

25.3 A VCO with Implicit Common-Mode Resonance

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CMOS VCO performance metrics have not improved significantly over the last decade. Indeed, the best VCO Figure of Merit (FOM) currently reported was published by Hegazi back in 2001 [1]. That topology, shown in Fig. 25.3.1(a), employs a second resonant tank at the source terminals of the differential pair that is tuned to twice the LO frequency (F_{LO}). The additional tank provides a high common-mode impedance at $2 \times F_{LO}$, which prevents the differential pair transistors from conducting in triode and thus prevents the degradation of the oscillator's quality factor (Q). As a consequence, the topology can achieve an oscillator noise factor (F) – defined as the ratio of the total oscillator noise to the noise contributed by the tank – of just below 2, which is equal to the fundamental limit of a cross-coupled LC CMOS oscillator [2]. There are, however, a few drawbacks of Hegazi's VCO: (1) the additional area required for the tail inductor, (2) the routing complexity demanded of the tail inductor, which can degrade its Q and limit its effectiveness, and (3) for oscillators with wide tuning ranges, the need to independently tune the second inductor, which again can degrade its Q. Moreover, it can be shown that the common-mode impedance of the main tank at $2 \times F_{LO}$ also has a significant effect on the oscillator's performance, which if not properly modeled can lead to disagreement between simulation and measurement, particularly in terms of the flicker noise corner. To mitigate these issues, this work introduces a new oscillator topology that resonates the common-mode of the circuit at $2 \times F_{LO}$, but does not require an additional inductor.

The proposed VCO is shown in Fig. 25.3.1(b). Whereas Hegazi's VCO makes use of an additional tank to realize a large common-mode impedance at $2 \times F_{LO}$, the proposed VCO tunes the common-mode resonant point of the primary tank to $2 \times F_{LO}$, which can be tuned independently of the differential resonant frequency. Typically the tank is composed of a differential spiral inductor with series inductance (L_S) and some positive coupling coefficient (k) and a combination of common-mode (C_{CM}) and differential (C_{DM}) capacitance. Therefore, the differential resonance (or oscillation frequency) is given by

$$F_{LO} = 1 / \left(2\pi \sqrt{L_S(1+k)(C_{CM} + C_{DM})} \right)$$

and the common-mode resonant frequency is given by:

$$F_{CM} = 1 / \left(2\pi \sqrt{L_S(1-k)C_{CM}} \right)$$

By selecting k, C_{CM} and C_{DM} such that $F_{CM} = 2 \times F_{LO}$, the common-mode of the circuit resonates at $2 \times F_{LO}$ without the need for an additional tank.

To gain insight into the performance of the proposed VCO, it is helpful to rewrite the expression for FOM in terms of oscillator efficiency (η) and oscillator noise factor (F):

$$FOM = \frac{\left(\frac{\omega}{\Delta\omega} \right)^2}{L\{\Delta\omega\}P_{DC[mW]}} = \frac{2\eta Q^2}{kTF} 10^{-3}$$

where $\eta = P_{TANK}/P_{DC}$, the total power consumption is P_{DC} , the power dissipated in the tank is $P_{TANK} = A^2/(2R_p)$, the oscillation amplitude is A, and the equivalent tank loss is given by R_p . This means that an oscillator's FOM depends on only three variables: quality factor, efficiency, and noise factor. Since Q is largely set for a given process and desired tuning range, a circuit designer can only optimize η and F. Bank's general result [3-5] explains that when the energy-restoring circuit is connected across the entire tank, the minimum possible noise contribution of the energy-restoring circuit is directly related to R_p through some proportional constant, which in the case of a CMOS design cannot be lower than $\gamma = 2/3$, giving a minimum achievable noise factor of $F_{MIN} = 1 + \gamma$. The other variable is efficiency, which by definition cannot exceed 1 (or 100%). Figure 25.3.2 shows the proposed topology complete with an idealized inductance with $Q = 12$ and an arbitrary arrangement of ideal differential and common-mode capacitors, whose ratio is defined by the variable X. The variable X was then swept, which moved the capacitors from fully common-mode to fully differential. At the optimum point of $X = 0.65$, the common-mode impedance at $2 \times F_{LO}$ is maximized and the

noise factor reaches the theoretically minimum value of 1.67, efficiency reaches 75%, and, therefore, FOM is also maximized. Indeed, for the given Q, the achievable FOM of the proposed VCO is only 1.5 dB less than any theoretically conceivable LC CMOS oscillator. Interestingly, at this optimum point, the flicker noise contribution of the differential pair transistors is also nulled (as noted by the fact that the FOM at 50kHz is equal to the FOM at 10MHz).

