A Differentially-Tuned Voltage Controlled Oscillator Using Symmetric Transformer

Seok-Ju Yun, Nguyen D. B. Yen, InYoung Lee, Jin-Taek Lee, and Sang-Gug Lee

***Abstract*—This letter proposes a new voltage controlled oscillator (VCO) topology that cancels common-mode noise by adoption of differential tuning varactor. To suppress common mode noise effectively, a symmetric three-coil transformer is proposed as a differential tuning resonator. The measured phase noise shows −128.7 dBc/Hz at 1 MHz offset frequency from the 1.2 GHz oscillation frequency. Over the whole frequency range, common-mode noise rejection is larger than 36 dB. Measured tuning range of the proposed VCO is about 204 MHz from the 1.18 GHz to 1.38 GHz while dissipating 1.2 mA at 1.8 V power supply.**

***Index Terms*—Differentially-tuned, phase noise, voltage controlled oscillator (VCO).**

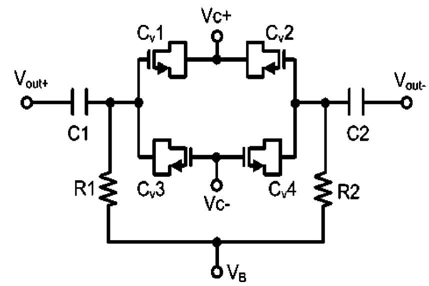

Fig. 1. Anti-parallel differential tuning varactor structure.

I. Introduction

With the improvement of radio frequency (RF) CMOS technology, active research to develop highly-integrated and low power wireless terminals are in progress using single-chip CMOS radio transceivers. A low phase noise voltage controlled oscillator (VCO) is important to achieve high performance in a single-chip CMOS transceiver. When VCOs are integrated into single-chip transceivers, common-mode (CM) noise that comes from supply, control signal and tail current is up-converted by CM modulation to frequency modulation (CMM–FM) mechanism, resulting in severe phase noise degradation in differential VCO [1].

A differentially-tuned VCO is known to provide significant reduction of up-converted common mode noise into phase noise and in the oscillator's sensitivity to supply and bias variations [2]. In order to implement differential tuning for a VCO, an anti-parallel pair of varactors consisting of a P/N or a MOS-based junction have been demonstrated (Fig. 1) [3], [4]. As a drawback of anti-parallel varactor, an asymmetric characteristic between anode and cathode results in the loss of ability to reject variations in common mode. To obtain better symmetry of differential tuning, a modified anti-parallel varactor tuning is suggested [5]. The required decoupling capacitor, however, leads to Q factor degradation of the resonator and wide tuning performance. In addition, inductively-coupled varactors [6], another method to implement the differential tuning, are difficult to be symmetric enough due to the mismatch of primary and secondary impedance. In this letter, a new differentially-tuned VCO using symmetric transformer is proposed for the common-mode noise immunity.

II. Proposed Differential Tuning VCO

In the differential VCO, the noise of active components can be considered as a common-mode noise because the inductor behaves like a short at the low frequency. This common-mode noise is up-converted to the oscillation frequency by changing capacitance of the varactors, resulting in considerable phase noise degradation [1]. Fig. 2 shows the proposed complementary VCO which adopts a three-coil transformer. The complementary topology achieves lower phase noise than nMOS-only topology for the same amount of power consumption due to the stacked switching transistor pairs. In the complementary VCO topology, since the oscillation amplitude is limited by the power supply, the CMM-FM mechanism is the main cause of increased phase noise, rather than amplitude modulation to FM.

Because of top adoption of the current source, the CM voltage of the differential VCO in Fig. 2 can be given by $V_{\rm CM} \approx V_{T\_{\rm NMOS}} + (I_1/g_{\rm mNMOS})$, where I_1 is the total bias current of the oscillator core and $V_{T\_{\rm NMOS}}$ and $g_{\rm mNMOS}$ are the threshold voltage and trans-conductance of the nMOS transistor, respectively. Thus, the low frequency noise of the cross-connected pair and fluctuation of current source, I_1, result in modulation of the varactor's bias condition [1].

