A Current-Switching and g_m-Enhanced Colpitts Quadrature VCO

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***Abstract*—This letter presents the design and analysis for a low-phase-noise and low-power Colpitts quadrature voltage-controlled oscillator (QVCO). The Colpitts QVCO employs current switching to lower the phase noise, g_m enhancement to improve the startup condition in the oscillator core, and device reuse to realize anti-phase injection locking for QVCO operation. The proposed Colpitts QVCO has superior phase noise than cross-coupled LC tank VCO and outperforms conventional QVCO in phase noise, quadrature phase accuracy, and tuning range. The fabricated 0.18 μm CMOS Colpitts QVCO draws 500 μA from a 1.5 V power supply and exhibits a phase noise of -118 dBc/Hz at 1 MHz offset and a quadrature phase error of 0.3° at the center frequency of 488 MHz.**

***Index Terms*—Colpitts VCO, low power, QVCO.**

I. Introduction

It is critical to offer quadrature signal generation with accurate quadrature phase and low phase noise at minimal power consumption for integrated communication systems in portable, wearable, or implantable devices. The most power-efficient approach is the quadrature voltage-controlled oscillator (QVCO) which couples two identical oscillators operating with 90° phase shift to provide quadrature outputs. To guarantee the quadrature phase accuracy, it is essential to keep the in-phase and quadrature-phase branches symmetrical as well as coupled with sufficient strength. However, the coupling devices used to realize anti-phase injection locking induce excess phase noise and consume extra power. The conventional QVCOs have several well-known limitations arising from the trade-off between quadrature phase accuracy, phase noise, tuning range, startup reliability, and coupling efficiency [1]–[3].

Since the oscillator core of QVCO plays an important role in low-phase-noise and low-power design, it should be carefully chosen among different configurations. The cross-coupled LC VCO has attracted much interest due to its easy implementation and reliable startup. However, the thermal and flicker noise perturbs the oscillator outputs at their zero-crossings and degrades the VCO phase noise. In contrast, a differential Colpitts oscillator with current-switching scheme alleviates the noise perturbation at the VCO output and features superior phase noise than the cross-coupled VCO [4], [5]. The current-switching technique exhibits better noise performance and higher power efficiency, however at the expense of increased voltage headroom and more stringent startup requirement. A g_m-enhancing technique combined with the tuned-input tuned-output (TITO) oscillator had been introduced to relieve start-up issues in Colpitts oscillator [6]. However, two LC tanks are required and separated frequency tuning is necessary for TITO oscillators, which require larger area at low-RF frequency and sensitive to tank mistuning.

In this letter, a fully-integrated Colpitts QVCO with current switching and g_m enhancement is presented that features low phase noise and low power consumption. It exhibits superior phase noise inherited from the Colpitts VCO topology, and low power dissipation enabled by the proposed current-switching technique which relaxes required startup condition significantly. The injection coupling devices for the QVCO configuration are reused from the Colpitts oscillator core without extra coupling devices needed. The design trade-off between phase noise and quadrature phase accuracy is consequently eliminated. The design prototype, implemented in 0.18 μm CMOS process, demonstrates sub-mW Colpitts QVCO for ISM band transceivers for biomedical applications [7].

II. Current-Switching and g_m-Enhanced Differential Colpitts VCO

Fig. 1 proposes a power-efficient Colpitts VCO scheme with g_m enhancement. In Fig. 1, the in-phase relationship between the source and drain voltages of M_{C1} and M_{C2} via the capacitive feedback implies an improved topology with higher coupling efficiency. Unlike the conventional differential Colpitts oscillator with current switching [4], the gates of M_{N1} and M_{N2} are directly coupled to VCO output, i.e., the drain nodes of M_{C1} and M_{C2}, instead of the source nodes. The cross-coupled pair reuses the current from the oscillator core while enhancing the small-signal loop gain and improving the startup condition. The enhanced loop gain can be simply expressed as the inverse of the capacitive divider factor

$$\frac{1}{n} = \frac{(C_A + C_B)}{C_A}. \tag{1}$$

Thus, the benefit is faster switching of M_{N1} and M_{N2} to improve the phase noise characteristics. In addition, directly connecting the gates of M_{N1} and M_{N2} to the VCO output relaxes the voltage headroom requirement and enhances the compliance to low Voltage design.

