Low Phase Noise Concurrent Dual-Band (5/7 GHz) CMOS VCO Using Gate Feedback on Nonuniformly Wound Transformer

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***Abstract*— A novel low phase noise concurrent dual-band complementary metal–oxide–semiconductor (CMOS) voltage-controlled oscillator (VCO) employing a gate-feedback enabled, nonuniform multiwinding transformer is proposed. The transformer consists of the wide-width looped main inductors and surrounding narrow-width looped feedback inductors, featuring a high degree of design freedom, owing to its controllable width, gap, and coupling coefficients. This novel topology enables both simultaneous and independent oscillation in two frequency bands using the main inductors with oscillation cores. In addition, the resonant tank's noise contribution can be reduced by boosting the loaded quality factor using gate-driving feedback inductors. The proposed VCO was fabricated in a 0.28-μm silicon on insulator (SOI) CMOS process. The measured results show concurrent oscillation from 4.6 to 5.6 GHz and 6.1 to 7.4 GHz with phase noise of –119.3 and –120.1 dBc/Hz at 1 MHz offset, corresponding to a figure-of-merit (FOM) of –184.4 and –185.1, whereas the FOM for low-band and high-band single-tone oscillation is –182.7 and –184.8 dBc/Hz, respectively. Finally, the FOM of the proposed VCO is compared with that of similar size concurrent dual-band VCO devices previously presented in literature.**

***Index Terms*—Complementary metal–oxide–semiconductor (CMOS), concurrent, dual-band, gate feedback, radio-frequency integrated circuits (RFIC), single resonator, voltage-controlled oscillator (VCO).**

I. Introduction

MODERN wireless communication systems expand their transceivers' capability by employing independently controllable concurrent multiband, multimode operating devices. Therefore, microwave components comprising a transceiver are expected to handle concurrent multiband operation. The dual-band voltage-controlled oscillator (VCO) is an essential component required to operate as a signal source in multiband communication systems.

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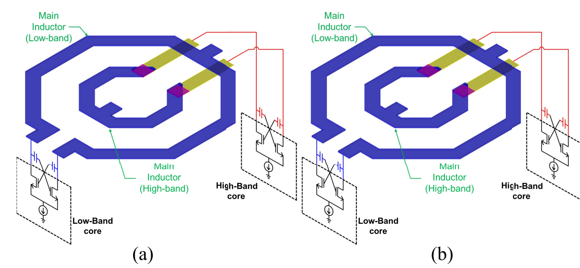


Fig. 1. Schematic of concurrent dual-band VCO with layout of (a) conventional and (b) proposed nonuniformly turned transformer.

Previous works suggest various types of dual-band VCOs [1]–[5]. In [1], a metal oxide semiconductor varactor-based band switching method was demonstrated in order to change the resonance mode. However, each switched operating mode can only generate a single-tone oscillation, resulting in a lack of concurrence. Other topologies in [2] and [3] employ dual-band bandpass filters to enable stable concurrent oscillation. Multiple resonators used to implement bandpass filters with dual-band characteristics typically occupy a large chip area, as they employ multiple inductors. Single transformer-like resonator topologies applied to VCOs are reported in [4] and [5]. However, the tuning range and phase noise of each VCO still need improvement under both concurrent and single-tone operation, since the previous VCO designs only rely on direct coupling between two inductors.

In this letter, a concurrent dual-band VCO using gate feedback on a nonuniformly wound transformer is designed using a 0.28-μm silicon on insulator (SOI) complementary metal–oxide–semiconductor (CMOS) process. To achieve lower phase noise while enabling concurrent operation, the proposed VCO employs a new type of nonuniform multiwinding transformer where the narrow-width windings render gate feedback to boost the loaded quality factor of the VCO. It is shown that a proper choice of the transformer dimensions, turn ratio, coupling coefficient, and the transistors' size can lead to improved concurrent operation.

II. Circuit Design

The schematic of the concurrent dual-band VCO along with the layout of the conventional and the proposed nonuniformly wound transformer is shown in Fig. 1. The proposed transformer consists of the main inductors ($W_M = 30$ μm) and surrounding feedback inductors ($W_F = 3$ μm). The loaded quality factor is boosted by optimizing the width and gap of the feedback inductor surrounding the main inductor and by minimizing the usage of lower metal layers in order to decrease the phase noise [6].

