspended plate, which can potentially be dominant within low offset frequency. This noise source can be suppressed by placing the oscillator in a vacuum environment.

INTRODUCTION

Increased demand for wireless communication motivates a growing interest in monolithic personal communication transceivers [1]. Current radio designs, however, depend on off-chip components to implement key building blocks such as the low noise RF VCOs. The off-chip devices increase package complexity, final system area, and cost. Therefore, monolithic implementations are highly desirable.

The various cellular telephony standards require VCOs with frequencies in the low Gigahertz range and a tuning range less than 5 % of the carrier frequency. Narrow channel spacing and large blocking signals call for an extremely low phase noise from the oscillator. Phase noise below –135 dBc/Hz at 3 MHz offset frequency, for example, is required for GSM [2].

Current VCO designs in personal communication transceivers employ an off-chip high-Q LC tank circuit to meet the low phase noise requirement. Typical values are on the order of 2 pF with a Q above 50 for the varactor diode, and 5 nH with a Q over 20 for the inductor. Frequency tuning is achieved through modulating the depletion width of the varactor diode. A typical capacitance change of at least 10% is required to cover the tuning range. However, the off-chip components reply on processes and materials that differ substantially from standard IC fabrication and are consequently not compatible for monolithic integration.

On-chip silicon junction capacitors and spiral inductors have also been used to implement monolithic VCOs. However, this approach results in a poor phase noise because of the low Q passive components [3, 4]. The silicon junction diodes exhibit an excessive series loss resulting in a limited Q value below 20. The on-chip spiral inductors suffer from an even lower Q around 3 at 1 GHz [5]. Two issues contribute to this low quality factor: Eddy currents in the substrate and metal resistive loss. The first problem can be addressed in part by removing the silicon substrate underneath the inductor, leading to a Q value around 5 [6]. Reference 7 reports a Q close to 10 at 1 GHz by using copper traces on a sapphire substrate. While improving the Q value, sapphire substrates are incompatible with standard IC processes.

In this paper, we present a low phase noise RF VCO using a silicon IC-compatible, high-Q micromachined variable capacitor [8] and 3-D coil inductor [9]. The oscillator achieves a low phase noise suitable for various wireless communication applications. To reduce the fabrication complexity of the prototype oscillator, the variable capacitor, inductor, and active electronics are realized on separate substrates and are wire bonded to form the VCO. Because all the components are fabricated on silicon wafers, they are amenable to integration on the same substrate. The micromachined VCO, however, exhibits an additional phase noise caused by mechanical-thermal vibration of the suspended plate. This noise source can potentially result in a dominant phase noise within low offset frequency. The noise characteristics and suppression methods with experimental verification results are described in the paper.

MICROMACHINED VARIABLE CAPACITOR

The high-Q variable capacitor is one of the key elements to achieve a low phase noise in the VCO. This is realized as a surface-micromachined all-aluminum microstructure [8]. Figure 1 presents an SEM of a fabricated single capacitor. It consists of a thin aluminum plate suspended in air nominally 1.5 μm above a bottom aluminum layer by four mechanical springs. Aluminum is selected as the structural material for its low sheet resistance, critical for achieving a high Q value. A DC bias applied across the capacitor causes an electrostatic pull-down force and consequent reduction of the air gap, resulting in a capacitance increase.