A. Analysis of Startup Requirement

For the reliable startup of the differential Colpitts oscillator, the loss in the LC tank needs to be compensated. In other words, the negative impedance from the positive feedback should be larger than R_P which is the equivalent parallel resistance at resonant frequency. In the Colpitts oscillator, the capacitive divider consisting of C_A and C_B forms a positive feedback with the transistor M_C. The current-switching cross-coupled pair is added under the Colpitts oscillator core to provide

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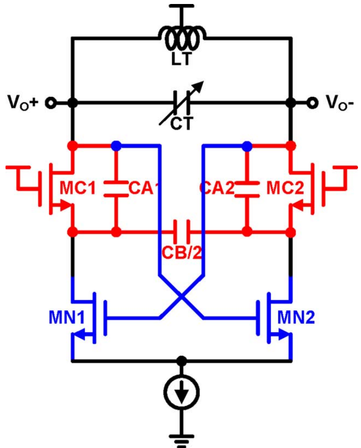

Fig. 1. Proposed g_m-enhanced differential Colpitts oscillator.

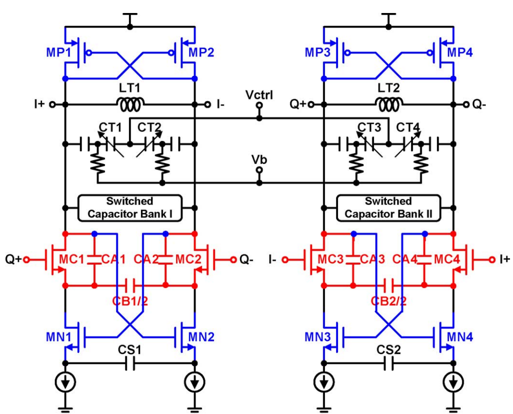

Fig. 2. Proposed Colpitts QVCO.

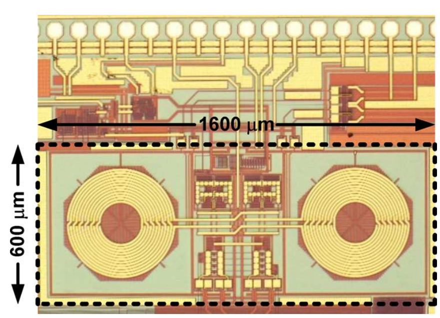

Fig. 3. Chip micrograph.

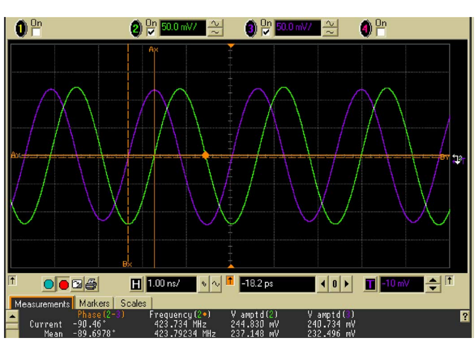

Fig. 4. Measured in-phase and quadrature-phase output waveforms of the Colpitts QVCO.

noise shaping and g_m enhancement. The oscillation frequency, startup condition are derived from the equivalent small-signal circuit model for the differential Colpitts oscillator excluding the inductors and varactors. The equivalent impedance looking into the drains of the Colpitts oscillator core contains a negative real part, which can be expressed as

$$\mathrm{Re}[Z] = -\frac{g_{mc} + g_{mn}\left(\frac{C_A}{C_B} + 1 + \frac{g_{mc}^2}{\omega^2 C_A C_B}\right)}{\omega^2 C_A C_B + g_{mn}^2\left(\frac{C_A}{C_B} + \frac{2g_{mc}}{g_{mn}} + \frac{g_{mc}^2}{\omega^2 C_A C_B}\right)} \quad (2)$$

where g_{mc} and g_{mn} are the transconductance of $\mathrm{M_C}$ and $\mathrm{M_N}$.

