A Micromachine-Based Low Phase-Noise GHz Voltage-Controlled Oscillator for Wireless Communications

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ABSTRACT

An RF voltage-controlled oscillator (VCO) employs high-Q, IC-compatible, micromachined variable capacitors and bondwire inductors. The micromachined variable capacitors demonstrate a Q value over 60 at 1 GHz and a 15% tuning range with a nominal 2pF capacitance. The bondwires also exhibit at least an order of magnitude Q improvement compared to spiral inductors. The micromachined capacitors are fabricated on silicon substrates and thus amenable to monolithic integration with standard IC processes. The prototype VCO achieves -105 dBc/Hz phase-noise at 100 KHz offset frequency from a 1.028 GHz carrier, suitable for most wireless communication applications, in particular GSM. The oscillator can be tuned over 20 MHz with 3V, limited by the test setup parasitics, and dissipates 3.8 mA from a 3.3V supply.

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. Monolithic implementations, therefore, are highly desirable.

The various cellular telephony standards require VCOs with frequencies in the low Gigahertz range and a tuning range of a few percent 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], which corresponds to -105 dBc/Hz at 100 KHz offset frequency.

Current VCO designs in personal communication transceivers employ an off-chip high-Q LC tank circuit to meet the low phase-noise requirement [3, 4]. Typical values are on the order of 5 nH with a Q of 30 for the inductor, and 2 pF with a Q of at least 50 for the varactor. Frequency tuning is achieved by 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 rely on processes and materials that differ substantially from standard IC fabrication and are consequently incompatible with monolithic integration.

On-chip silicon junction capacitors and spiral inductors have also been attempted to implement monolithic VCOs. These passive components, however, have limited Q values. Silicon junction diodes exhibit an excessive series loss resulting in a limited Q value below 10. On-chip spiral inductors suffer from an even lower Q around 3 at 1 GHz [5]. Consequently, RF oscillators relying on these components produce a poor phase noise typically ranging from -85 dBc/Hz to -100 dBc/Hz at 100 KHz offset frequency [6, 7, 8]. This level of performance falls well short from the requirements for cellular telephony applications.

In this paper, we present a RF VCO using high-Q, IC-compatible, micromachine-based variable capacitors and bondwire inductors to achieve a low phase noise, suitable for most wireless communication applications. To reduce the fabrication complexity of the prototype oscillator, the micromachined variable capacitors and active electronics are currently fabricated on separate silicon substrates and wire bonded to form the VCO. Because the micromachining process is fully compatible with standard IC technology, they are amenable to integration on a same substrate.

MICROMACHINED VARIABLE CAPACITOR

The high-Q variable capacitor is a key element to ensure low phase noise from the VCO. This is realized through building a surface-micromachined all-aluminum microstructure [9]. 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.

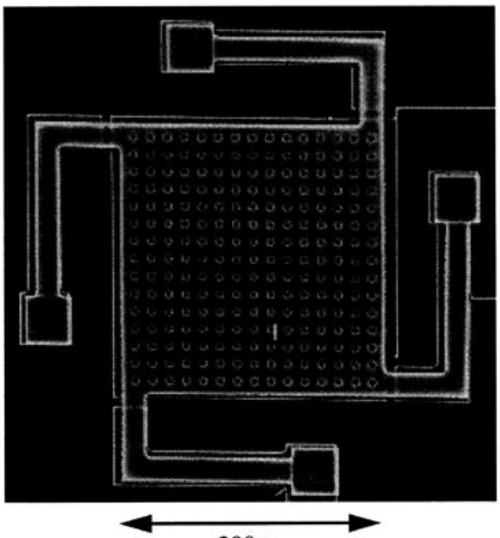

Figure 1. SEM of a Micromachined Variable Capacitor

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 2 shows four such capacitors connected in parallel with 2.04pF at zero bias and 2.35pF at 3V, corresponding to a 15% capacitance increase. The variable capacitor achieves a measured Q over 60 at 1GHz. This matches or exceeds the quality factor of discrete varactor diodes, and is at least an order of magnitude better than that of a typical on-chip silicon junction capacitor. This device will be used to implement a high-performance prototype RF VCO presented in the following. The micromachining fabrication technology is fully compatible with standard IC processing [9], permitting the capacitors to be fabricated on top of wafers with completed electronics.