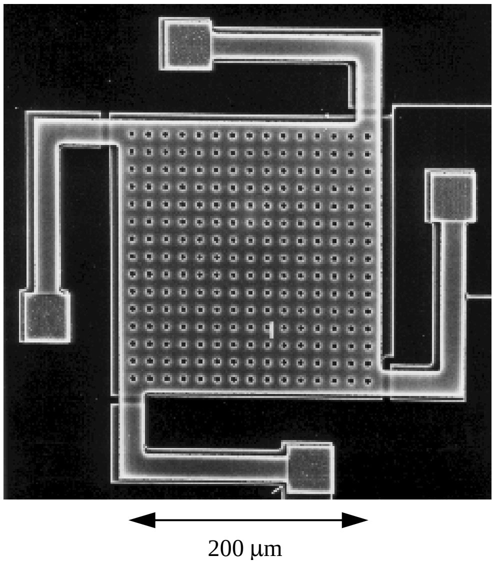

Figure 1. SEM of Micromachined Variable Capacitor

Four such capacitors connected in parallel obtain 2.04 pF at zero bias and 2.35 pF at 3V, corresponding to a 15 % capacitance increase. The variable capacitor achieves a Q over 60 measured at 1 GHz. This performance matches or exceeds the quality factor of discrete varactor diodes and represents a significant improvement over typical on-chip silicon junction capacitors. The fabrication technology is fully compatible with standard IC process [8], permitting the capacitor to be fabricated on top of wafers with completed electronics without affecting the characteristics of active devices. This is particularly crucial in RF applications where the availability of the most recent IC technology provides a critical competitive advantage.

ON-CHIP 3-D COIL INDUCTOR

The 3-D high-Q coil inductor, shown in Figure 2, is another key element in low phase noise VCO.

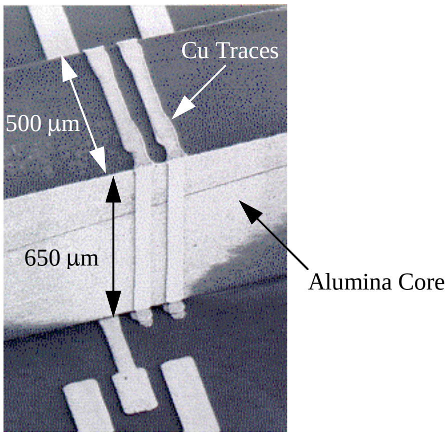

Figure 2. SEM of Two-Turn 3-D Coil Inductor

The device consists of two turns of 5 µm-thick, 50 µm-wide copper traces electroplated around an alumina core. Compared to spiral inductors, this geometry minimizes the coil area in close proximity to the substrate and hence the Eddy current loss, which is the dominant contributor to the limited Q value of spiral designs. The proposed device thus achieves a maximized Q and self-resonant frequency. Copper is selected as the interconnected metal for its low sheet resistance, critical for achieving a high Q. Alumina is used as the core material because of its negligible loss tangent at high frequencies, another key parameter to ensure a high Q value. The fabrication process is described in reference [9] in detail. Due to the low processing temperature (170 °C maximum), the inductors can be fabricated on top of wafers with completed electronics. The fabricated two-turn inductor achieves 8.2 nH inductance with a Q of 16 measured at 1 GHz. This performance is substantially superior to that of spiral inductors with typical Q values around 3.

PROTOTYPE VCO AND MEASUREMNTS

The high-Q components and a CMOS IC containing active electronics are attached to a test board and wire bonded to form the VCO, as shown in Figure 3.

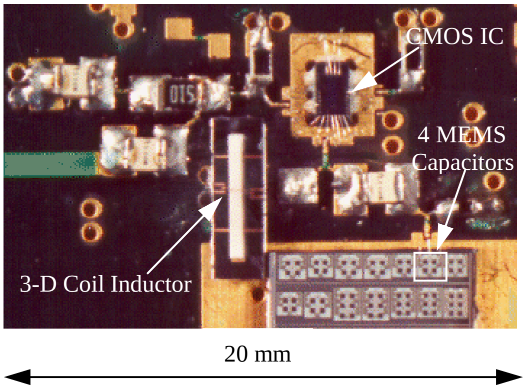

Figure 3. Prototype VCO Test Board

Figure 4 presents the oscillator output power spectrum at 863 MHz with a phase noise of –136 dBc/Hz measured at 3 MHz offset frequency, as plotted in Figure 5.