A wideband, practical realization of this topology that was fabricated in 28nm CMOS is shown in Fig. 25.3.3. The ratio of common-mode to differential capacitance is set by the coupling coefficient of the inductor through the expression:

$$\frac{C_{DM}}{C_{CM}} = \frac{3 - 5k}{1 + k}$$

A higher k requires less differential capacitance, but results in a reduced common-mode Q. By contrast, choosing a low or negative k maintains a large common-mode Q but requires a very small amount of common-mode capacitance, which is difficult to achieve in a practical design. As a compromise, the fabricated design used an inductor with $k \approx 0.33$, which therefore requires $C_{DM}/C_{CM} \approx 1$. To keep k small, a two-turn inductor was employed and the radius of the inner turn was purposely reduced. Additionally, in order to allow the supply rail to be solidly AC-shorted to ground with minimal common-mode Q degradation due to routing, the inductor was flipped inside out and the common-mode terminals were routed on the outside (highlighted on the top of Fig. 25.3.3). The differential inductance was simulated as 1.5nH. The tunable differential switched-capacitor bank and the tunable common-mode bank are highlighted in Fig. 25.3.3. Both capacitors banks were composed of 32 identical unit cells that were controlled using an interleaved thermometer code. When the switches are off, a common-mode path is presented to ground through the digital inverter controlling the switch. Therefore, it is important to make these inverters large enough that they don't degrade the common-mode Q. The measured tuning range of the fabricated VCO was 2.85 GHz to 3.75 GHz. Figure 25.3.4 shows the measured phase noise profile and FOM profile versus carrier offset for three frequency settings. Note that the FOM (in the thermal noise region) is always better than 192, and the flicker noise corner is around 200kHz. Figure 25.3.5 shows the phase noise, FOM, current consumption and flicker noise corner (measured as the frequency at which FOM degrades by 3dB from the FOM at 5MHz) versus oscillation frequency. Note that the good FOM and low flicker noise corner is maintained across the band. As the VCO is voltage-biased, by monitoring the current and assuming an efficiency of around 65%, we can calculate the Q of the tank as approximately 11.5. Figure 25.3.6 compares our work to the current state-of-the-art VCOs. The FOM is within 2.5dB of Hegazi's VCO [1], but requires no additional inductor, has a wider tuning range (18% versus 27%) and operates from a much lower supply voltage (0.9V versus 2.5V). Compared to other recent low-voltage, low-noise designs [6,7], the proposed design has a comparable or better FOM, and has a significantly lower flicker noise corner (200kHz versus 750kHz to 2000kHz).

References:

- [1] E. Hegazi, H. Sjolund, and A. A. Abidi, "A filtering technique to lower LC oscillator phase noise," *IEEE J. Solid-State Circuits*, vol. 36, no. 12, pp. 1921-1930, Dec. 2001.
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- [4] A. Mazzanti and P. Andreani, "Class-C harmonic CMOS VCOs, with a general result on phase noise," *IEEE J. Solid-State Circuits*, vol. 43, no. 12, pp. 2716-2729, Dec. 2008.
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- [7] M. Babaie and R. B. Staszewski, "Third-Harmonic Injection Technique Applied to a 5.87-to-7.56GHz 65nm CMOS Class-F Oscillator with 192 dBc/Hz FOM," *ISSCC Dig. Tech. Papers*, pp. 348-349, Feb. 2013.

