An Ultra Low-power and Low-noise VCO Using Transformer Coupled Dual LC Tanks Topology

Tzu-Yun Chou, **Kuan-Hsiu Chien**, and **Hwann-Kaeo Chiou**
Department of Electrical Engineering, National Central University, Jhongli City, Taoyuan, Taiwan

Abstract— A K-band low power voltage-controlled oscillator (VCO) using transformer coupled dual LC tanks is implemented in a 90-nm CMOS process. The use of transformer provides tight coupling factor between two LC tanks that improves the phase noise performance by increasing the output signal swing and waveform symmetry of the VCO. In addition, taking advantage of the tight-coupling transformer, the inductor layout is properly designed to obtain a high Q-factor and a die area comparable to single-inductor VCO. The VCO core dissipates very small DC power of 1.61 mW from a 0.7-V supply due to the benefit of tight-coupled transformer. The measured phase noise is −97.61 dBc/Hz at 1-MHz offset from 23.99 GHz oscillation frequency.

1. INTRODUCTION

Fully integrated voltage controlled oscillators play an important role in RF transceivers. Over the past few years, the development of low-cost and low-power RF integrated circuits for wireless communication have attracted great attention. Numerous VCO topologies constructed in CMOS technology have been developed to achieve the performance of low power consumption, low phase noise and high operation frequency [1–5]. Work [1] proposed an asymmetrical current-reused oscillator that used only one pair of NMOS and PMOS transistors to achieve low DC power of 1 mW. However, as compared to conventional complementary cross-coupled CMOS counterpart, the differential outputs of the mentioned oscillator exhibit unbalanced output power level. Even though low-voltage operation can save the power consumption of the circuits, low-voltage operation may limit the output signal swing which in turn reduces the signal-to-noise ratio and degrades system performance [2]. The cross-coupled LC VCO has attracted much interest due to its easy implementation and reliable start-up condition [3, 4]. However, it limits in terms of reducing phase noise owing to the fact that the output swing of the VCOs is constrained. oscillation frequency of 24 GHz is −97.61 dBc/Hz. With only a power dissipation of 1.61 mW, the proposed VCO has an excellent FOM of −183.14 dBc/Hz.

In this work, the authors propose a transformer-based VCO for high frequency application that adopts the strength of magnetic coupling between two LC tanks to obtain large oscillation amplitude and achieve low phase noise under low supply voltage.

2. CIRCUIT DESIGN

By using the proposed transformer, a coupled dual LC tanks VCO is fabricated in a 90-nm CMOS technology. Fig. 1 shows the schematic of the proposed VCO. It consists of a transformer-based resonator that includes two identical LC tanks coupled by the transformer. The cross-coupled transistors (M_1) with the size of 8 µm/90 nm provide an effective negative resistance for the VCO core to compensate the resistive loss in the LC-tanks. The fine-tuned varactors C_{var} ($7 \sim 10.3$ fF) are used for frequency tuning. L_p and L_s are the self-inductances of each coil of the transformer. L_p incorporating with C_{var} acts as the primary LC tank, while L_s and MIM capacitor C_2 (27.4 fF) form the secondary LC tank. The secondary LC tank is DC isolated from the primary one, thus it does not consume DC power from the primary LC tank. Accordingly, compared to the conventional topology, this core power consumption can be significantly reduced. The drain voltage could swing above the supply voltage by using the proposed transformer. Effectively, the oscillation amplitude is enhanced, and the supply voltage can be reduced for the same phase noise with lower power consumption or for better phase noise with the same power consumption. By using the transformer equivalent T-model, the input admittance of transformer is shown in (1).

$$Y_{in} = \frac{1 + s^2 L_S C_2}{s^3 C_2 \left[L_S L_P - M^2\right] + s L_P} \tag{1}$$

Figure 2(a) shows the equivalent circuit model I of the VCO which consists of the input admittance of the transformer in parallel with the varactors. Fig. 2(b) depicts the small-signal model of the VCO. The oscillation frequency ω_0 can be derived as (2).

$$\omega_0 = \sqrt{\frac{A + \sqrt{A^2 - 8C_{var}C_2(L_P L_S - M^2)}}{2C_{var}C_2 \left[L_P L_S - M^2\right]}} \tag{2}$$

where $A = L_P C_{var} + 2C_2 L_S$, $M = k\sqrt{L_P L_S}$ is the mutual inductance, and $k$represents of the coupling factor between L_P and L_S.

