A 1V 3.8-5.7 GHz Differentially-Tuned VCO in SOI CMOS

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Abstract – A 1 V 3.8-5.7 GHz VCO was designed and fabricated in a 0.13 μm SOI CMOS process [1]. This VCO features differentially-tuned accumulation MOS varactors that (a) provides 40% frequency tuning when biased between 0 to 1 V, and (b) rejects common-mode noise such as flicker noise. At 1 MHz offset, the phase noise is -121.67 dBc/Hz at 3.8 GHz, and -111.67 dBc/Hz at 5.7 GHz. The power dissipation is between 2.3 to 2.7 mW depending on the centre frequency. When V_{DD} is reduced to 0.75 V, the VCO only dissipates 0.8 mW at 5.5 GHz.

I. INTRODUCTION

As modern CMOS technology feature size is scaled down to deep-submicron, the supply voltage V_{DD} has to decrease in proportion. One of the main reasons is the low breakdown voltage due to gate oxide thinning, which is required to maintain short-channel effects at an acceptable level. The downscaling of V_{DD} imposes many design challenges to analog/RF designs [2], and the VCO is no exception. The most obvious problem is the reduction of voltage swing, which lowers the output power and degrades the phase noise. This can be partially resolved by using complementary topology to improve the phase noise [3].

Another problem, which is often overlooked, is the frequency tuning range. Limited frequency tuning is one of the bottlenecks that hinders commercialization of the CMOS VCO. The accumulation MOS (AMOS) varactor [4] offers a solution to this problem. High-Q AMOS varactors giving C_{max}/C_{min} of 5 with ±1 V tuning voltage have been demonstrated in a 0.13 μm SOI CMOS technology [1]. A VCO with more than 50% frequency tuning was measured [5] using this technology. However, high C_{max}/C_{min} ratio over low voltage tuning range implies high varactor gain k_v (and hence VCO gain k_{vco}), which is unfavourable to phase noise performance [6].

In this paper, a simple theory will be introduced to explain how varactors upconvert low-frequency common-mode noise, such as flicker noise, near the carrier, and how the differentially-tuned varactors can be used to suppress such upconversion. The theory will be verified by measurement.
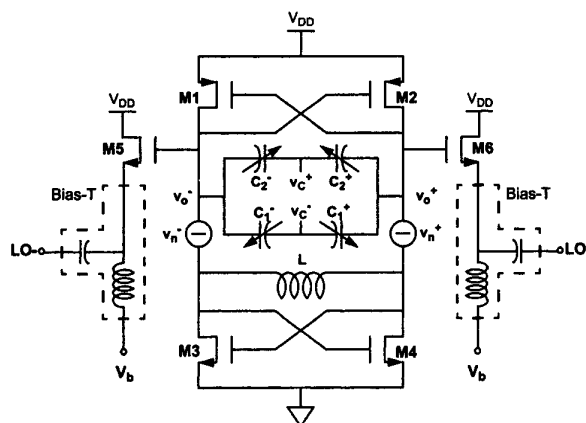

Fig. 1. Schematic of Differentially-Tuned VCO. v_n^+ and v_n^- are noise sources from each branch.

II. VARACTOR NOISE ANALYSIS

A. Low-Frequency Noise Upconversion

One mechanism for upconversion of low-frequency noise, such as flicker noise, is the non-linearity of the circuit [3]. However, the low-frequency noise can also modulate the varactor directly and this is seen as jitter near the carrier. Consider a complementary LC-VCO as shown in Fig. 1. The resonator consists of the inductor L and the capacitor C, which consists of C_1^+, C_1^-, C_2^+ and C_2^-. The resonant frequency ω_o is given by

$$\omega_o = \frac{1}{\sqrt{LC}} \quad (1)$$

Consider v_n^+ and v_n^- as the total noise from the transistors at each side as shown in Fig. 1. At low frequency, the inductor L behaves like a short-circuit, so

