Low Phase Noise G_m-Boosted Differential Colpitts VCO with Suppressed AM-to-FM Conversion

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Abstract — **A g_m-boosted differential Colpitts VCO is proposed, which allows lower oscillation start-up current and suppressed AM-to-FM conversion by the switching transistors. The proposed architecture allows wider range of saturation mode operation for the switching transistors which helps to suppress the AM-to-FM conversion. The proposed VCO is implemented in 0.18-µm CMOS for 1.75~1.93 GHz operation. Measurement shows, at 1.84 GHz, the phase noise of -105 and -128 dBc/Hz (FOM = 191.2) at 100-KHz and 1-MHz offset, respectively, while dissipating 1.8 mA from 0.9-V supply.**

I. INTRODUCTION

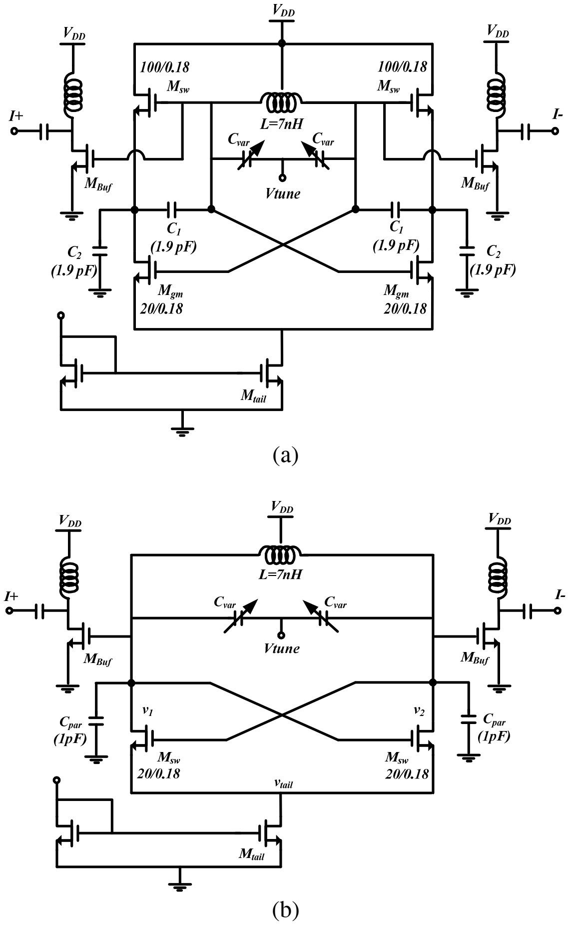
Only a few decades ago, despite a superior phase noise property, single-ended Colpitts VCOs are rarely used due to their non-differential output and poor start-up characteristic which requires higher power dissipation. Lately, several differential Colpitts structures have been reported which overcome those disadvantages through the g_m-boosting techniques [1]-[4].

In the current limited operation of a conventional cross-coupled *LC*-VCO, when the switching transistors enter into the triode region, the low offset frequency ($1/f^3$ region) phase noise degradation through the AM-to-FM conversion is mainly caused by the effective capacitance variation of the switching transistors with voltage swing [5]. In addition, as the transistor enters triode mode, the slope of phase noise in the $1/f^2$ region increases due to the average Q-factor degradation of the LC resonance circuit [6], [7]. Therefore, many techniques that make the switching transistors not to enter triode mode even at large output oscillation amplitude have been reported [5]-[9].

This paper reports a g_m-boosted differential Colpitts VCO that improves start-up condition and allows wider range of saturation mode operation for the switching transistors.

II. G_m-BOOSTED DIFFERENTIAL COLPITTS VCO DESIGN

Fig. 1 shows the schematics of the proposed g_m-boosted differential Colpitts and the conventional crossed- coupled *LC*-VCO including output buffer. In the proposed Colpitts VCO, shown in Fig. 1(a), the transistor M_{tail} is the current source and M_{gm} is the g_m-boosting transistors. In Fig. 1(a), the differential operation is obtained by adopting the current source M_{tail}, and g_m-boosting is achieved by connecting the gates of M_{gm} to the gates of the opposite



(a)

(b)

Fig. 1. Schematic of (a) proposed g_m-boosted differential Colpitts and (b) a conventional cross-coupled *LC*-VCO including output buffer