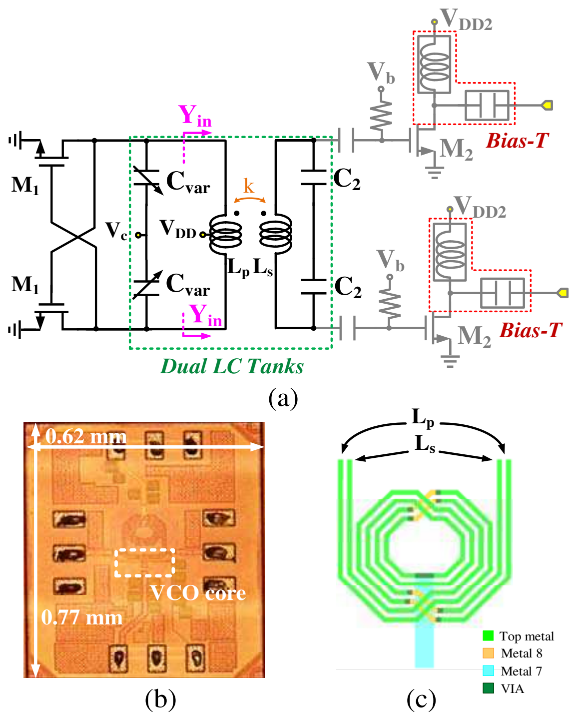

Figure 1: The proposed low-power K-band CMOS VCO. (a) Schematic of the proposed VCO. (b) Chip photograph of the proposed VCO. (c) Top view of transformer.

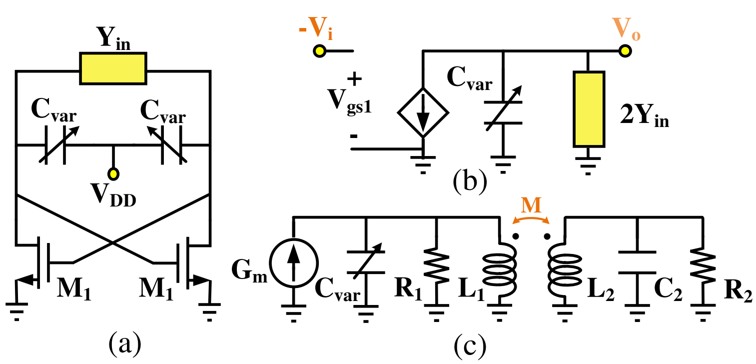

Figure 2: The proposed VCO equivalent circuit with admittance. (a) Equivalent circuit model I of the proposed VCO. (b) Small-signal model of the proposed VCO. (c) Equivalent circuit model of the proposed VCO.

On-chip transformer design: The implementation of the transformer is the major challenge to facilitate the strong coupling required for two coils and the connections with the varactors. The planar transformer is realized by the turn ratio 1 : 1 transformer as shown in Fig. 1(c). The transformer consists of a three-turn primary coil (L_p) and secondary coil (L_s), which wound together in a common-centric configuration. The outer dimension of the transformer is 113 µm, and the metal width of each coil is 3 µm. The extracted self-inductances of the primary coil L_p and the secondary coil L_s are 946.6 and 760.8 pH at 24 GHz, respectively. The electromagnetic simulation

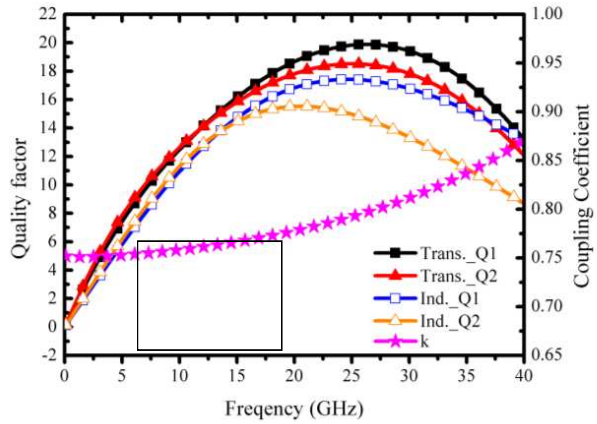

Figure 3: The quality factors and coupling coefficients of transformer and single inductor.

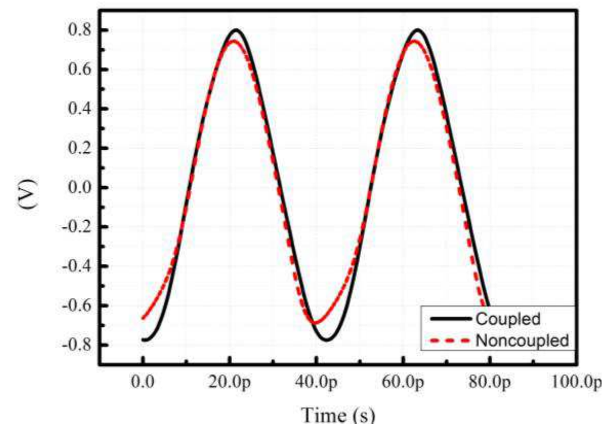

Figure 4: The output voltage waveforms of the coupled and non-coupled VCOs.

results using ADS Momentum are shown in Fig. 3, where the coupling coefficient of the transformer k is 0.79 at 24 GHz. k represents the transformer coupling factor between two LC tanks. Works [4] and [5] conclude that the tighter coupling factor, the higher quality factor. Fig. 3 shows the quality factor (Q) of the self-inductances of the transformer and single inductor. The quality factors of the proposed transformer are higher than that of the single inductor.