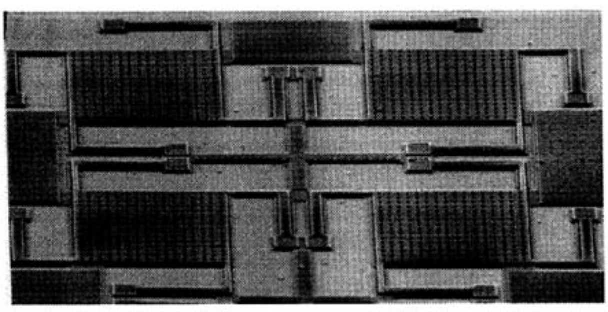

Figure 2. Four Parallel-Connected MEM Capacitors

The micromachined variable capacitor is extremely linear compared to a varactor diode. Because of the mechanical frequency response roll off it is insensitive to high-frequency signals, thus very attractive for implementing low-distortion communication systems in addition to the low phase noise VCO application. The device can also withstand a larger signal swing than varactor diodes since it does not have the potential problems of becoming forward-biased and breakdown. This is an important advantage when building high power VCOs for direct modulated transmitters.

This type of capacitor potentially suffers from two practical problems: microphonics and Brownian-motion. However, vibrations are substantially attenuated at frequencies above the mechanical resonance, typically a few ten Kilohertz. Low frequency capacitance changes are corrected by a phase-locked loop enclosing the VCO in practical communication systems. Therefore, they cause a negligible effect on the oscillator performance.

HIGH-Q INDUCTORS

A high-Q inductor is another key element to achieve a low phase noise VCO. In recent years bondwires have been chosen as an attractive alternative because they offer Q values at least an order of magnitude higher than that of on-chip spiral inductors. RF oscillators [10], VCOs [11, 12], and high-efficiency power amplifiers [13] have been implemented using this approach. Recently micromachining technology has also produced an on-chip, IC-compatible, three-dimensional coil inductor achieving a high Q value comparable to that of discrete counterparts [14]. Furthermore, an RF VCO using the micromachined variable capacitors and three-dimensional coil inductor has demonstrated a low phase noise performance suitable for most wireless communication applications [15]. In the current prototype VCO, a bondwire is employed as a high-Q inductor for its simplicity. Typically every millimeter of bondwire contributes approximately 1 nH inductance value. Therefore, a few nH inductances, commonly required for GHz wireless applications, can be readily obtained through bondwire and lead frame of a standard IC package.

PROTOTYPE RF VCO AND MEASUREMENTS

The VCO topology is illustrated in Figure 3. The Colpitt's oscillator is chosen as a vehicle because of its robustness. The 6 nH inductor is achieved through an approximately 5 mm-long bondwire from the active electronics die to the test board. The inductor resonates with the capacitive load at 1 GHz. The active electronic circuitry is fabricated using Conexant's 25 GHz f_T silicon bipolar process. Figure 4 shows the die photo. This silicon die is attached to a test board and wire bonded with the micromachined capacitors, shown in Figure 2, to form the VCO. The test board configuration with bondwires is illustrated in Figure 5. The critical bond-pads for interfacing the variable capacitors and 6 nH bondwire inductor are also indicated in Figure 4. These pads are shielded by a diffusion layer underneath to ensure a high Q value and prevent noise coupling through the substrate.