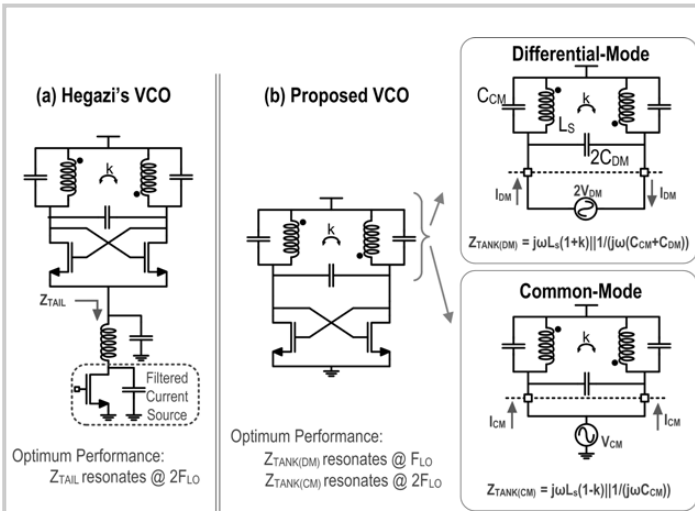


Figure 25.3.1: Hegazi's VCO, and the proposed VCO topology that does not require an additional LC tank.

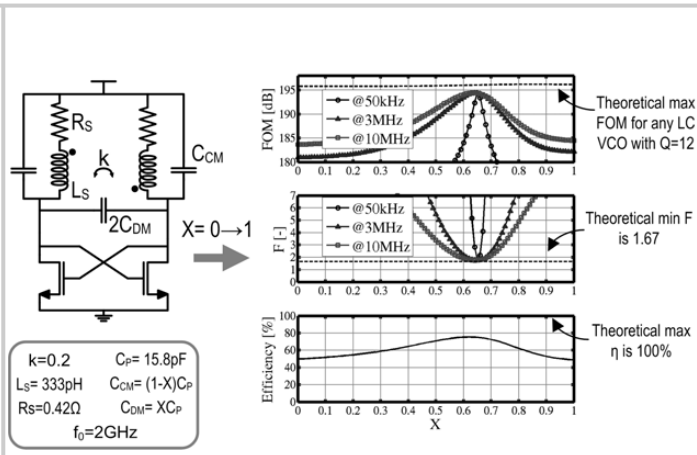


Figure 25.3.2: Proposed VCO with idealized LC Tank. For a given inductor coupling coefficient, there is an optimum ratio of common-mode to differential capacitance that simultaneously maximizes FOM and efficiency, minimizes F and nulls flicker noise.

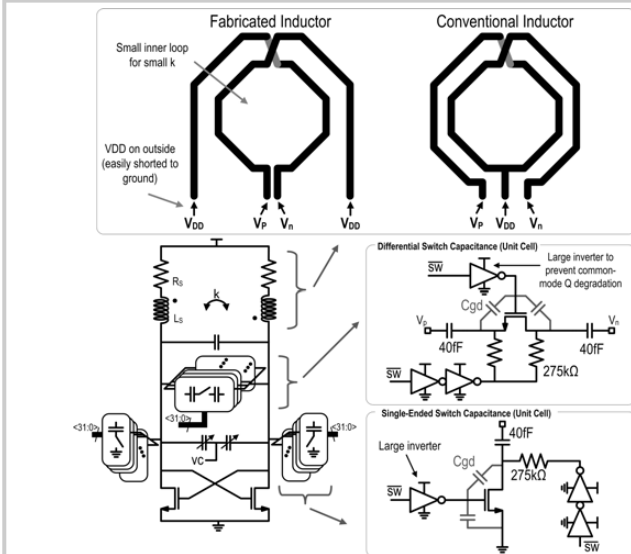


Figure 25.3.3: Schematic of fabricated 28nm design.