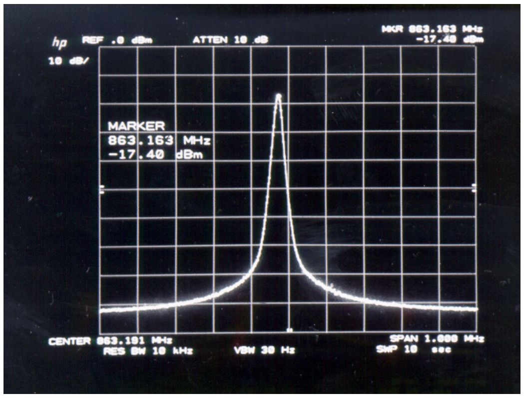

Figure 4. VCO Output Power Spectrum

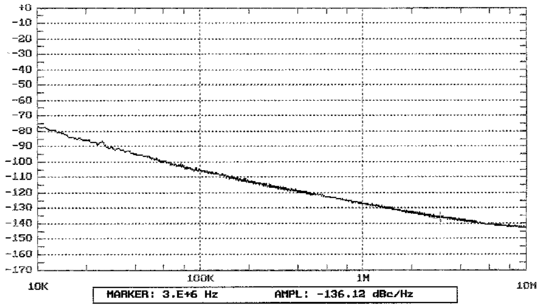

Figure 5. Measured Phase Noise Plot

This performance is suitable for various wireless communication applications, in particular GSM. The prototype oscillator dissipates 43 mW from a 3.3 V supply and is tunable from 855 MHz to 863 MHz under 3 V, limited by the parasitics of the test setup.

MICROMACHINED VCO PHASE NOISE

In a micromachined VCO besides the electronic noise, mechanical-thermal vibration from the variable capacitor, commonly referred as Brownian motion, contributes an additional phase noise. Vibration of the suspended plate causes variation in the capacitance; hence, jitter in the output frequency. The plate displacement noise power spectral density can be expressed in Equation 1,

$$\overline{X_n^2(\omega)} = \frac{4kTb}{k_m^2\left[\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + \frac{1}{Q_M^2}\frac{\omega^2}{\omega_n^2}\right]} \quad , \qquad (1)$$

where k is the Boltzman's 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 presents the mechanical quality factor. This additional phase noise can be further expressed in Equation 2,

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

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 total tunable capacitance and tank circuit parasitics. For a typical design condition of $x_o = 1.5\ \mu\text{m}$, $m = 100$ ng, $Q_M \cong 1$ at 1 atm, $\omega_n = 2\pi(30\ \text{KHz})$, $N = 4$, $\alpha \cong 0.5$, and $f_o = 1$ GHz, the phase noises at offset frequencies of 10 KHz, 100 KHz, and 3 MHz are calculated as –64 dBc/Hz, -105 dBc/Hz and –194 dBc/Hz, respectively. Typical wireless communication applications specify a low phase noise requirement at a relatively large offset frequency, for example –135 dBc/Hze at 3 MHz offset for GSM. Therefore, the Brownian motion effect does not prevent oscillators from achieving the required performance. However, if a close-in low phase noise is demanded for certain stringent applications, then this additional noise must be suppressed.

An increased number of parallel devices can reduce the average displacement noise power. But the N value is limited by the required capacitance in an oscillator design. It is not practical to build capacitors with small plate sizes since it would result in an increased tuning voltage. Enlarging capacitor nominal air gap will suppress the Brownian motion effect however with a penalty of large tuning voltage. Reducing the ratio between the tunable capacitance and tank parasitics will improve the phase noise performance but causing a narrowed tuning range. Therefore, $\overline{\mathrm{X}_\mathrm{n}^2(\omega)}$ must be reduced to suppress the phase noise. The structure mass and compliance are typically limited by the current fabrication technology. However, Q_M of the microstructure can be increased with a reduced ambient pressure, causing phase noise suppression away from the mechanical resonance. This can be accomplished by placing the oscillator in a vacuum environment, which is commonly used for resonant sensor applications. However, at the mechanical resonance the noise is enhanced due to the increased Q_M. Therefore, depending upon applications, this phase noise shaping can potentially be attractive especially when there is no adjacent channel at ω_n away from the desired channel. Besides all the suppression methods described above, close-in low phase noise can be achieved when the VCO is enclosed in a wide-band phase-locked loop (PLL). By extending the PLL loop bandwidth, an improved suppression on close-in phase noise can be accomplished [11].

A prototype micromachined RF VCO, similar to the one shown in Figure 3, however employing a discrete inductor is implemented for investigating the Brownian-motion-induced phase noise behavior. The VCO oscillates at 721 MHz with output power spectrum shown in Figure 6.

