LETTER

An LC-VCO Strongly Suppresses the AM-FM Conversion Caused by Varactor

So Bong SHIN[†a)], *Nonmember and* Sang-Gug LEE[††], *Member*

SUMMARY A differential LC-VCO that adopts a transformer with asymmetric turns-ratio has been proposed. The asymmetric turns-ratio of the transformer leads to the suppression of the AM to FM conversion which is caused by the 1/f noise of the current source transistor. The analysis of the proposed scheme and the improvement in phase noise compare to conventional CMOS LC-VCOs are described. The transformer used in proposed VCO occupies about $430\times430\,\mu\text{m}^2$ of silicon area while the inductor in compared conventional VCO does $390\times390\,\mu\text{m}^2$.

key words: *LC-VCO, AM to FM conversion, 1/f noise, varactor nonlinearity, transformer, CMOS*

1. Introduction

As one of the key sources for the phase noise degradation, the 1/f noise of the current source transistor of the differential LC-VCO has been a constant concern for the designers. Levantino [1] and Hegazi [2] reported the principle of how the 1/f noise of the current source transistor leads to phase noise degradation through the effective varactor capacitance ($C_{var-eff}$) modulation caused by the peak VCO output voltage swing (v_{peak}) variation, i.e., AM to FM conversion. Though they provides clear basis of the AM to FM conversion behavior, still there is some uncertainness for fundamental solution. This work reports a transformer based solution for the AM to FM conversion problem of the current source based LC-VCO. Previously on the transformer based approach by straayer [3], the low phase noise performance was achieved by enhancing Q of the resonator with nearly symmetric transformer, while this work adopts highly asymmetric transformer for suppression of the AM to FM conversion without any modification of the resonator Q.

2. Proposed Idea

Figure 1 shows the schematic of a conventional LC-VCO. As described in [1] and [2], the phase noise degradation caused by the AM to FM conversion originates from the effective varactor capacitance ($C_{var-eff}$) variation which is a function of the peak VCO output voltage (v_{peak}). The amount of phase noise degradation by this AM to FM conversion is a strong function of the sensitivity of the $C_{var-eff}$ with respect to v_{peak}. With the conventional differential VCO, its sensitivity can be given by

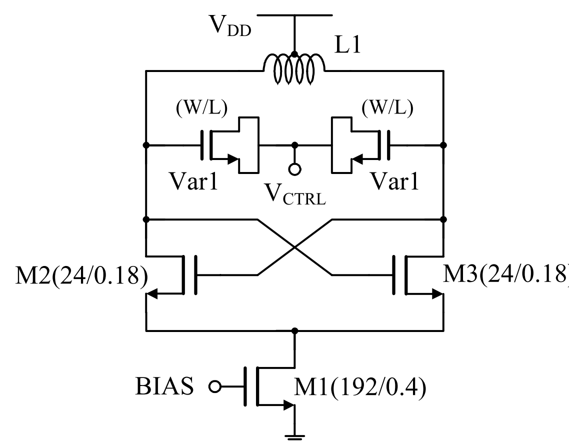

Fig. 1 The schematic of conventional LC-VCO.

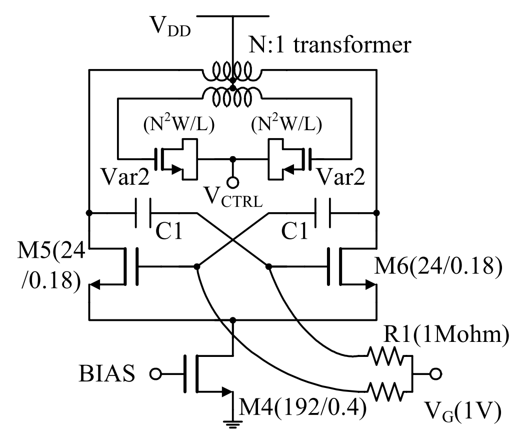

Fig. 2 The proposed C-coupled XC-VCO.

$$S_{conv}\Big|_{v_{peak}}^{C_{var-eff}} = \lim_{\Delta v_{peak}\to 0} \frac{\Delta C_{var-eff}/C_{var-eff}}{\Delta v_{peak}/v_{peak}} = \frac{v_{peak}}{C_{var-eff}}\frac{\partial C_{var-eff}}{\partial v_{peak}} \tag{1}$$

where $C_{var-eff}$ represents the effective varactor capacitance which is a function of v_{peak}.