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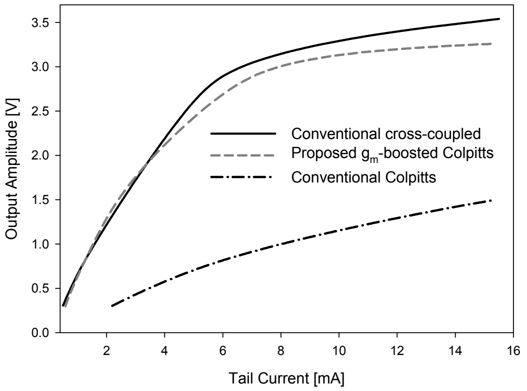


Fig. 2. Simulated output oscillation amplitude versus tail bias current at 1.8-V supply

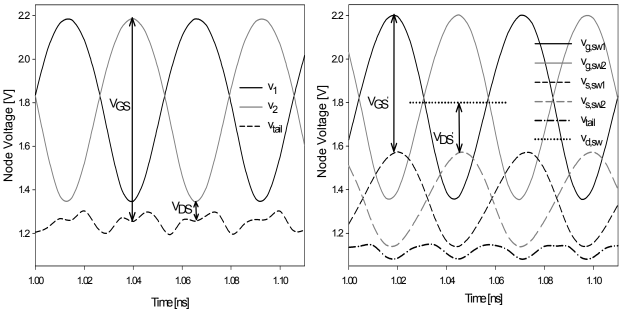
switching transistors M_{sw} for the positive feedback generation. In Fig. 1(a), instead of source, the gate terminal of M_{sw} is selected for the feedback path allowing lower supply voltage operation. The g_m-boosting transistors M_{gm} enhance the overall small signal loop gain of the proposed Colpitts VCO, increasing the negative conductance and reducing the start-up current. The negative small-signal conductance of the g_m-boosted Colpitts VCO shown in Fig. 1(a) is given by

$$\mathrm{Re}[Y_{IN}] = -\frac{g_{m1}\omega^2 C_1 C_2 + 0.5 g_{m3}\omega^2 C_1 (C_1 + C_2)}{g_{m1}{}^2 + \omega^2 (C_1 + C_2)^2} \qquad (1)$$

From equation (1), the negative conductance of the proposed Colpitts VCO increases by $1+0.5(g_{m3}/g_{m1})(1+C_1/C_2)$ compared to that of the conventional Colpitts VCO. Fig. 2 shows the simulated output (single) oscillation amplitude of the conventional differential Colpitts, the g_m-boosted differential Colpitts [Fig. 1(a)], and the cross-coupled *LC*-VCO [Fig. 1(b)], under the same set-up which will be explained later. As can be seen from Fig. 2, the oscillation start-up current of the proposed Colpitts VCO is far less than that of the conventional Colpitts VCO, and close to the conventional cross-coupled VCO.

III. G_m-Boosted Colpitts VCO with Wide Range of Saturation Mode Operation

In the conventional cross-coupled VCO, the variation of the tail current gives rise to the change in voltage swing which leads to increase in the phase noise by the AM-to-FM conversion mechanism. The $1/f^3$ phase Noise is mostly upconverted from the flicker noise of the tail current transistor by this AM-to-FM conversion. In the conventional VCO, the AM-to-FM conversion results from the effective capacitance variation of varactors and switching transistors with output voltage swing change [5], [10]. This mechanism appears only in the current limited regime, but not in the voltage limited regime. During the current limited operation, if the switching transistors do not enter the triode region, the AM-to-FM conversion by the varactors is the dominant mechanism of the phase noise degradation in the $1/f^3$ region. To minimize this effect, the VCOs are designed with small VCO gain K_{VCO} and large amplitude at the same bias current [10]. Whereas, as the switching transistors start to enter deep triode mode operation, the AM-to-FM conversion by the switching transistors becomes a significant contribution for the phase noise degradation. Therefore, the switching transistor effect can be avoided by prohibiting the triode mode operation even at large output oscillation amplitude [5], [9].



(a) (b)

Fig. 3. Simulated node voltage behaviors of the VCOs (a) conventional cross-coupled (b) g_m-boosted differential Colpitts.