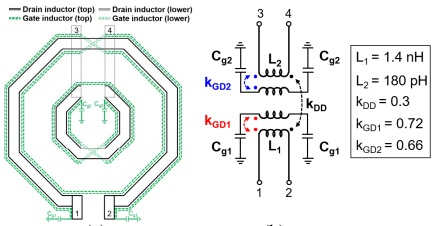


Fig. 2. (a) Proposed transformer under the capacitor loaded gate feedback condition state and (b) its equivalent circuit.

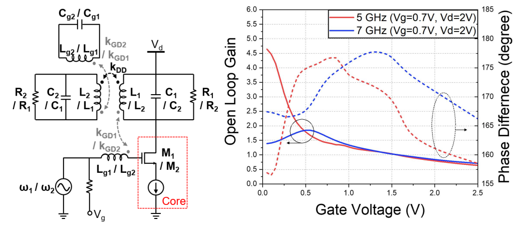


Fig. 3. (a) Half-circuit of the proposed transformer topology connected to the oscillator core for each frequency band (low / high) and (b) simulated open-loop gain/phase difference for 5 and 7 GHz to gate voltage swing.

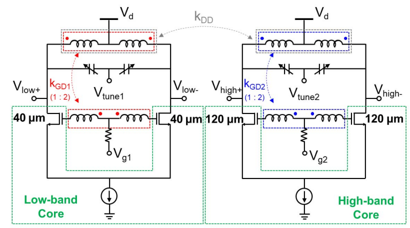


Fig. 4. Simplified schematic of designed concurrent dual-band VCO.

A. Proposed Concurrent-Mode Transformer

The stable oscillation conditions considering the startup for a conventional second-order LC resonator are $g_{m,\omega} \cdot R_D > 2$ and $\angle Z(\omega) = 2n\pi$, where $g_{m,\omega}$ is the transistor's transconductance at the oscillation frequency, R_D is the load impedance, and n is an integer (Barkhausen's oscillation criteria) [7]. However, satisfying the oscillation condition at each frequency does not guarantee concurrent steady-state oscillation for a higher-order LC resonator with multiwinding transformer coupling [5]. For a better intuitive understanding, the loop gain of the half-circuit model with electromagnetic (EM) simulated transformer is investigated with two-tone analysis.

To apply the EM simulation results to the half-circuit model, the odd-mode analysis of the proposed transformer was performed. The feedback inductors are assumed to be connected to the capacitor C_g, representing the parasitic capacitance of the transistor's gate, which includes C_{gs} and C_{gd}, as shown in Fig. 2(a). To satisfy the gain condition, C_{g1} and C_{g2} are determined to be 232 and 694 fF, corresponding to the parasitic capacitance of the transistors having 5 μm × 8 μm and 8 μm × 15 μm sizes, respectively. The capacitive loading in the proposed transformer configuration is represented by the equivalent circuit in Fig. 2(b), consisting of the transformer and the capacitor. L_1, L_2 are the inductances of each transformer winding. The parameters' values given in Fig. 2(b) are obtained based on the EM simulation of the proposed resonator under the capacitive load condition. The relative loop gain and phase are obtained through the half-circuit model shown in Fig. 3(a). By applying two-tone signals of 5 and 7 GHz to the transistor's gate, the open-loop gain and phase difference between gate and drain are plotted in Fig. 3(b). The open-loop gain at both frequencies shows positive, substantially equal values, for both transformer sections above 0.5-V gate swing range, whereas the open-loop gain is about 2. The simulated loop gain and phase difference values enable resonances in the proposed VCO to generate two tones concurrently.