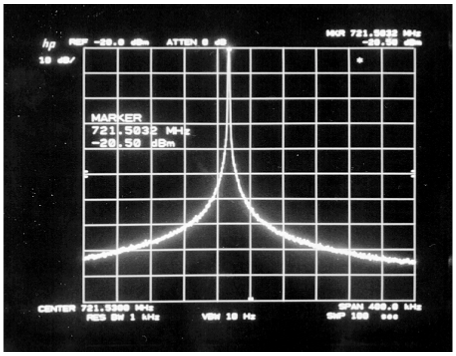

Figure 6. VCO Output Power Spectrum

Figure 7 presents the measured phase noise plot indicating that a phase noise of –139 dBc/Hz is achieved at 3 MHz offset frequency. The low phase noise is due to the high-Q micromachined capacitors and discrete inductor used in the design.

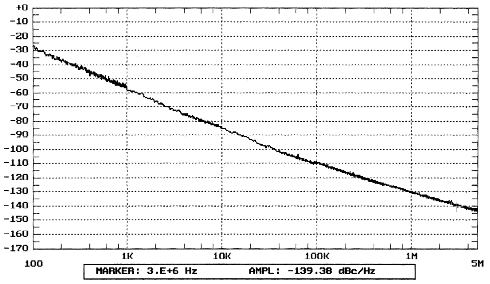

Figure 7. VCO Phase Noise Plot

From the measurement results obtained in the atmospheric pressure, the VCO phase noise is limited by the 1/*f* noise from the active circuits for the close-in region with a corner frequency around 30 KHz and thermal noise from the electronics at large offset rather than the Brownian motion. This is because the total tunable capacitance of 0.8 pF used in this design is small compared to the tank parasitic capacitance of approximately 5 pF, 3 pF of which is due to the measurement setup. To verify the pressure-dependent noise shaping effect for the Brownian-motion-induced phase noise, the VCO is tested in a vacuum environment. Figure 8 presents the oscillator output power spectrum measured in a 20 mT vacuum chamber.

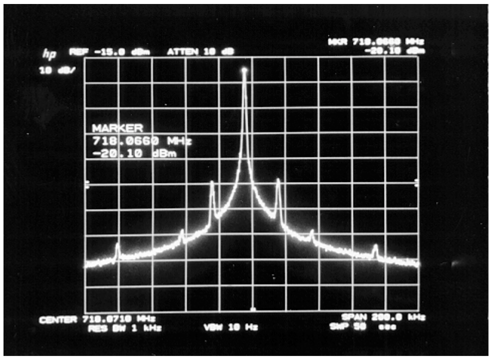

Figure 8. VCO Output Power Spectrum in Vacuum

The spectrum reveals two main side-band peaks occurring at 20 KHz away from the carrier with a 15 dB noise enhancement. This indicates that the micromachined capacitors have a fundamental mechanical resonant frequency of 20 KHz. The Brownian-motion-induced phase noise is at least 15 dB higher than the floor at that frequency. The overall phase noise remains the same away from the resonance because it is dominated by noise sources associated with the active electronics in this design. Also shown in Figure 8 are four additional side-band peaks occurring at approximately 40 KHz and 78 KHz away from the carrier each with 5 dB noise enhancement. These peaks are caused by the higher-order mechanical resonance of the micromachined capacitors.

CONCLUSION

Micromachining technologies provide IC compatible RF tunable capacitors and 3-D coil inductors with high-Q values that cannot be achieved through conventional IC process. These high-Q passive components are crucial for integrating high performance RF building blocks, in particular the low phase noise RF VCOs. A prototype RF VCO has been designed and built using micromachined high-Q tunable capacitors and 3-D coil inductor. The oscillator meets the stringent GSM phase noise requirements and demonstrates that complete monolithic high performance VCOs can be achieved for cellular telephony applications. The micromachined VCO exhibits an additional phase noise caused by mechanical-thermal vibration of the suspended plate, which can potentially be dominant within low offset frequency. This noise can be suppressed by placing the oscillator in a vacuum environment.

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