$$v_n^+ = v_n^- \quad (2)$$

Therefore, all the noise power at low frequency can be considered as common-mode noise, defined as v_{ncm}. One mechanism for low-frequency noise upconversion is that v_{ncm} injects into the varactor through the nodes v_o^+ and v_o^-. This
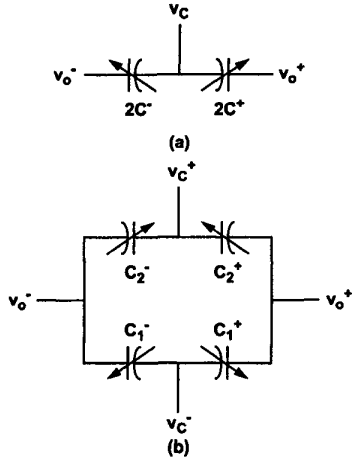
Fig. 2. (a) Single-Ended and (b) Differentially-Tuned Varactor

noise is subsequently upconverted to the carrier frequency by the resonator, contributing to the phase noise of the VCO. Mathematically, the expression for C in (1) is

$$C = C_0 + k_v(v_{tune} + v_{ncm}) \qquad (3)$$

where C_0 is the zero bias capacitance, k_v is the varactor gain, and v_{tune} is the voltage across the varactor. Equation (3) clearly shows that C is modulated by v_{ncm}, and the higher the k_v, the higher the low-frequency noise injection. Therefore, many VCOs have the worst phase noise in the middle of the tuning range where k_v is the highest. Meanwhile, the best phase noise usually occurs at the boundaries of the tuning range where k_v is minimum. As the power supply scales down, the varactor gain k_v becomes large in order to maintain the same tuning range. Therefore, this upconversion mechanism is critical for low-voltage VCO.

B. Single-ended vs. Differentially Tuned Varactor

In this section, common-mode noise rejection in the differentially-tuned varactor will be analyzed. The effect of common-mode noise in single-ended tuned varactors is first analyzed starting from the varactor topology given in Fig. 2a. To demonstrate common-mode noise rejection, the equivalent capacitance C between v_C and v_o^+ is calculated. From (3), it is given by

$$C = 2C^+ = 2C_0 + 2k_v(v_C + v_{ncm}) \qquad (4)$$

Hence, the common-mode noise modulates the varactor, which will result in jitter and phase noise. If the varactor is differentially-tuned as shown in Fig. 2b, then the capacitances are given by v_C^+, v_C^- and v_o^+ such that

$$C_1^+ = C_0 + k_{v1}(v_C^+ + v_{ncm}) \qquad (5)$$

$$C_2^+ = C_0 - k_{v2}(v_C^- + v_{ncm}) \qquad (6)$$

Since $C = C_1^+ + C_2^+$, if the varactor is perfectly symmetrical

such that $k_{v1} = -k_{v2}$, the expression for C is

$$C = 2C_0 + 2k_v v_C \qquad (7)$$

where v_C is $v_C^+ - v_C^-$. If $|k_{v1}|$ and $|k_{v2}|$ are not the same, the gain of the common-mode noise is reduced to $|k_{v1}-k_{v2}|$. Therefore, it has been shown that differential tuning can be used to reject common-mode noise, such as flicker noise and shot noise.

III. IMPLEMENTATION AND MEASUREMENT

As shown in Fig. 1, the VCO is an LC cross-coupled differential circuit with both PMOS and NMOS latches, which generate negative resistance to cancel losses in the LC resonator. The monolithic inductor is a horseshoe shaped single loop with a diameter of 460 μm as shown in the micrograph (Fig. 9). The measured inductance is 0.85 nH and Q is above 20 between 3.8 and 5.7 GHz as shown in Fig. 3. The AMOS varactors are differentially tuned for common-mode noise rejection. Bias-T source followers are used as the output buffers. The inductive choke inside the bias-T is used to provide high ac impedance, so that small transistors can be used to provide enough output current drive without loading the VCO core heavily.