Figure 2 shows the schematic of the proposed transformer based LC-VCO where the tank inductor is replaced with a N:1 transformer. In Fig. 2, the coupling capacitor C1 is adopted for the separation of the gate-drain bias of the switching transistors M5 and M6. For the transformer

Manuscript received May 2, 2008.
[†]The author is with RadioPulse Inc., Seoul, 134-883, Korea.
[††]The author is with Information and Communication University, Daejeon, 305-372, Korea.
a) E-mail: rio99@icu.ac.kr
DOI: 10.1093/ietele/e91–c.9.1516

based LC-tank shown in Fig. 2, the varactor sensitivity can be given by

$$S_{xfr}\Big|_{v'_{peak}}^{C'_{var-eff}} = \frac{v'_{peak}}{C'_{var-eff}(v'_{peak})}\frac{\partial C'_{var-eff}(v'_{peak})}{\partial v'_{peak}} = \frac{1}{N}\frac{v_{peak}}{C_{var-eff}(v_{peak}/N)}\frac{\partial C_{var-eff}(v_{peak}/N)}{\partial(v_{peak}/N)} \quad (2)$$

where $C'_{var-eff}$ is the effective varactor capacitance on the secondary port of the transformer and v'_{peak} the peak voltage across the corresponding varactor. For the same frequency of oscillation, for both conventional and the newly proposed, the $C'_{var-eff}$ in Fig. 2 should be equal to $N^2C_{var-eff}$. Therefore, considering $v'_{peak} = v_{peak}/N$ and by substituting $C'_{var-eff}$ with $N^2C_{var-eff}$, S_{xfr} can be expressed as a function of $C_{var-eff}(v_{peak}/N)$, v_{peak}/N and the derivatives of these parameters as shown in Eq. (2). From a set of computer simulations, we have found a useful relationship, which is for the given varactor bias, $C_{var-eff}$ is a slow function of v_{peak} while the fractional variation of the derivative, $\partial C_{var-eff}/\partial v_{peak}$, is significant such that

$$C_{var-eff}(v_{peak}/N) \approx C_{var-eff}(v_{peak}) \quad (3)$$

$$\frac{\partial C_{var-eff}(v_{peak}/N)}{\partial(v_{peak}/N)} \approx \frac{1}{N}\frac{\partial C_{var-eff}(v_{peak})}{\partial v_{peak}}. \quad (4)$$

From (3) and (4), Eq. (2) can be approximated as

$$S_{xfr}\Big|_{v'_{peak}}^{C'_{var-eff}} \approx \frac{1}{N^2} S_{conv}\Big|_{v_{peak}}^{C_{var-eff}}. \quad (5)$$

Equation (5) indicates that the adoption of the N:1 transformer effectively suppresses the varactor sensitivity by $1/N^2$ times that of the conventional case. Therefore, in the proposed transformer based LC-VCO, the phase noise degradation caused by the 1/f noise of the current source transistor through the AM to FM conversion mechanism is expected to be reduced by the factor of $1/N^2$.

3. VCO Design and Comparison

Three LC-VCOs are designed based on 0.18 μm TSMC CMOS technology for 1.9–2.0 GHz operation at 1.5 V supply voltage: the conventional LC-VCO shown in Fig. 1 (conventional LC-VCO), the conventional LC-VCO but adopts coupling capacitor for separation of the gate-drain bias as shown in Fig. 4 (C-coupled LC-VCO) and the proposed transformer based LC-VCO shown in Fig. 2 (C-coupled XC-VCO). Since the varactors in both LC-VCOs are identical, the expected sensitivity of varactor in C-coupled LC-VCO is same to conventional ones. In the C-coupled XC-VCO, the transformer with 9:2 turn ratios shown in Fig. 3 is adopted to ensure enough suppression of the AM to FM conversion. This transformer effectively shows the 4.5:1 transformer's characteristics. Based on Eq. (5), expected suppression ratio of this transformer against the AM to FM conversion is about 1/20.