As shown in the Fig. 2, the differential VCO in Fig. 2 adopts three-coil transformer for suppressing CMM-FM mechanism. The transformer in Fig. 2 consists of a primary coil (L_1) and two symmetric secondary coils (L_2). The three-coil transformer accompanies differentially-tuned varactors (accumulation MOS-type) at its two secondary coils (L_2) which are symmetric to each other. Therefore, the low frequency, common-mode variation from the active components does not change the varactor capacitance due to the negligible coupling.

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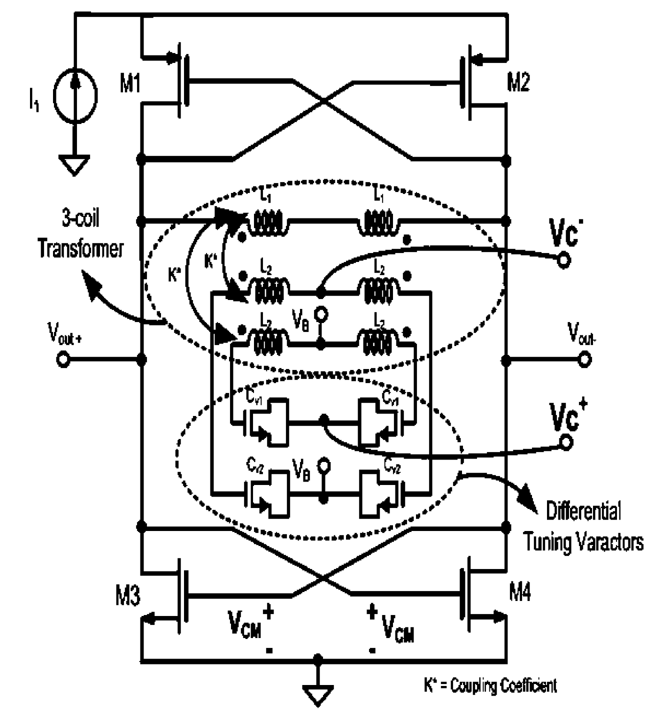

Fig. 2. Proposed differential-tuning VCO with three-coil transformer.

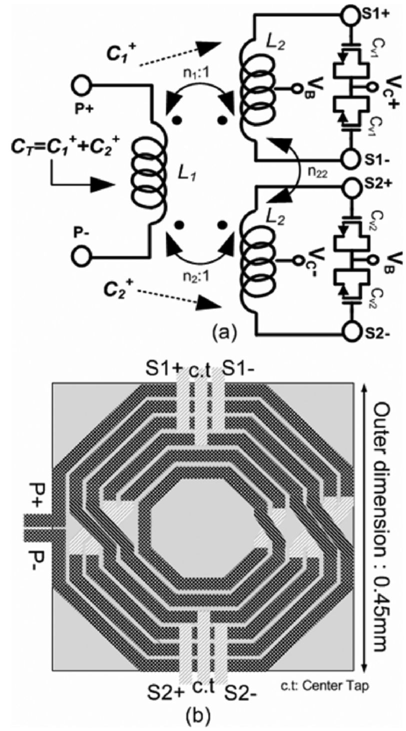

Fig. 3. (a) Schematic of differential tuning LC-tank and (b) the physical layout of three-coil transformer.

The only common-mode noise which generates capacitance variation can come from the bias voltage, V_B. To remove the common-mode noise from V_B, the symmetrical implementation of the differential tuning is essential. It means that the ability to suppress the common-mode noise is proportional to the symmetry of positive and negative tuning terminals of the varactors. In Fig. 2, for the symmetry, a positive control voltage V_C^+ is connected to the common node of varactor C_{v1} while a negative control voltage V_C^- is connected to the common node of secondary coils L_2. As a result, all gates of varactors are connected to the secondary coil in the same direction, ensuring the symmetry.

