23.5 An Inverse-Class-F CMOS VCO with Intrinsic-High-Q 1st- and 2nd-Harmonic Resonances for 1/f²-to-1/f³ Phase-Noise Suppression Achieving 196.2dBc/Hz FOM

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Second-harmonic common-mode (CM) resonance has been explored for LC oscillators to improve their phase noise (PN) in the past. Its implementation evolves from an explicit design [1] that relies on an extra tail tank, to a recent implicit design [2], where the resonator itself offers a CM impedance peak at 2× the oscillation frequency (F₀): Explicit design (Fig. 23.5.1-upper): a high-Q tail tank (QTAIL) is desirable to raise its impedance |ZTAIL| at 2FLO and to prevent the loss of LTAIL from penalizing the PN in the 1/f² region [3]. To compare with the theoretical limit (FOMth), the FOM in the 1/f² PN region is plotted against LTAIL at different QTAIL. Closing the gap between FOMth and FOM imposes an excessive QTAIL of 20 or beyond, which can hardly be achieved and maintained over a wide tuning range.

Implicit design (Fig. 23.5.1-lower): a CM resonance at 2F₀ can avoid the physical area and loss of the tail tank. Besides, if the 2nd-harmonic current is trapped in the resistive impedance at 2F₀ due to the CM resonance, the flicker-noise upconversion can be suppressed [4]. Yet, its practical effectiveness is limited by the presence of PN, which renders both F₀ and 2F₀ to drift randomly around their resonances. If the 2nd-harmonic current spends more time “trapped” in the resistive part of the tank, the effect of flicker-noise upconversion can be further reduced, but it demands a high-Q impedance at 2F₀. Unfortunately, the implicit CM impedance |ZCM| is relatively low for two reasons: 1) CM inductance LCMP=(1-k) is small due to magnetic-flux cancellation and 2) the CM resonance has a low Q at 2F₀ up to 1/4 of its differential-mode counterpart [4] (i.e. Q0/Q1≈0.25). Although lowering k returns a higher ZCM, more die area is sacrificed, and the required CM capacitance becomes exceedingly small.

This paper proposes an inverse-Class-F CMOS VCO free of CM resonance. A transformer-based dual-band LC resonator generates two intrinsic-high-Q resonances at F₀ (denoted Q₁) and 2F₀ (denoted Q₂). A high Q₀ corresponds to low PN in both 1/f² to 1/f³ regions, while the transformer voltage gain aids suppressing the thermal noise contributed by the -g m transistors. The high-Q resonances lead to high FOMs at both 100kHz offset (191-to-192.5dBc/Hz) and 10MHz offset (195.6-to-196.2dBc/Hz) over 3.49 to 4.51GHz, while showing low frequency pushing (4.5 to 15MHz/V).

Let us consider a single-ended NMOS VCO using a 1:n transformer (Fig. 23.5.2) to satisfy Barkhausen’s criterion. The transformer model [5] reveals that two impedance peaks can be produced despite the VCO being single-ended. To map them at F₀ and 2F₀, we have to satisfy 16ξ²+68ξ+100ξk₁+16=0 for a mutual coupling factor 0.3≤k≤0.66, where ξ is the product of the transformer inductance ratio (Lp/Ls) and capacitance ratio (Cp/Cs), arriving at the inverse-Class-F operation. It implies that the effective inductance at F₀ (2F₀) is determined not only by Lp (Ls), but also by ξ and k. Increasing the tank impedance at 2F₀ is feasible by sizing ξ≤1. Based on Fig. 23.5.2, a small k (0.34) is desired to raise ξ (3.2), leading to a higher Q₀/Q₁ ratio (0.8) than that of [2] by 3.2x and a large transformer voltage gain (Aᵥ) resulting in a low-PN VCO design. For a low-power VCO design, a moderate FOM at 1/f² region varies within ±0.5dB and peaks to 1/f³ corner is 100kHz at fMIN and up to 300kHz at fMAX due to the AM-PM conversion when the varactor and parasitic capacitance dominate. Figure 23.5.5 shows the PN and FOM plots across the frequency tuning range and its benchmarking with the prior art (Fig. 23.5.6), our inverse-Class-F CMOS VCO exhibits the highest FOMs at both 100kHz and 10MHz offsets over a comparable tuning range, while achieving low frequency pushing, which is among the best reported in Fig. 23.5.6. The die micrograph of the VCO is depicted in Fig. 23.5.7.

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References:
**Figure 23.5.1:** Upper: VCO with explicit $2f_0$ resonance [1] and its FOM dependence on $Q_{TAIL}$. Lower: VCO with implicit $2f_0$ resonance [2] to avoid an extra LC tank, but the implicit CM resonance has low impedance and low Q at $2f_0$.

**Figure 23.5.2:** A single-ended NMOS VCO using a 1:n transformer; the transformer model reveals that 2 impedance peaks can be generated at $f_0$ and $2f_0$. $\xi=3.2$ and $k_m=0.34$ yield high $Q_2/Q_1$ ratio (0.8) and $A_v$.

**Figure 23.5.3:** Proposed inverse-Class-F CMOS VCO. By varying $C_p$ and $C_s$, $f_0$ and $2f_0$ can be aligned to suppress the flicker-noise upconversion.

**Figure 23.5.4:** Measured phase noise and FOM at different offset frequencies.

**Figure 23.5.5:** Upper: Measured phase noise and FOM vs. the oscillation frequency. Lower: Measured frequency pushing at $f_{MIN}$ and $f_{MAX}$.

**Figure 23.5.6:** Performance benchmark with the previously published VCOs.
Figure 23.5.7: Die micrograph of the fabricated VCO in 65nm CMOS.