For fair comparison of the proposed versus the other two VCOs, the size of the transformer is adjusted to make the Q of XC tank close to that of LC tank. The size of the square transformer is about $430 \times 430\,\mu\text{m}^2$, while the octagonal inductors used in the other VCOs are $390 \times 390\,\mu\text{m}^2$. The estimated Q is about 10 for both LC and XC tank. The inductor used in the LC-tank is taken from the PDK, while the transformer in the XC-tank has been designed in-house and simulated in EM-simulation tool (Agilent Momentum).

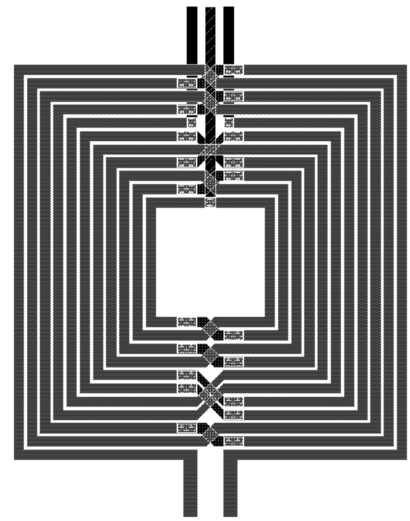

Fig. 3 Layout of the 9:2 transformer.

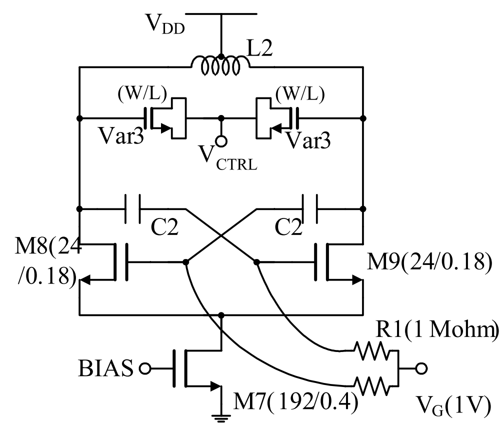

Fig. 4 The schematic of C-coupled LC-VCO.

The capacitively coupled designs, in C-coupled LC-VCO and XC-VCO, are adopted to avoid the switching transistors entering triode mode operation. The switching transistors entering triode mode operation can lead to the reduction of the average Q of the resonator [4] and/or additional AM to FM conversion through the parasitic capacitance of the switching transistor [5].

Figure 5 shows the simulated frequency characteristic of the C-coupled LC-VCO and C-coupled XC-VCO versus varactor bias voltage for the two different supply currents, 0.6 and 1.2 mA. In Fig. 5, in agreement with [1] and [2], the C-coupled LC-VCO (dashed-line) shows much more significant frequency change over the varactor bias while the C-

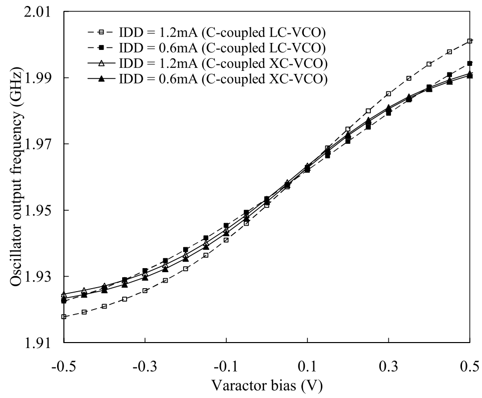

Fig. 5 Simulated frequency characteristics of the C-coupled LC-VCO and C-coupled XC-VCO versus varactor bias.

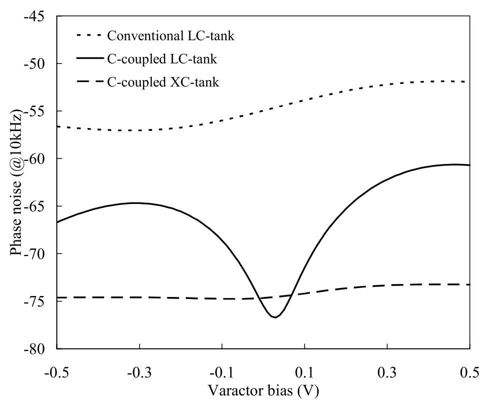

Fig. 6 Simulated phase noise of conventional and C-coupled LC-VCO, and the C-coupled XC-VCO versus varactor bias.

coupled XC-VCO (solid-line) shows only a slight frequency shift. The variation of oscillation frequency for the change in supply current is a direct indication of the AM to FM conversion [1], [2]. The small frequency change in the C-coupled XC-VCO can be referred to the small change in gate-source capacitance with bias current.