Fig. 3(a), (b) show the circuit schematic of the differential tuning LC-tank and the physical layout of the three-coil transformer, respectively. With CM noise (V_{ncm}) generated at control bias V_B, the capacitances seen from the secondary coils can be given by

$$C_1^+ = \frac{C_0}{n_1^2} + \frac{K_v}{n_1^2}\left(V_C^+ + V_{ncm}\right)$$
$$C_2^+ = \frac{C_0}{n_2^2} - \frac{K_v}{n_2^2}\left(V_C^- + V_{ncm}\right) \quad (1)$$

where K_v is the varactor sensitivity versus the control voltage, C_0 is the zero bias capacitance, and n_1 and n_2 are the turns ratio between L_1 and L_2, respectively ($n_1 = L_2/M_2$, $n_2 = L_3/M_3$; M_2 and M_3 are mutual inductances). From (1), to remove the total capacitance ($C_T = C_1^+ + C_2^-$) variance by CM noise, the mutual couplings between L_1 and the two L_2 should be equal. As shown in the Fig. 3(b), the transformer layout with two symmetric secondary coils provides a fully differential tuning environment to cancel out the CM noise. Accordingly, by the same mutual coupling ($M_2 = M_3$, $n = n_1 = n_2$), C_T can be represented by

$$C_T = \frac{2(C_0 + K_v V_C)}{n^2} \quad (2)$$

where V_c is $V_c^+ - V_c^-$. As can be seen in (2) the CM noise can be removed effectively with symmetric differential tuning.

The other advantage of transformer-based differential tuning shown in Fig. 2 is that quality factor can be preserved as no additional decoupling capacitors are necessary as in the case of [4] and [5]. From the electromagnetic (EM) simulation, the Q factor and inductances of the primary coil, L_1, is 10 and 4.2 nH at the 1.25 GHz oscillation frequency, respectively. The quality factor is expected to increase by the mutual coupling between primary and secondary coils. Therefore, considering suppression CM noise and the preservation of the quality factor, the proposed VCO in Fig. 2 is expected to show significantly better phase noise than that of the conventional topology.

III. Measurement Results

To verify experimentally the effectiveness of the proposed transformer-based differential tuning method, the differential VCO shown in Fig. 2 is implemented using 0.18 μm CMOS technology. To wind a three-coil transformer for differential tuning, a 2-μm-thick top AlCu metal is used. Fig. 4 shows the measurement results of VCO tuning curve versus the various control voltages, V_C^+, V_C^-, common mode voltage (V_{CM}) and differential tuning voltage (V_d), respectively. ($V_C+ = V_B - V_d$, $V_C- = V_B + V_d$, $V_d = (V_C^- - V_C+)/2$), As shown in the Fig. 4, the tuning curve shows almost flat response for whole

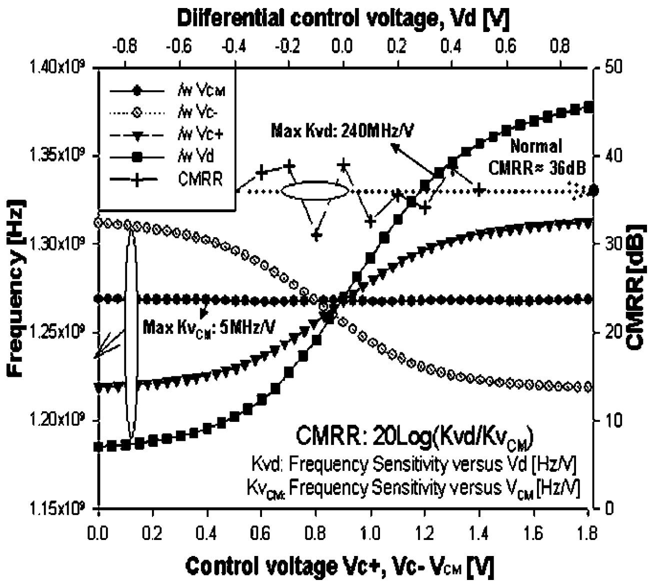

Fig. 4. Measured tuning curves as a function of $Vc+$, $Vc-$, $V_{\rm CM}$ and Vd.