According to the oscillation criteria, the necessary condition for the oscillation to start is that the total resistance in the equivalent LC tank is negative and purely real at oscillation frequency, ω. The oscillation frequency is expressed as (3) by assuming $g_{mc}L_T$ and $g_{mn}L_T$ are much smaller than $R_P(C_A + C_B)$

$$\omega = 1/\sqrt{L_T\left(C_T + \frac{C_A C_B}{(C_A + C_B)}\right)} \quad (3)$$

where L_T and C_T are the inductance and capacitance of the LC tank. Substituting (3) into (2), the minimum transconductance to compensate the loss from the LC tank can be obtained. Hence, the design equations for g_{mc} and g_{mn} result in

$$g_{mc}R_P \geq \frac{(C_A + C_B)^2 - g_{mn}R_P C_A (C_A + C_B)}{C_A C_B}. \quad (4)$$

The minimum required values for g_{mc} are derived as

$$(g_{mc} + g_{mn})\,R_P \geq 2 + 2\sqrt{1 - g_{mn}R_P} \quad (5)$$

and the minimum occurs when

$$C_A = \frac{C_B}{\sqrt{1 - g_{mn}R_P}}. \quad (6)$$

From the previous small-signal analysis, (5) reveals the proposed current switching technique plays two important roles at the same time: g_{mn} relaxes the startup requirement and makes contribution to the overall g_m, which is distinguished from the conventional design. Without the contribution of g_{mn}, (5) can be simplified as (7) when C_A is equal to C_B

$$g_{mc}R_P \geq 4 \quad (7)$$

which is the well-known startup expression for the Colpitts oscillator. Moreover, if $g_{mn}R_P$ is close to 1, and g_{mn} is equal to g_{mc}, (5) can be simplified as

$$g_{mc}R_P \geq 1 \quad (8)$$

which is the same startup condition as the cross-coupled LC-tank oscillator. With the optimized design parameters provided above, the proposed differential Colpitts VCO can

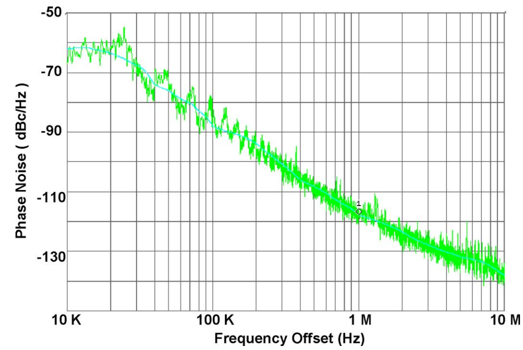

Fig. 5. Measured phase noise of the Colpitts QVCO at 488 MHz.

TABLE I
QVCO PERFORMANCE SUMMARY AND COMPARISON

	This Work	[10]	[11]	[12]
CMOS process	0.18 μm	0.5 μm	0.18 μm	0.13 μm
F_{VCO} (MHz)	488	433	403	403
Phase noise @ freq. offset (dBc/Hz)	-118 @ 1M	-100 @ 600k	-98 @ 160k	-127 @ 1M
Tuning range (%)	20	19	27.5	1.5
I/Q phase error	0.3°	NA	NA	0.5°
Supply Voltage (V)	1.5	3.3	1.5	1
DC Power (mW)	0.75	1.2	1.2	1
FOM*	173	156	165	179
FOMT**	179	162	174	163

$$*\mathrm{FOM} = 10 \cdot \log\left[(\omega_0/\Delta\omega)^2 \cdot 1/P_{diss/mW}\right] - L(\Delta\omega)$$

$$**\mathrm{FOMT} = 10 \cdot \log\left[(\omega_0/\Delta\omega)^2 \cdot (TR/10\%)^2 \cdot 1/P_{diss/mW}\right] - L(\Delta\omega)$$

achieve its maximum power efficiency which is as high as the cross-coupled LC VCO, making it very suitable for low-power and low voltage design.