From the equation for the MOSFET operation within its saturation mode, V_{GS}-$V_{TH} \leq V_{DS}$, to achieve wide range of the saturation mode operation in the VCO, the gate-source voltage V_{GS} or the drain-source voltage V_{DS} are kept small at high output oscillation amplitude. Fig. 3 shows the node voltage waveforms of the two VCOs shown in Fig. 1 at 1.3 mA tail current. As can be seen in Fig. 3(b), in the proposed Colpitts VCO, the dynamic voltage swing at the gate of M_{sw} divides between C_1 and C_2 leading to smaller gate-source voltage V_{GS}' drop, while in the conventional *LC*-VCO shown in Fig. 3(a), the total dynamic output voltage swing drops across the gate-source terminal. Furthermore, the gate-drain voltage V_{DS}' of the switching transistors, at the peak gate-source voltage, is larger in the proposed Colpitts VCO than that of the conventional *LC*-VCO. Therefore, the switching transistors of the proposed Colpitts VCO operates longer period in saturation mode, while those of the conventional VCO operate into the

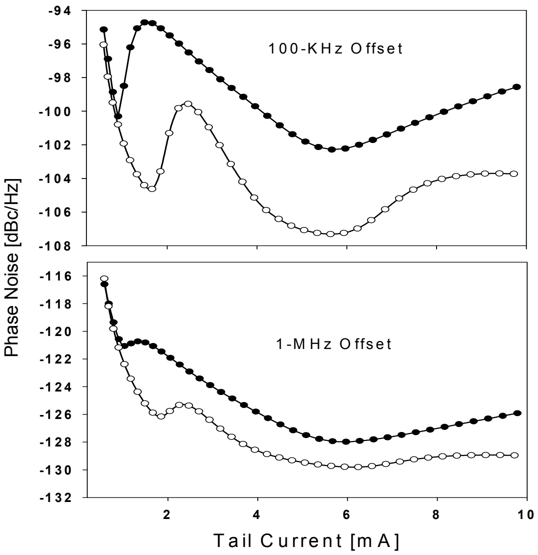


Fig. 4. Simulated phase noise versus tail current for the conventional cross-coupled (black filled-circle) and g_m-boosted differential Colpitts (white filled-circle) VCO

triode mode for the same large output oscillation amplitude.

The two VCOs shown in Fig. 1 are designed to oscillate from 1.78 to 1.98 GHz with 1.8-V supply using the same value of the varactors and center-tapped inductor. In the conventional VCO shown in Fig. 1(b), the size of the parallel capacitors C_{par} is chosen for the same frequency tuning range and K_{VCO} as the proposed VCO in Fig. 1(a). Fig. 4 shows the simulation result of the phase noise versus tail bias current for the two VCOs at 100-kHz and 1-MHz offset frequency. The simulations are done at the center frequency of 1.88-GHz where the effect of the AM-to-FM conversion by the varactors is negligible. It can be seen in Fig. 4 that the AM-to-FM conversion by the switching transistors is the major source of the phase noise degradation at the triode mode region in the conventional cross-coupled *LC*-VCO while the proposed Colpitts VCO is more robust to the same effect. The range of the saturation mode operation in the proposed Colpitts VCO is approximately twice wider than that of the conventional VCO, as shown in Fig. 4. As can be seen from Fig. 1(a), in the proposed Colpitts VCO, the amount of the switching transistors AM-to-FM conversion effect can be controlled by adjusting the size ratio of C_1 and C_2. The phase noise of the proposed Colpitts VCO improves 5 dB at the maximum saturation mode, and shows better performance overall tail current range, compared to the conventional VCO.

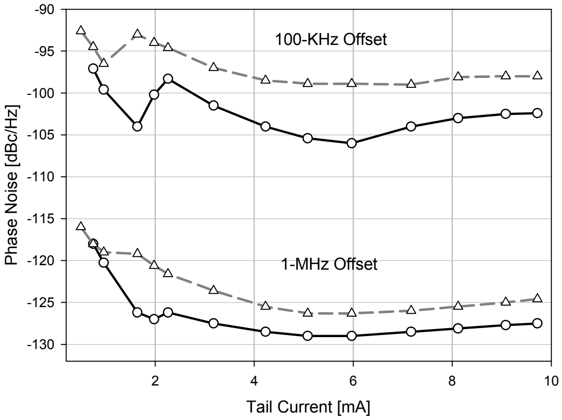


Fig. 5. Measured phase noise versus tail current of the proposed (circle) and conventional VCO (triangle) at 1.84 GHz with 1.8-V supply