Fig. 4 shows the output voltage waveforms of the coupled and non-coupled VCOs. Work [6] suggests that the oscillator with symmetric waveform will have better phase noise performance. As noted, the waveform of the coupled VCO has larger swing and better symmetric waveform than those of the non-coupled one. Thus, the proposed VCO yields better phase noise than conventional one. In transformer model, the turn ratio between primary and secondary coils can be derived as (3).

$$n = \sqrt{\frac{L_s}{L_p}} = \frac{V_2}{V_1} = \frac{I_1}{I_2} \quad V_2 = V_1\sqrt{\frac{L_1}{L_2}} \tag{3}$$

Figure 2(c) shows the equivalent model for the transformer of Fig. 1(a), where the port voltages of the tight-coupled lossy transformer V_1 and V_2 have the following relations as (4)–(5).

$$V_1(j\omega) = \left.\frac{G_m j\omega}{\left(\omega_{o1}^2 - \omega^2\right) + j\omega\left(\frac{\omega_{o1}}{Q_1}\right)}\right|_{\omega=\omega_{01}} = \frac{G_m Q_1}{\omega_{o1}} \tag{4}$$

$$V_2 = \frac{k}{M}\frac{G_m Q_1 L_1}{\omega_{o1}} = \frac{k}{M} G_m Q_1 \sqrt{L_1^3 C_{var}} \tag{5}$$

where $G_m = -g_m/2$, and $Q_1 = R_1\sqrt{C_{var}/L_1}$.

At parallel resonance, the voltage is at a maximum and the impedance is also at a maximum. Hence, it can be derived that V_2 is maximum when the resonant frequency at $\omega_{o1} = \omega_{o2}$.

3. MEASUREMENTS

Measurement Results: The proposed VCO is implemented in a 90-nm CMOS technology. The transformer provides strong coupling between the two LC tanks. The Q values of L_p and L_s are 18.5 and 19.7. Fig. 1(b) shows the micrograph of the VCO with a chip size of $0.77 \times 0.62\,\text{mm}^2$, including the pads. The phase noise is measured by an Agilent E5052B signal source analyzer. The VCO operates at a power supply of 0.7 V and consumes a current of 2.3 mA. The measured output power is −7.16 dBm. Fig. 5 shows the measured and simulated phase noise at 24 GHz, where the measured phase noise at 1 MHz and 10 MHz offset frequency are −97.61 and −123.6 dBc/Hz. As seen, the phase noise of the transformer coupled VCO obtains a 15-dB improvement compared to the non-coupled inductor VCO. The measured tuning range is from 23.6 to 24 GHz when the tuning voltage V_c changes from 0 to 0.7 V.

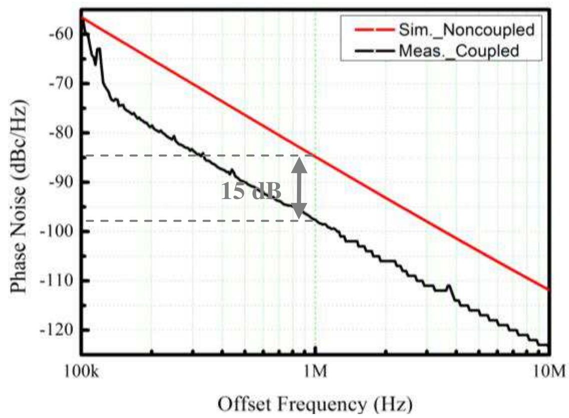

Figure 5: Measured (transformer coupled VCO) and simulated (non-coupled VCO) phase noise.

4. CONCLUSION

A novel dual LC tanks VCO has been proposed to obtain low power operation using the strength of magnetic coupling in the transformer. The proposed design also makes certain symmetry properties exist in the waveform of the oscillation which improves the phase noise noticeably. The proposed VCO has successfully demonstrated in good performance based on a 90-nm CMOS process. The measured phase noise at 1-MHz offset frequency from the oscillation frequency of 24 GHz is -97.61 dBc/Hz. With only a power dissipation of 1.61 mW, the proposed VCO has an excellent FOM of -183.14 dBc/Hz.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Technology, Taiwan, R. O. C. under Contract MOST 101-2221-E-008-073-MY3. National Chip Implementation Center (CIC) of National Applied Research Laboratories, Taiwan, R. O. C., is also acknowledged for chip fabrication.

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