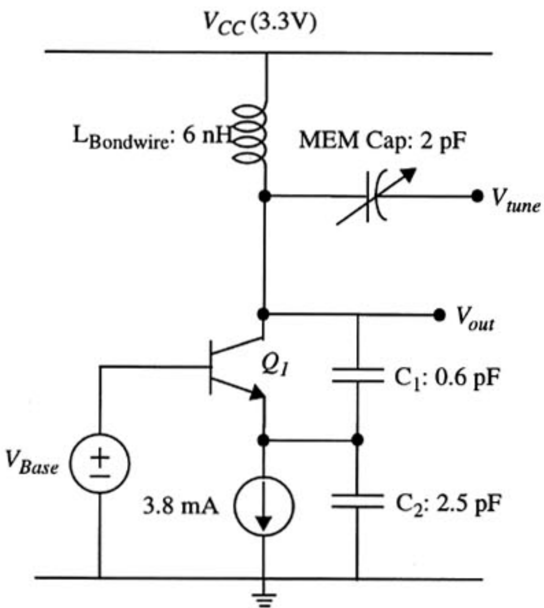

Figure 3. VCO architecture

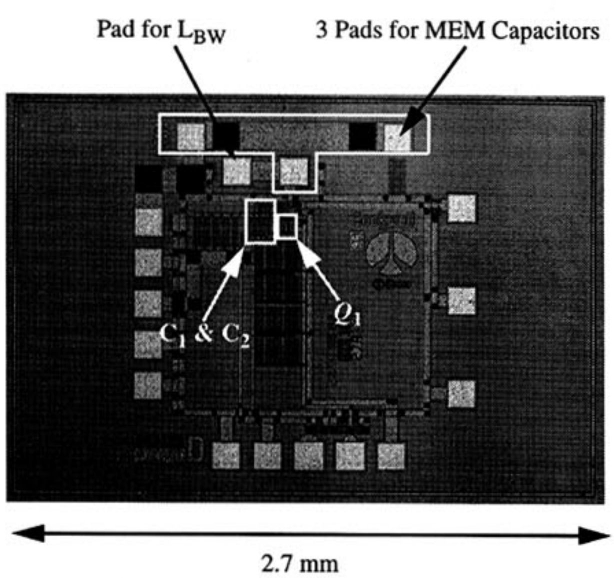

Figure 4. VCO Electronics Die Photo

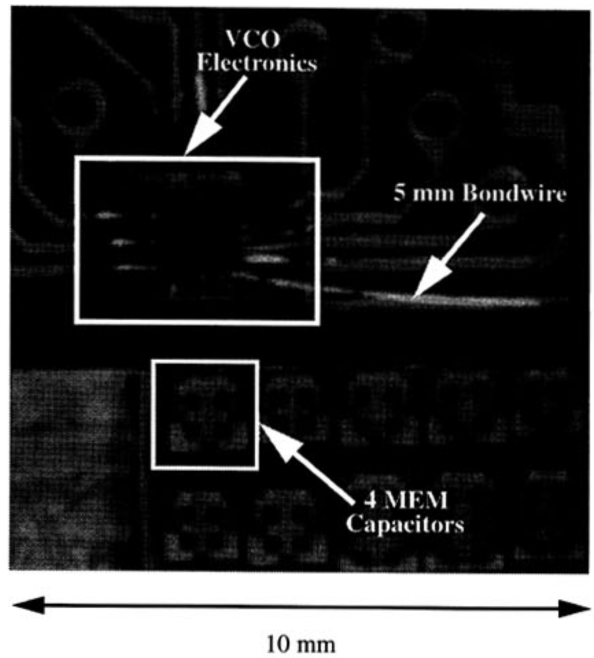

Figure 5. Prototype VCO Test Board

Figure 6 presents the oscillator output power spectrum at 1.028 GHz with a phase-noise of -105 dBc/Hz measured at 100 KHz offset frequency, as plotted in Figure 7.

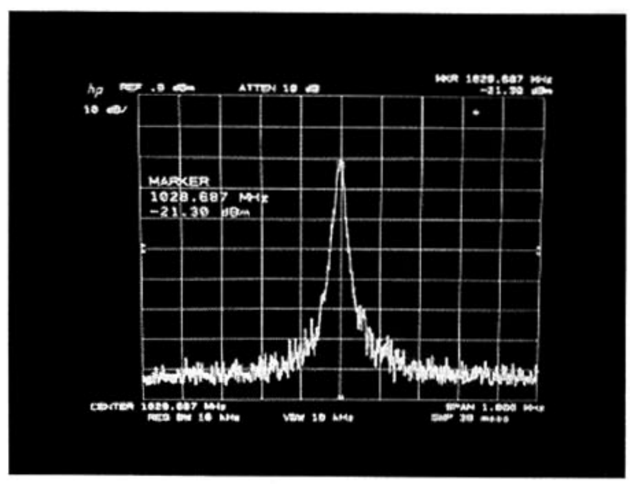

Figure 6. VCO Output Power Spectrum

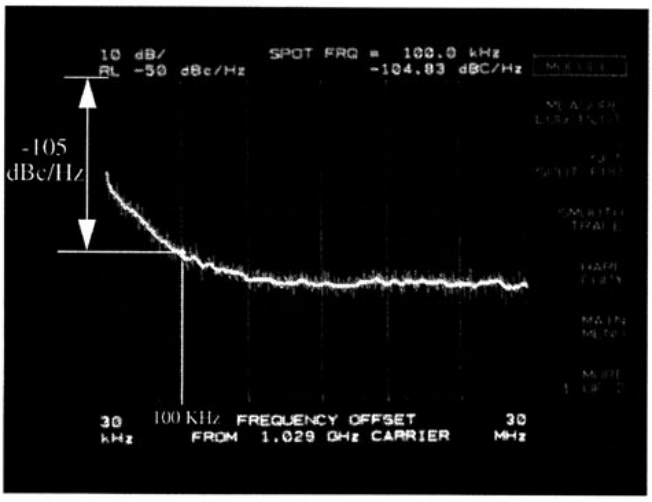

Figure 7. Measured Phase Noise Plot

This performance is suitable for most cellular telephony applications, in particular GSM. The prototype oscillator dissipates 3.8 mA from a 3.3 V supply. The VCO has a tuning range of 20 MHz with 3V limited by the test setup parasitics.

CONCLUSION

A prototype RF VCO was built using high-Q, IC-compatible, micromachined variable capacitors and bondwire inductor. These passive components match or exceed the performance of discrete counterparts. They are also amenable to monolithic integration with standard IC processes. The oscillator meets the stringent GSM phase-noise requirement and demonstrates that a complete monolithic high-performance VCO can be achieved for cellular telephony applications.

ACKNOWLEDGMENTS

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