A Feedback Class-C VCO with Robust Startup Condition over PVT Variations and Enhanced Oscillation Swing

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Abstract— This paper presents a feedback class-C VCO with PVT-robustness and enhanced oscillation swing. The proposed VCO starts oscillation as a differential LC-VCO for robust startup, and automatically adapts to an amplitude-enhanced class-C VCO in steady-state for lower phase noise. The proposed VCO is implemented in a 0.18-μm CMOS process. The measured phase noise at room temperature is -125 dBc/Hz @ 1MHz offset with a power dissipation of 3.4mW, from a carrier frequency of 4.84GHz. The figure-of-merit is -193 dBc/Hz.

I. INTRODUCTION

The phase noise of voltage-controlled oscillators (VCOs) determines the performances in both wireline and wireless communication systems. Techniques for improving the phase noise characteristics of full integrated VCOs have attracted a large scale of attentions from both industry and academy. Recently, many high spectral purity, low power consumption, full integration VCOs have been reported. For example, an amplitude-redistribution technique [1] with relatively small drain voltage is developed to achieve low phase noise performance; a transformer-feedback VCO reported in [2] demonstrated low phase noise characteristics at a supply voltage below the threshold voltage. Among these reported literatures, the differential cross-coupled LC-tank VCO topology is widely used due to its property to reduce $1/f$ noise.

For further improvement of the phase noise characteristic, another oscillator architecture, which refers to class-C harmonic VCO, is proposed in [3] [4]. This topology utilizes the merits resulting from biasing the cross-coupled transistors in a class-C condition. Then a more efficient generation of oscillation currents can be obtained under a class-C operation. Consequently, for a predetermined power budget, the phase noise performance of class-C harmonic VCO achieves a significant improvement compared with standard differential-pair LC VCOs. In this paper, a feedback class-C VCO is proposed to guarantee the robust start-up condition over process, voltage and temperature (PVT) variations, and maximize achievable oscillation swing, simultaneously, which solves the trade-off between startup condition and oscillation amplitude in conventional class-C VCO. Thus, the improvement of phase noise can be obtained in the proposed feedback class-C VCO.

This paper is organized as follows: In section II, issues of present class-C VCO will be investigated in detail and the topology of proposed feedback class-C VCO will be discussed. The following section describes experimental results of proposed VCO. Finally, conclusion is summarized in section IV.

II. ANALYSIS AND DESIGN OF VCO ARCHITECTURE

A. Issues of present class-C VCO

As it is known, the phase noise of class-C VCO can be improved by increasing oscillation swing A_t. Unfortunately, according to the operation condition of class-C VCO, the oscillation amplitude is limited by the following equation.

$$A_t < \frac{V_{DD} - V_{gbias} + V_{th}}{2} \quad (1)$$

where V_{DD} is the supply voltage, V_{gbias} is the bias voltage of differential NMOS transistors, V_{th} is the threshold voltage.

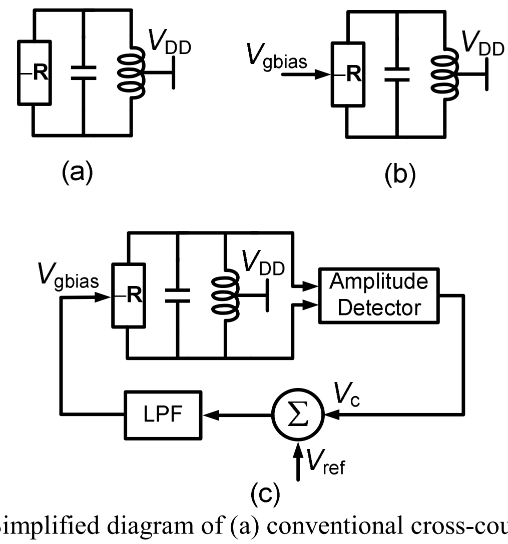

Fig.1. Simplified diagram of (a) conventional cross-coupled LC-VCO (b) conventional class-C VCO, and (c) proposed feedback class-C VCO.

For example, on the assumption that V_{gbias} is set to approximately close to V_{th}, theoretically, the maximum achievable oscillation swing is only half of supply voltage, which is quite a pessimistic estimation for oscillation amplitude.