A. Frequency Tuning

The VCO was measured using on-wafer probing together with a 26.5 GHz HP8563 spectrum analyser with a phase noise module. The frequency vs. varactor tuning voltage at 1 V V_{DD} is shown in Fig. 4. The differential tuning voltage v_{dtune} is related to v_C^+ and v_C^- by

$$v_C^{+/-} = (V_{DD}/2) \pm v_{dtune} \qquad (8)$$

For example, if $v_{dtune} = 0$ V, then $v_C^+ = 0.5$ V and $v_C^- = 0.5$ V. If $v_{dtune} = -0.5$ V, then $v_C^+ = 0$ V and $v_C^- = 1$ V. For a tuning voltage from 0 to 1 V, the carrier frequency can be tuned from 3.812 GHz to 5.716 GHz, achiev-
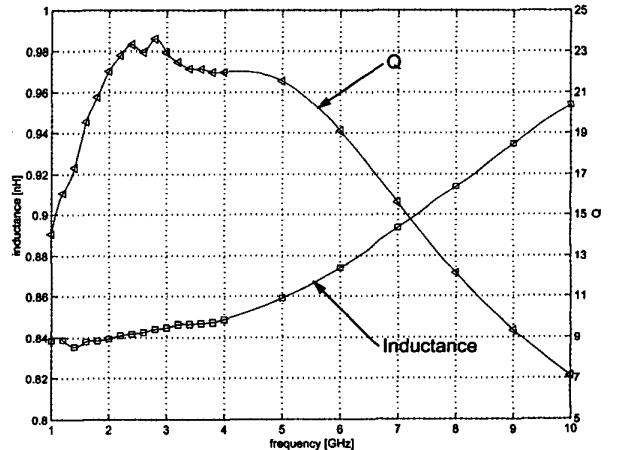

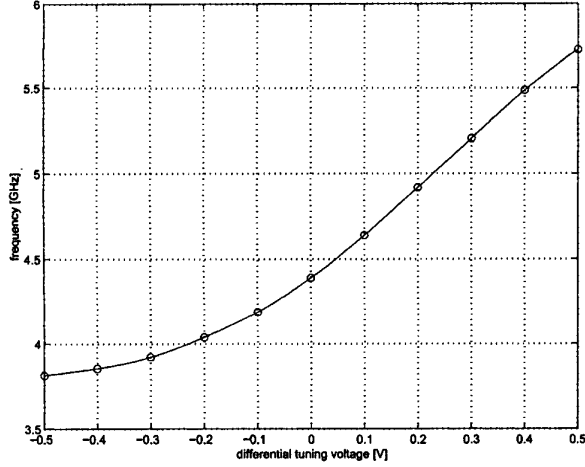Fig. 3. Measured Inductance and Q (Single-Ended) vs. Frequency

Fig. 4. Frequency vs. Tuning Voltage at 1V V_{DD}

Fig. 5. Phase Noise vs. V_{DD}

ing 40% tuning range. This wide tuning range is made possible by the reduced parasitic due to the buried oxide of SOI that minimizes junction capacitance, and improved lithography that reduces overlap capacitance.

B. Common-Mode Rejection

At 1 V V_{DD}, common-mode voltage was applied such that $v_C^+ = v_C^-$, and the result is summarized in Table I.

TABLE I. Common-Mode Performance Measurement

$v_C^+ = v_C^-$	f_c	phase noise @ 1 MHz
0.0 V	4.492 GHz	-117.00 dBc/Hz
0.5 V	4.401 GHz	-117.83 dBc/Hz
0.6 V	4.404 GHz	-118.33 dBc/Hz
1.0 V	4.475 GHz	-118.50 dBc/Hz

The frequency variation is within 2%, while the phase noise variation is within ±1 dB. Therefore, it is concluded that the varactors are highly symmetrical, which should result in good common-mode noise rejection.