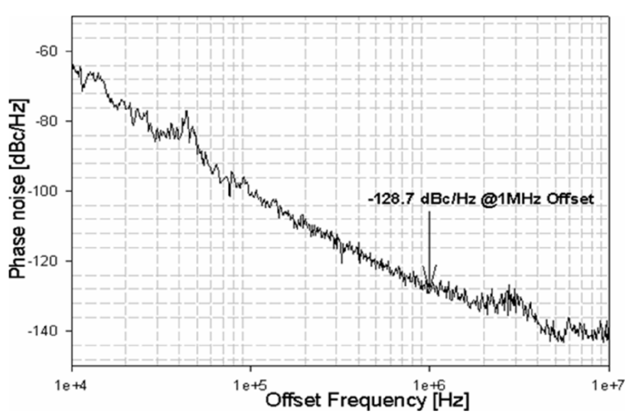

Fig. 5. Measured phase noise performance of the proposed VCO.

range of common-mode control voltage ($V_{\rm CM}$), while the tuning curve of the differential tuning voltage (V_d) varies from 1.18 to 1.38 GHz. From the measured tuning curves in Fig. 4, the common mode rejection ratio, CMRR, [2] of the proposed differential VCO is about 36 dB, which represents the effectiveness of the proposed architecture. Fig. 5 shows the measured phase noise of the proposed VCO for $V_d = 0$ V. As shown in the Fig. 5, the phase noise is -101.8 and -128.7 at 100 kHz and 1 MHz offset frequency, respectively and it varies only 1.5 dB over the whole control voltage variation showing good common-mode noise immunity. Fig. 6(a) and (b) show output spectrum of the VCO with 2 MHz span, and the micrographs of the fabricated VCO, respectively. In Table I, measurement results are summarized and compared with previously reported works. As shown in the Table I, the measured overall performance of the proposed VCO is better or comparable to previous works and showing the best CMRR value.

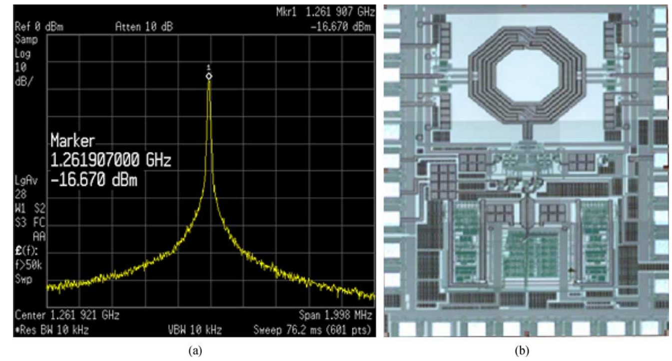

Fig. 6. (a) Output spectrum and (b) chip photograph of fabricated VCO.

TABLE I
COMPARISON OF DIFFERENTIAL TUNING VCO PERFORMANCES

	This work	[2]	[4]	[5]	[6]
I_{DC} (core) [mA]/ VDD[V]	1.2 /1.8	2.3~2.7 /1	3.3 /2.6	2.5 /1.7	5.5 /2.5
Output Frequency/ Tuning range [GHz]	1.18~1.38 /0.204	3.8~5.7 /1.9	0.98~1.1 /0.07	4.2~4.4 /0.17	4.2~4.9 /0.7
CMRR [dB]	≈ 36	20	23.6	29.4	20
Phase Noise @1MHz[dBc]	-128.7	-121	-129	-119	-124
Figure of merit	186.9	187	180	185	185
Technology	0.18μm CMOS	0.13μm SOI	0.25μm CMOS	0.5μm BICMOS	0.25μm CMOS

IV. CONCLUSION

A new differential tuning technique which adopts a symmetric transformer in CMOS VCO is proposed. The symmetric transformer provides fully differential varactor tuning to suppress common-mode noise effectively. The complementary CMOS VCO with transformer-based differential tuning is fabricated with 0.18 μm technology. The measurement results show that the phase noise -128.7 at 1 MHz offset frequency and CMRR above 36 dB for whole tuning voltage. Measured tuning is about 204 MHz from 1.18 to 1.38 GHz while dissipating only 1.2 mA at 1.8 supply.

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