To improve the oscillation swing of class-C VCO, the authors in [4] also pointed out that V_{gbias} can be set slightly lower than V_{th}, if the sub-threshold transcondutance of cross-coupled transistors is large enough to satisfy the startup condition. However, in sub-threshold region, transistors are extremely sensitive to PVT variations caused by exponential property of CMOS devices. For lower V_{gbias}, conventional class-C VCOs may fail to oscillate due to the violation of startup condition, which is a problem for practical application. To guarantee robust startup to PVT variations, V_{gbias} cannot be reduced lower than V_{th} under the worst case, resulting in limited oscillation amplitude as discussed previously.

To overcome the startup issue under low supply voltage, the authors in [5] proposed a class-C VCO with dual conduction. One extra conduction branch is added for the robustness of startup. However, this dual-conduction class-C VCO is optimized for a low supply voltage such as 0.2V, and is not preferable for a nominal supply voltage (*e.g.* 1.2V) in mainstream commercial processes.

B. Proposed VCO using amplitude feedback

Fig. 1 (c) shows the simplified diagram of proposed feedback VCO derived from a conventional class-C VCO (see Fig. 1(b)). Fig.2 shows the detailed schematic of proposed VCO with negative feedback mechanism.

There are three stages in the feedback loop. The first stage, which serves as a negative amplitude detector, consists of two NMOSs (M1, M2) and capacitors. The second stage is a voltage follower formed by an operational amplifier (OA1). The purpose of OA1 is to provide a necessary isolation between V_{ref} and RC charging circuit in the stage 1. The final stage is a voltage summing circuit, that is:

$$V_{gbias} = V_{ref} + V_{c.} \quad (2)$$

At the initial state, the gate and drain voltage of M1 and M2 in the first stage is initially at V_{DD}. Thus, M1 and M2 are both turned on, V_{gbias} (=V_{ref} + V_c) is high enough to ensure the startup condition. Consequently, the proposed VCO will start oscillation such as the conventional differential LC VCO with robust startup. As the VCO starts to oscillate, the amplitude detector in the feedback loop detects the negative envelope of VCO, and then the output V_c becomes slightly higher than the negative envelope of VCO. As a result, V_{gbias} also becomes lower along with the commencement of oscillation. Here, with the properly selection of V_{ref}, the proposed VCO can steadily operate at class-C condition. Therefore, the proposed feedback class-C VCO solves the robust startup issue over PVT variation.

The second significance of the proposed VCO is amplitude enlargement. With the robust startup provided by the feedback mechanism, the VCO could start and maintain oscillation with large amplitude. Once stable oscillation has been built up, note that the voltage across tail capacitor increases rapidly due to the rectifying action of tail capacitor itself, V_{gbias} can automatically become even lower with sustainable class-C operation, which, in turns, increases the oscillation swing, thereby improving phase noise.

To validate the effectiveness of proposed feedback method, a transient simulation was conducted. As illustrated in Fig.3, the VCO starts to oscillate as a standard differential LC-tank VCO with robust startup condition. At this moment, the