Figure 6 compares the simulated phase noise of the three VCOs above at 10 kHz offset. As can be seen in Fig. 6, the conventional (dotted-line) and C-coupled LC-VCO (solid-line) not only shows poor but strong varactor bias dependent phase noise characteristic. Especially the C-coupled LC-VCO shows better plot, which is owing to the capacitively coupled design that mentioned before, preventing the Q reduction and/or the AM to FM from switching transistor's parasitic capacitance. Since those two varactor-independent phase-noise sources are added to the varactor AM to FM conversion behavior, the plot of the conventional LC-VCO shows varactor bias dependency but the null point is buried as shown in Fig. 6.

However, the C-coupled XC-VCO (dashed-line) shows significantly reduced phase noise with little dependence on varactor bias. In Fig. 6, for the limited ranged of varactor bias, the phase noise of the C-coupled LC-VCO shows a few dB better than that of the C-coupled XC-VCO, which

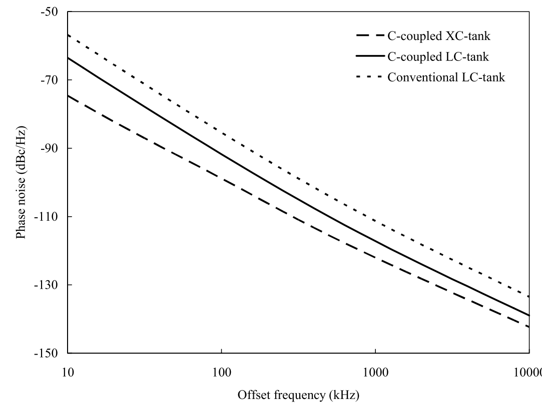

Fig. 7 Simulated phase noise of conventional and C-coupled LC-VCO, and the C-coupled XC-VCO versus offset frequency at 1.92 GHz w/−0.3 V of varactor bias.

is described as a null region in [2]. This null conforms to the frequency plot shown in Fig. 5 where the frequency change of the C-coupled LC-VCO is small near the cross over point. Likewise, the uniform phase noise improvement of the C-coupled XC-VCO shown in Fig. 6 is in agreement with slight frequency shift as observed in Fig. 5.

Figure 7 shows phase noise of three VCOs for 10k–1 MHz offset at 1.92 GHz operation. As can be seen in Fig. 7, the XC-VCO shows better phase noise performance for all offset frequency and shows the least frequency of $1/f^3$ corner in three VCOs. The conventional LC-VCO has the AM to FM conversion induced from both varactor and parasitic capacitance, while C-coupled LC-VCO has the AM to FM conversion from varactor. However, the proposed XC-VCO has neither of the origins of AM to FM conversion, which leads to the least $1/f^3$ corner of phase noise.

4. Conclusions

A topological solution to suppress the effect of the AM to FM source transistor, to the phase noise of the LC-VCO is investigated. By replacing the tank inductor with an asymmetrically turn-ratioed transformer, the voltage across the varactor can be scaled down and the varactor capacitance modulation by the variation of output voltage can be reduced. According to the sensitivity analysis, the effective varactor capacitance sensitivity with peak output voltage swing can be reduced by the square of the transformer turn ratio (N^2). A set of comparative simulations show that the strong dependencies of the phase noise to the varactor bias in conventional LC-VCOs are almost vanished in the proposed transformer based LC-VCO, which demonstrates the effectiveness of the proposed approach in reducing the AM to FM conversion caused by the 1/f noise of the current source transistor.

Acknowledgement

This work was sponsored by ETRI SoC Industry Promotion Center, Human Resource Development Project for IT SoC

Architect.

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