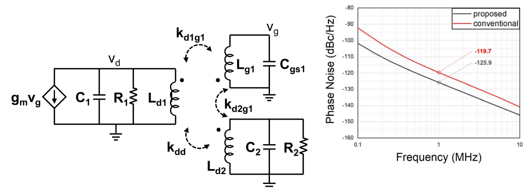
B. Proposed Transformer-Based Concurrent VCO

Fig. 4 shows a simplified schematic of the designed dual-band VCO built on the proposed transformer-based resonator structure. Fig. 5(a) shows the simplified half equivalent circuit of each core connected to the proposed transformer. The coupling between drain and gate and the drain–drain inductor is the most dominant, and the coupling between gate and gate is negligible. Therefore, utilizing the equivalent circuit of the three winding transformer, the gate (V_g) to drain (V_d) voltage function, A_v and drain to gate function, can be expressed as [8], (1) and (2), as shown at the bottom of the page. In the case of the transformer with the structure proposed in this letter, substituting each parameter obtained through Keysight ADS simulation, $\beta = 1.5$. Through the calculation, the gate impedance can be modeled as having a negative value, and the loaded q-factor, Q_{loaded}, is boosted. The boosted loaded q-factor is verified through the simulation results presented in Fig. 5(b), and the proposed topology enhances the phase noise with 6.2 dB compared with the transformer-based capacitive feedback conventional scheme. The coupling coefficient of the two main inductors, k_{dd}, and main inductor to feedback inductor, k_{d1g1}, are critical for stable concurrent oscillation with enhanced phase noise. k_{dd} and k_{d1g1} are appropriately set to 0.3 and 0.65 for inductors' diameters of 460 and 184 μm, respectively. The feedback inductors' coupling effect on gain and phase can be neglected compared with other factors, as the coupling coefficient between the two feedback inductors is about 0.1.

The designed concurrent dual-band VCO consists of an independent oscillation core for each main inductor, enabling both concurrent and single-tone stable oscillation modes. The resonant frequency of the designed VCO can be tuned by two methods. Coarse tuning can be performed by controlling

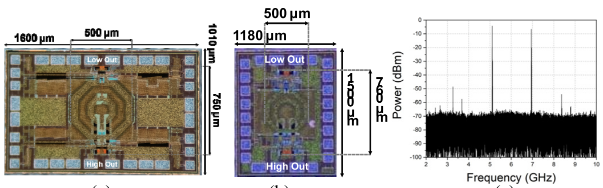
$$A_v = -\frac{R_1\left(\left(k_{dd}C_{gs1}L_{g1}\sqrt{L_{d1}L_{d2}} - k_{d1g1}k_{d2g1}C_{gs1}L_{g1}\sqrt{L_{d1}L_{d2}}\right)s^2 + \left(g_m k_{d2g1}L_{d1}\sqrt{L_{d2}L_{g1}} - g_m k_{d1g1}L_{d1}\sqrt{L_{d2}L_{g1}}\right)s + k_{dd}\sqrt{L_{d1}L_{d2}}\right)}{\left(k_{d2g1}R_1C_1L_{d1}\sqrt{L_{d2}L_{g1}} - k_{d1g1}k_{dd}R_1C_1L_{d1}\sqrt{L_{d2}L_{g1}}\right)s^2 + \left(k_{d2g1}L_{d1}\sqrt{L_{d2}L_{g1}} - k_{d1g1}k_{dd}L_{d1}\sqrt{L_{d2}L_{g1}}\right)s + k_{d2g1}R_1\sqrt{L_{d2}L_{g1}}} \quad (1)$$

$$\beta = \frac{v_{g1}}{v_{d1}} = \frac{k_{d2g1}\sqrt{L_{g1}}}{k_{dd}\sqrt{L_{d1}}}. \quad (2)$$



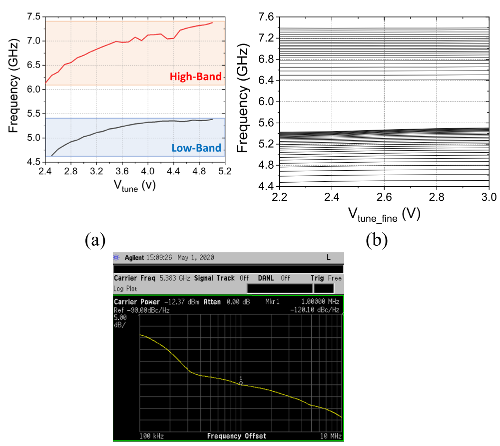
(a) (b)

Fig. 5. (a) Simplified equivalent half-circuit diagram of the proposed concurrent oscillator and (b) comparison of conventional and proposed dual-band VCO simulated phase noise.



(a) (b) (c)

Fig. 6. Die photograph of fabricated (a) proposed and (b) conventional concurrent dual-band VCO and (c) measured spectrum of concurrent oscillation.