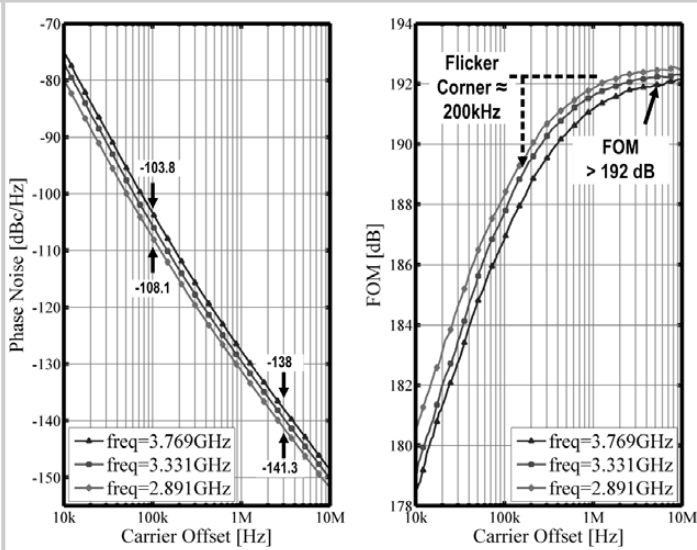


Figure 25.3.4: Measured phase noise and FOM versus carrier offset.

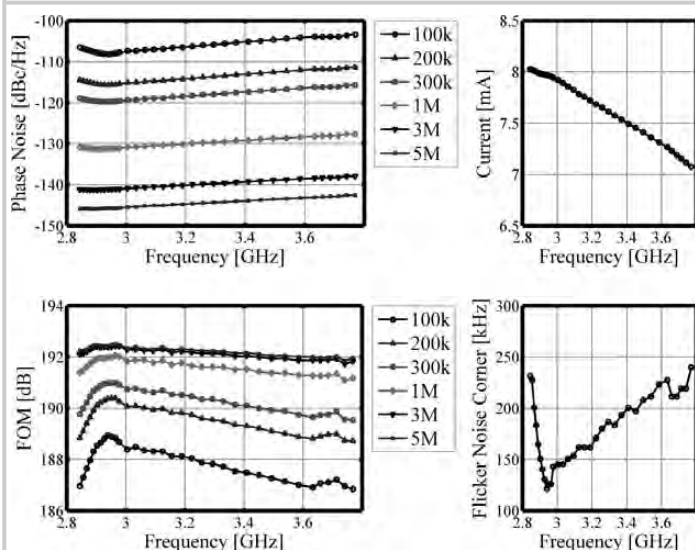


Figure 25.3.5: Performance metrics versus oscillation frequency.

	JSSC 2001 [1]	ISSCC 2013 [6]	ISSCC 2013 [7]	This Work
Topology	2F _{LO} Explicit Resonance	Class-D	Class-F	2F _{LO} Implicit Resonance
Technology	0.35 μ m	65 nm	65 nm	28 nm
Supply Voltage	2.5	0.4	1.25	0.9
Frequency [GHz]	1.2	2.5	3.7	3.33
Tuning Range	1-1.2 (18%)	2.5-3.3 (27.6%)	2.94-3.78 (25%)	2.85-3.75 (27.2%)
Phase Noise [dBc/Hz @ 3 MHz]	-153.2	-139.5*	-142.2	-139.6
Power [mW]	9.1	6.8	15	6.8
FOM [dB] (Thermal noise region)	194.5	189-190	192.2	192.2
Core Area [mm ²]	N/A	0.12	0.12	0.19
Flicker Noise Corner [kHz]	\approx 200*	\approx 2000	\approx 750	\approx 200
Inductors	2	1	1 XFMR	1

*Estimated from plots

Figure 25.3.6: Table of comparison.

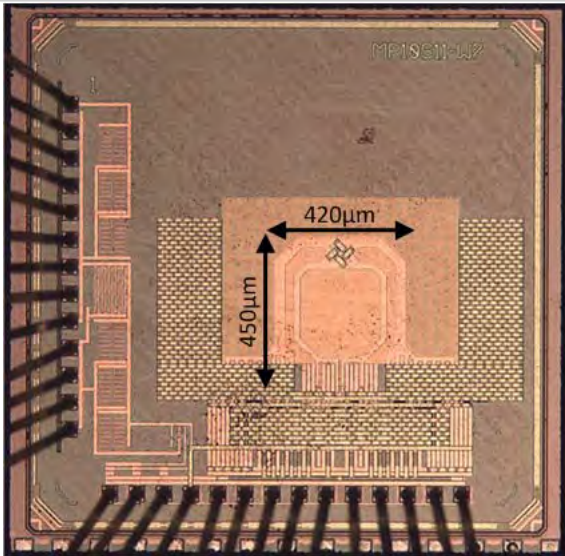


Figure 25.3.7: Die micrograph.