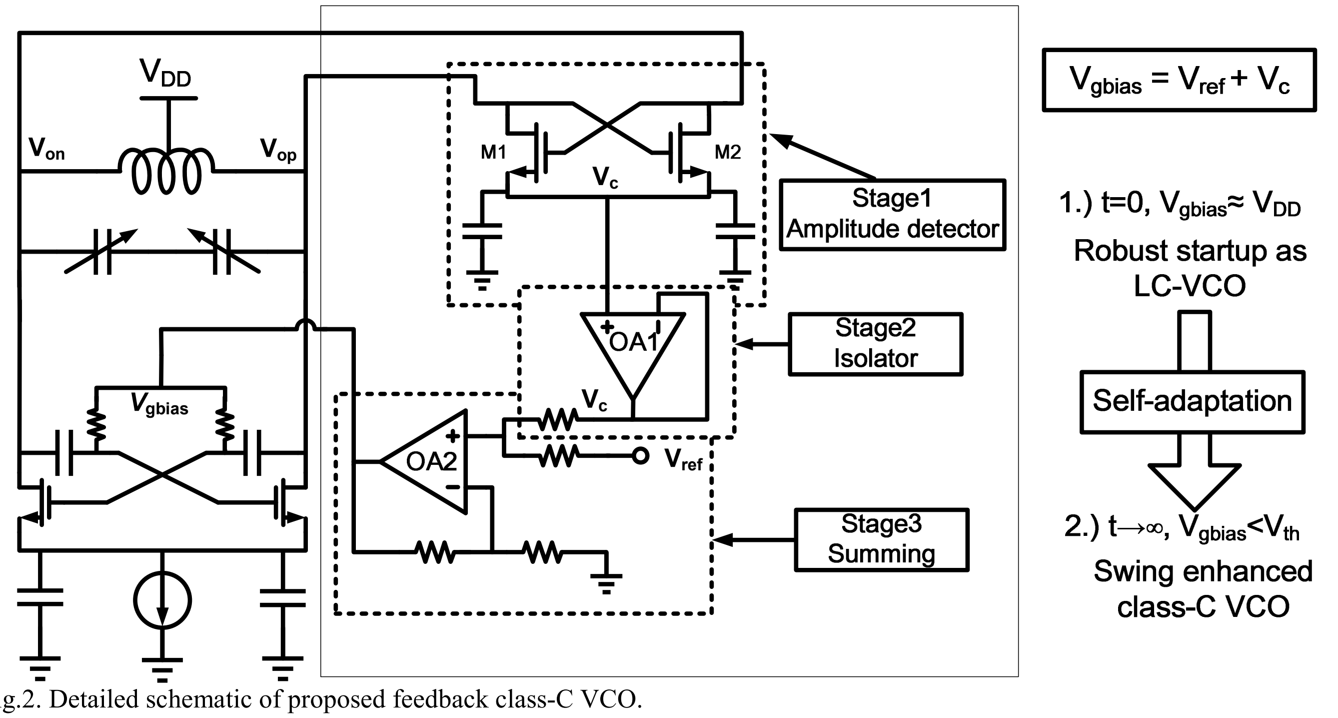

Fig.2. Detailed schematic of proposed feedback class-C VCO.

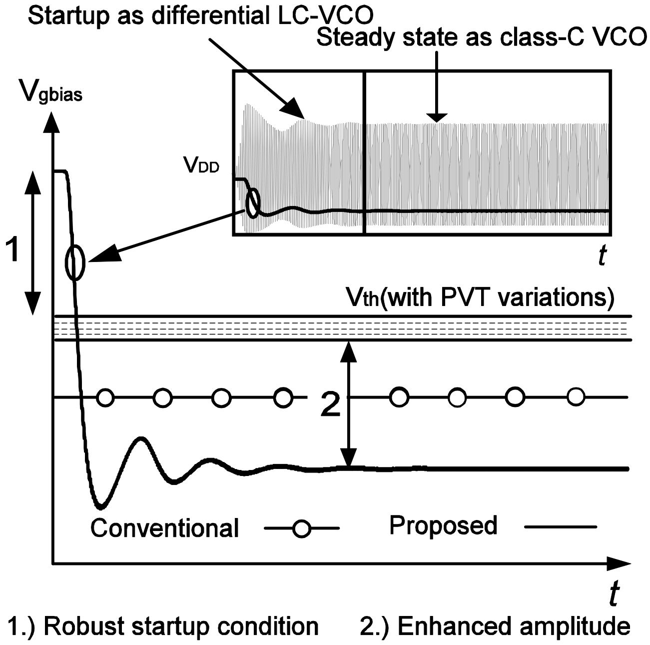

Fig.3. Graphical analysis and comparison of gate bias voltage in the conventional and proposed class-C VCOs.

value of V_{gbias} is large enough to meet the requirement for startup condition. In the steady state, the VCO performs as a standard class-C VCO with improved oscillation amplitude. Here the value of V_{gbias} is lower than the threshold voltage of cross-coupled differential NMOSs. To sum up, the transient simulation results are perfectly in agreement with theoretical analysis.