C. Phase Noise

The phase noise was measured at several different frequencies across the wide tuning range. At 1 V V_{DD}, the best phase noise is -121.67 dBc/Hz at 1 MHz offset, measured at the lower frequency bound (3.812 GHz at $v_{dtune} = -0.5$ V) where the VCO gain is minimal and the inductor Q is near its peak. At the middle of the range (4.4 GHz at $v_{dtune} = 0$), k_v is high and the phase noise is -117.83 dBc/Hz at 1 MHz offset. At the upper end of the tuning range (5.716 GHz at $v_{dtune} = 0.5$), the phase noise is -111.67 dBc/Hz at 1 MHz offset. The phase noise was also measured for V_{DD} between
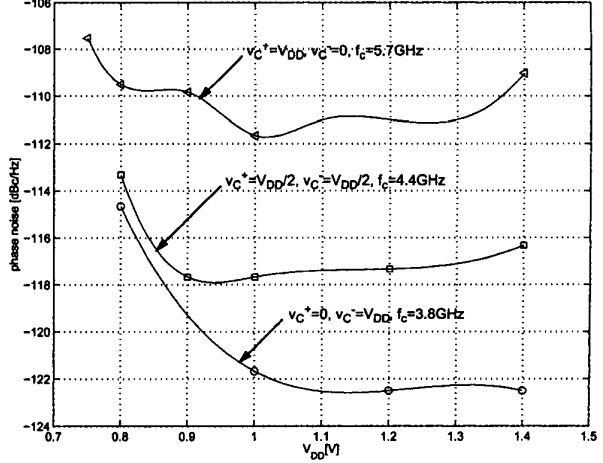
0.75 V and 1.4 V, and the result is summarized in Fig. 5.

To evaluate the phase noise improvement over a conventional single-ended tuning scheme, a reference VCO with varactor topology as shown in Fig. 2a was fabricated and measured. At 4.4 GHz, with both VCOs operating in the high k_v region (middle of the tuning range), the phase noise was measured and compared as shown in Fig. 6. At 1 MHz offset, the differential-tuning topology improves the phase noise by about 9 dB. Due to common-mode rejection, the upconverted low-frequency noise near the 100 kHz offset is filtered out, offering a cleaner frequency spectrum. Furthermore, reduction in noise implies that less current is required for the VCO to oscillate. The differentially-tuned VCO can be operated at 0.75 V V_{DD}, drawing only 0.8 mW at 5.5 GHz. Meanwhile, the reference VCO can only operate down to 0.83 V, drawing about 1 mW at that frequency.
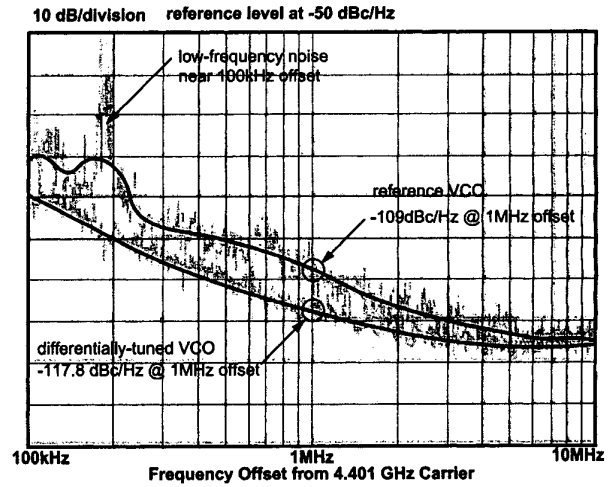

Fig. 6. Phase Noise Comparison at 4.4 GHz

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D. FOM and Power Dissipation