III. CURRENT-SWITCHING AND g_m-ENHANCED COLPITTS QUADRATURE VCO

A novel Colpitts QVCO based on the proposed differential Colpitts VCO with current switching and g_m enhancement is presented in Fig. 2. The transistors $\mathrm{M_{C1-4}}$ in the Colpitts oscillator core are reused as the coupling devices without extra ones added. The gates of $\mathrm{M_{C1}}$ and $\mathrm{M_{C2}}$ in the I-phase VCO are connected to the output of the Q-phase VCO, and those of $\mathrm{M_{C3}}$ and $\mathrm{M_{C4}}$ are connected to the output of the I-phase VCO in an inverse fashion. The advantage of this coupling topology is that there is no additional coupling devices required like those in the conventional QVCOs connected in parallel [1] or in series [2], [3]. The additional coupling devices cause the trade-off between phase noise, I/Q phase accuracy, tuning range, and coupling efficiency. Moreover, they induce excess device noise and degrade phase noise performance. Although some back-gate-coupling approaches suggest that the coupling signals can be connected to the back gate of the switching transistors [8], the drawbacks are the requirement of triple-well process to provide isolated NMOS transistors and the limitation of output swing to prevent forward-biased PN junctions.

The proposed coupling scheme without any extra decoupling device doesn't suffer from the disadvantages mentioned above. It exhibits superior phase noise performance inherited from the Colpitts VCO topology and low power dissipation enabled by the proposed current switching scheme which is implemented with $\mathrm{M_{N1-4}}$ and relaxes the required startup condition significantly. The injection coupling devices for QVCO configuration are reused from the Colpitts oscillator core, so that the maximum coupling efficiency can be achieved without extra coupling devices needed. The design trade-off between phase noise and quadrature phase accuracy is consequently eliminated in this design. Benefiting from the relaxed voltage headroom of the proposed design, additional PMOS cross-coupled pairs (M_{P1-4}) can be added to implement the current-reuse complementary VCO configuration for further g_m enhancement and power consumption reduction. In addition, the tail current is split and coupled with $\mathrm{C_S}$ to reduce the up-converted flicker noise [9]. C_{T1-4} are chosen as accumulation-mode MOS varactors for monotonic tuning. Oscillator outputs are ac coupled to the varactors, and the common-mode voltage for varactors can be adjusted via a dc bias. This provides a linear control freedom for frequency fine tuning of QVCO. Furthermore, coarse frequency tuning is achieved by using digitally controllable capacitor banks at oscillator outputs.

IV. MEASUREMENT RESULTS

Fig. 3 shows the chip micrograph of the proposed Colpitts QVCO with a core area of $0.6 \times 1.6\ \mathrm{mm}^2$ fabricated in Global Foundries 0.18-μm CMOS process. Fig. 4 depicts the measured in-phase and quadrature-phase output waveforms of the Colpitts QVCO with the steady-state phase error of 0.3°. Fig. 5 presents the measured phase noise of $-118\ \mathrm{dBc/Hz}$ at 1 MHz offset. The QVCO has the tuning range from 420 MHz to 513 MHz, draws the 0.5 mA current from a 1.5 V power supply, and achieves the figure of merit with the tuning range of 179. The measured performance is summarized in Table I, along with the performance of other state-of-the-art LC VCO and QVCO designs for MICS and sub-GHz ISM band [10]–[12].

V. CONCLUSION

A new Colpitts QVCO design is presented for low power, low phase noise, high quadrature phase accuracy, and large tuning range. The enhancement of effective transconductance leads to easier startup and reduced power consumption. The quadrature outputs are obtained by coupling two differential Colpitts VCOs with current switching via Colpitts oscillator core without extra coupling devices required. When operating at 488 MHz, the measurement shows the phase noise of $-118\ \mathrm{dBc/Hz}$ @ 1 MHz offset, quadrature phase accuracy of 0.3°, and tuning range of 20%, while consuming only 0.75 mW.

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