Note that conduction angle $2\phi_n$ is defined as $\cos(\phi_n)=(-V_{gbias}+V_{th})/A_t$. Fig. 4 shows current waveforms of conventional class-C with conduction angle $2\phi_0$ and the proposed feedback class-C VCO in the initial state with conduction angle $2\phi_1$, and in the steady-state with conduction angle $2\phi_2$, respectively. Initially, ϕ_1 is 0.5π for robust startup condition. In the steady state, ϕ_2 is 0.3π for oscillation swing enhanced class-C operation with lower phase noise.

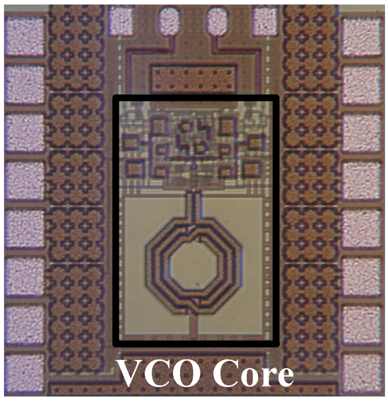

Fig.5. Chip microphoto.

The negative feedback loop in the proposed feedback class-C VCO is conditionally stable with an easy stability condition to meet. A reference voltage V_{ref} mainly provides extra offset to make the settled V_{gbias} large enough (less than V_{th} but could maintain the sustainable oscillation under all operation condition). As a consequence, with properly selection of V_{ref}, the steady-state operation can be obtained in the proposed feedback class-C VCO.

III. Measurement results of proposed class-C VCO

Fig.5 shows the microphotograph of the proposed VCO fabricated in a 0.18μm CMOS process. The core chip area is 490μm×300μm. A conventional class-C VCO with identical parameters and layout, but with no feedback mechanism, is also fabricated as a reference on the same die. As illustrated in Fig.6, the proposed (conventional) VCO achieves -125 (-122) dBc/Hz phase noise at 1-MHz offset from a 4.84GHz carrier, with a total power dissipation of 3.4mW including 2 OAs (3.5mW for V_{gbias}=0.65V) from a 1.2-V power supply. The corresponding FOM is -193 (-190 for V_{gbias}=0.65V) dBc/Hz. Fig.7 shows the measured phase noise over temperature variation [−20°C, 100°C] for the conventional VCO at various V_{gbias}, and the proposed VCO. The phase noise of conventional VCO decreases significantly or even fails to oscillate due to the degradation of transcondutance along with the increasing of temperature. On the other hand, the proposed feedback

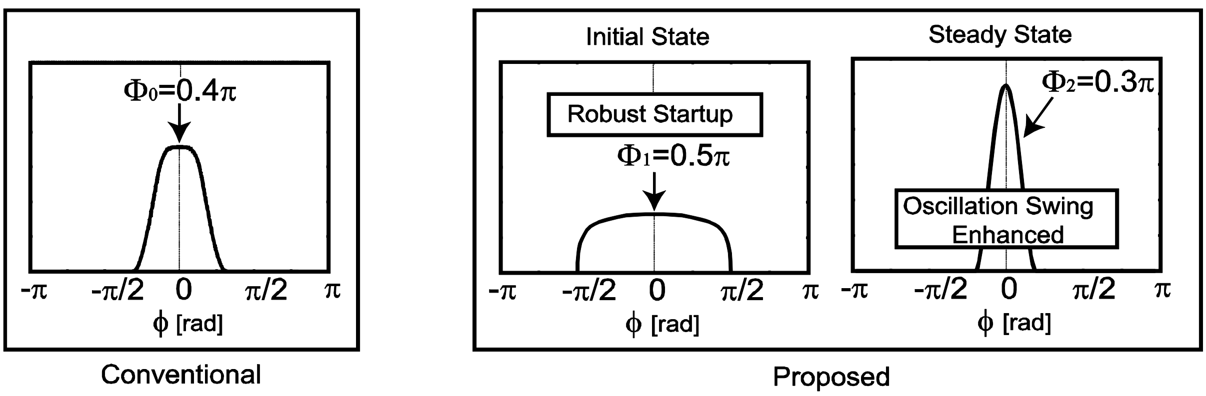

Fig.4. MOS current waveform of conventional class-C VCOs (left), proposed feedback class-C VCO at initial state (middle), and at steady state (right).

class-C VCO demonstrates robust characteristic over temperature variations. The measured frequency tuning range is 2.1%.