A widely used figure of merit (FOM) for VCO performance is defined as

$$FOM = L\{f_{off}\} - 20\log(f_c/f_{off}) + 10\log(P_{dc}) \quad (9)$$

where $L\{f_{off}\}$ is the measured phase noise at the frequency offset f_{off} from the carrier at f_c, and P_{dc} is the measured DC power dissipation in mW (Fig. 7). The result is plotted in Fig. 8. The lowest power dissipation is achieved at 0.75 V V_{DD}, where only 0.8 mW of power is drawn at 5.5 GHz. To the authors' knowledge, this VCO has the lowest power dissipation compared to any published CMOS VCOs at this frequency. Meanwhile, the best FOM is -189 dBc/Hz at 1 V V_{DD}.
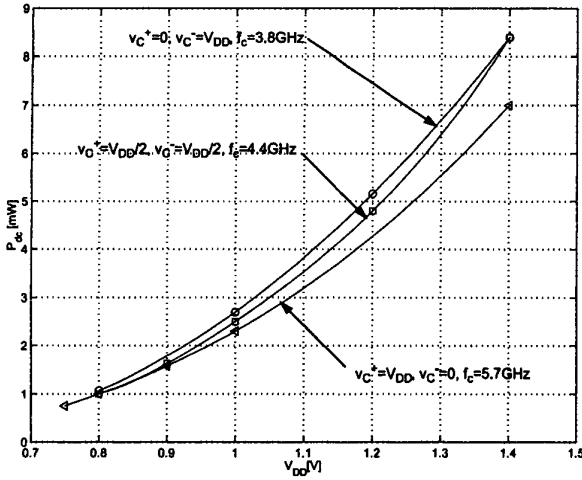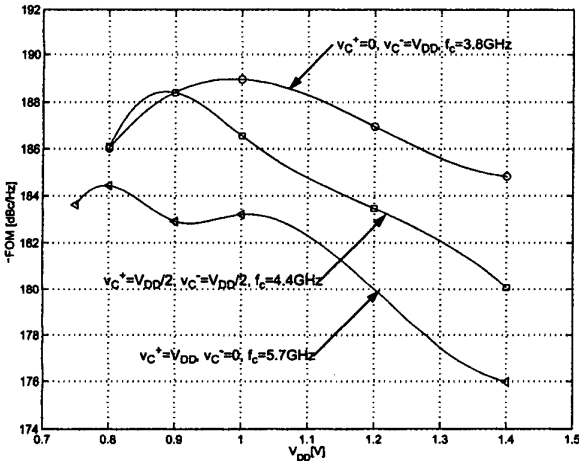

Fig. 7. Power Dissipation vs. V_{DD}

Fig. 8. Figure of Merit vs V_{DD}

IV. CONCLUSION

In this article, a 1 V 3.8-5.7 GHz differentially-tuned com-

plementary LC-VCO with 40% tuning range was designed and fabricated using the IBM 0.13 μm SOI CMOS technology. The VCO has demonstrated that differentially-tuned varactors can provide wide tuning range and reject common-mode noise. At 1 MHz offset, the nominal phase noise (4.4 GHz at $v_{dtune} = 0$) is -117.83 dBc/Hz, and the FOM is 187 dBc/Hz. The power consumption is between 2.3-2.7 mW, and the buffered output power is -9 dBm. If the VCO is operated at 0.75 V V_{DD}, the circuit only draws 0.8 mW of power, the lowest power dissipation compared to any published CMOS VCO. The VCO occupies a total area of 650 μm by 460 μm excluding the pads, as shown in the micrograph Fig. 9.
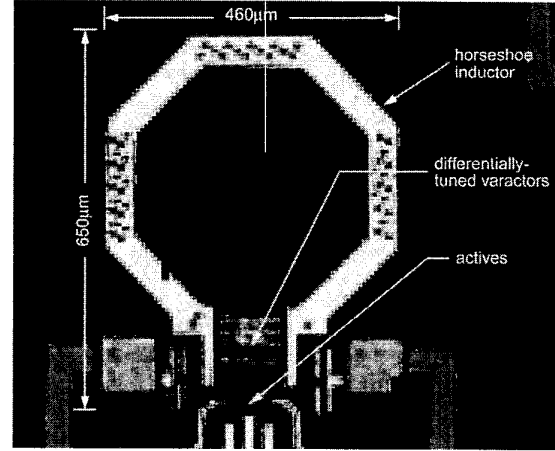

Fig. 9. Micrograph of Differentially-Tuned VCO

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