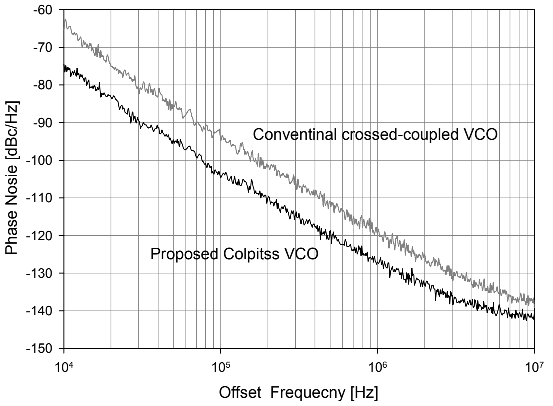
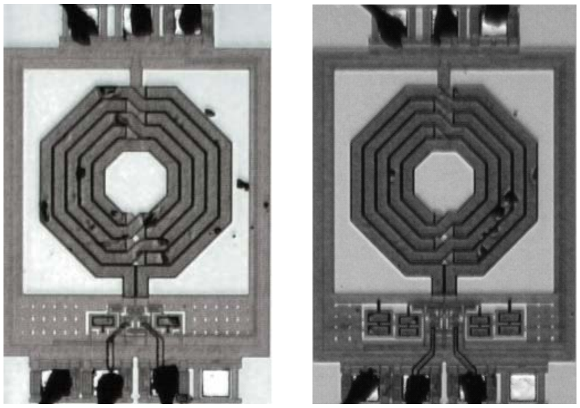


Fig. 6. Measured phase noise of two VCOs at 1.84 GHz, drawing of 1.8 mA from 0.9-V supply.

In the proposed Colpitts VCO, the influence of the capacitance variation in M_{gm} is insignificant to the total LC-tank capacitance, since the g_m-boosting transistor M_{gm} initially operate in the deep triode region where the effective capacitance of M_{gm} is less variable. Therefore, the variation of the effective capacitance in M_{sw} is the dominant source for the AM-to-FM conversion by the transistors in the proposed VCO.

IV. MEASUREMENT RESULTS

The proposed g_m-boosted differential Colpitts and conventional cross-coupled *LC*-VCO shown in Fig. 1 are implemented in a 0.18-μm CMOS technology to operate from 1.75 to 1.93 GHz. Fig. 5 shows the measured phase noise (100-kHz and 1-MHz offset) with 1.8-V supply as a function of the tail bias current at the center frequency of



(a) (b)

Fig. 7. Fabricated chip photograph of (a) the conventional cross-coupled differential VCO and (b) proposed g_m-boosted Colpitts VCO

1.84 GHz where the contribution of the varactor AM-to-FM conversion is negligible. It can be seen that the overall phase noise behavior shown in Fig. 5 is in good agreement with simulation results shown in Fig. 4.

Fig. 6 shows the measured phase noise of the two VCOs at 1.84 GHz while drawing 1.8 mA from 0.9-V supply. The measured phase noise of the proposed g_m-boosted differential Colpitts VCO are -105 and -128 dBc/Hz at 100-kHz and 1-MHz offset frequency, respectively, which correspond to the figure-of-merit (FOM) of 191.2 dBc/Hz at 1-MHz offset. Fig. 7 shows the fabricated chip photograph of the two VCOs with size of 800×680 μm^2 each excluding the pads.

V. CONCLUSION

This work reports a g_m-boosted differential Colpitts VCO architecture which reduces start-up bias current compare to the conventional Colpitts oscillator. Due to the structural advantage of the proposed Colpitts oscillator, the switching transistor operation into the triode mode is delayed with increase in output voltage swing, which helps to suppress the phase noise degradation by the AM-to-FM conversion. The performance advantage of the proposed g_m-boosted differential Colpitts VCO is demonstrated by simulations and measurements in comparison with the conventional Colpitts and the conventional cross-coupled *LC*-VCO. The proposed g_m-boosted differential Colpitts VCO, which is implemented in 0.18-µm CMOS for 1.75~1.93 GHz operation, shows the phase noise of -105 and -128 dBc/Hz (corresponds to FOM of 191.2) at 100- kHz and 1-MHz, respectively, at 1.84 GHz while dissipating 1.8 mA from 0.9-V supply.

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