(a) (b)

(c)

Fig. 7. Measured frequency tuning range of (a) concurrent, (b) low- and high-band single-tone oscillation, and (c) phase noise of the proposed VCO.

V_{tune1} using the low-band core varactor that is directly coupled to the tank. Controlling V_{tune2} results in fine-tuning, due to the indirect coupling through the transformer-coupled varactor of the high-band core, showing the same operation as the varactor bank. The single-tone operation in the high-band and the concurrent mode are performed on the same principle as that in the low-band.

III. Measurement Results

The proposed design and conventional concurrent dual-band VCO were fabricated for side-by-side comparison using a 0.28-μm SOI CMOS process. Fig. 6(a) and (b) shows a die photograph of the manufactured proposed VCO, the total core sizes being 1.6 mm$^2\times$ 1.01 mm^2 and 0.5 mm$^2\times$ 0.75 mm^2, and conventional VCO. Measurements were performed for concurrent operation and both low-band and high-band modes with each VCO core operating at 1.9- and 2-V drain voltage. Both V_{g1} and V_{g2} gate voltages were controlled to set the operating mode, achieving the ON-state by applying 0.7 V and OFF-state with 0 V. In the ON-state, the low-band and high-band cores consume 4.1 and 7.8 mA, respectively.

Fig. 6(c) shows the measured output spectrum when operating in the concurrent mode. The tuning ranges of concurrent, low-band, and high-band modes are 14.9/18.4%, 20.2%, and 16.0%, respectively, with low-band and high-band center frequencies of 5 and 6.9 GHz, as shown in Fig. 7(a) and (b). The respective phase noises are –119.1/–118.5, –119.3, and –120.1 dBc/Hz at 1-MHz offset [Fig. 7(c)]. Table I shows a comparison of the different types of state-of-the-art concurrent and dual-band operating VCO devices. The proposed topology shows an 8-dB phase noise enhancement compared with the conventional transformer-based capacitive feedback scheme fabricated with the same process.

TABLE I
PERFORMANCE COMPARISON OF CONCURRENT VCOs

	This Work			[4]	[5]
	Low / High	**Concurrent**	Concurrent	Concurrent	Concurrent
Process	0.28-μm SOI CMOS			0.18-μm BiCMOS	65-nm CMOS
Topology	Gate feedback on Non-uniformly Wound Transformer		Transformer-based Capacitive feedback (Conventional)	Capacitive Coupled	4th Order Tank with Cross-coupled Capacitors
Center Freq. (GHz)	5 / 6.9	5 / 6.8	5 / 6.79	4 / 6	5.15 / 9.28
Tuning Range (%)	20.2 / 16	14.9 / 18.4	12.4 / 15.4	N.A.	34.7 / 22.8
Phase Noise (dBc/Hz)	-119.1 / -118.5 @ 1 MHz	-119.3 / -120.1 @ 1 MHz	-112.1 / -113.7 @ 1 MHz	-112 / -121.8 @ 1 MHz	-129.94 / -127.68 @ 10 MHz
P_{DC} (mW)	7.8 / 14.8	21.8	21	2.3	1.92
FOM*	-182.7 / -184.8	-184.4 / -185.1	-175.9 / -180.1	-180.4 / -193.7	-184 / -187
Size (mm²)	0.5 × 0.75		0.5 × 0.76	1.178 × 0.583	0.4 × 0.575

* $FOM = L(\Delta f) - 20\log_{10}(f_0/\Delta f) + 10\log_{10}(P_{DC}/1mW)$

IV. Conclusion

In this letter, a concurrent dual-band VCO has been developed for oscillating at 5 and 7 GHz, in both concurrent and independent operating modes, with low phase noise. To implement concurrent as well as single-tone operation with an enhanced loaded quality factor, a novel nonuniformly wound transformer with gate feedback was proposed. The analysis was performed based on an equivalent circuit model and bias control to show the principle of the concurrent and single-tone operation. The proposed VCO was fabricated in a SOI CMOS process, the measurements demonstrating an 8-dB phase noise enhancement compared with the conventional scheme employing the same process. Using the proposed transformer, to the authors' knowledge, this is the first concurrent dual-band VCO achieving a figure of merit (FOM) below –182.7 dBc/Hz for both concurrent and single-tone operation modes.

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