Figure-of-merit (*FOM*), which allows fair comparison between other oscillators in terms of different frequencies and

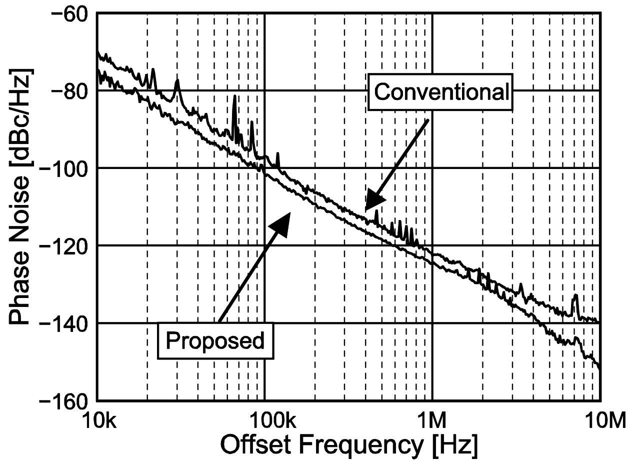

Fig.6. Measured phase noise characteristic: conventional class-C VCO (upper), and proposed VCO (lower) @ 4.84-GHz.

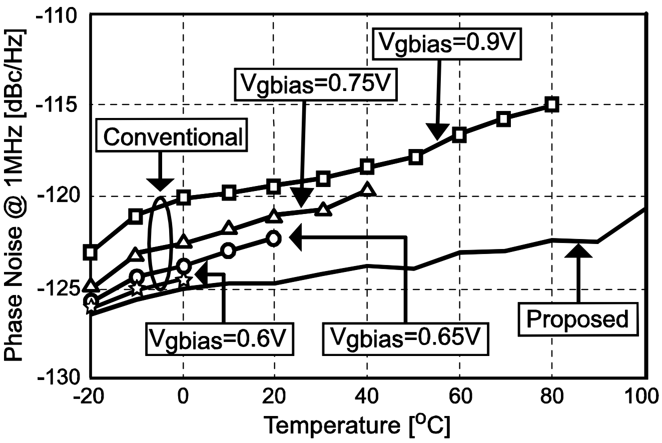

Fig.7. Measured phase noise characteristic over temperature for the proposed and conventional class-C VCOs at different V_{gbias}.

power dissipations, is utilized in [7]:

$$FOM = \mathcal{L}(f_{\text{offset}}) - 20\log\left(\frac{f_0}{f_{\text{offset}}}\right) + 10\log\left(\frac{P_{\text{dc}}}{1\text{mW}}\right). \quad (3)$$

where $\mathcal{L}(f_{\text{offset}})$ is phase noise performance at oscillation carrier, f_{offset} is offset frequency from oscillation carrier, f_0 is center frequency and P_{dc} is power consumption. Table I summarizes the comparison with other published LC-VCOs.

IV. Conclusion

This paper proposes a feedback class-C VCO with PVT-robustness and enhanced oscillation swing. With carful design, the proposed feedback class-C VCO can be suited for the PVT- robust PLLs in wireline and wireless systems.

Acknowledgment

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TABLE I Performance comparison between the-state-of-the-art VCOs.

	CMOS Process	Topology	Freq./Offset Freq. [GHz/MHz]	Phase Noise [dBc/Hz]	P_{dc} [mW]	FOM [dBc/Hz]
[1]	0.13μm	LC	28/1	-119	1.6	-191
[2]	0.18μm	Transformer	3.8/1	-119	0.57	-193
[3]	0.13μm	class-C[single]	4.9/3	-130	1.3	-196
[5]	0.18μm	class-C[dual]	4.5/1	-109	0.16	-190
[6]	0.18μm	Colpitts	1.86/1	-128	1.6	-191
Conventional	0.18μm	class-C[single]	4.84/1	-122	3.5	-190
Proposed		class-C[**feedback**]	4.84/1	-125	3.4	-193