A 0.07mm² 18.7-to-28.5GHz Dual-Mode Class-F VCO with Compact Harmonic Shaping Topology Achieving 193.1dBc/Hz FoM at 1MHz Offset

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***Abstract*—In this paper, a dual-core dual-mode class-F VCO with compact harmonic shaping topology is proposed. The proposed VCO concurrently realizes DM 3rd and tuning-free wideband CM 2nd harmonic shaping via a dual-mode single-turn 8-shaped class-F topology and an inner CMR with gate-drain CM coupling. Fabricated in 40nm CMOS process, the proposed VCO achieves a peak 1MHz-offset FoM and FoM$_A$ of 193.1dBc/Hz and 204.6dBc/Hz, corresponding to a core area of 0.07mm². The wideband CM 2nd harmonic shaping which comprise the initial wideband shaping and our developed CM band expansion, achieves a 1/f³ PN corner of 150-to-320kHz.**

***Keywords*—VCO, phase noise, multi-mode VCO, harmonic shaping, compact topology, area**

I. Introduction

Voltage-controlled oscillators (VCO) with wide frequency tuning ranges (FTRs) and consistently superior performance are in increasing demand for robust signal modulation and multi-standard transceivers in millimeter-wave (mm-wave) communications. Among these VCOs, multi-core multi-mode configurations are especially significant [1-8]. However, achieving high-performance wideband VCOs in the high frequency (HF) regime (>20GHz) remains challenging. Key bottlenecks include: (1) The self-coupling effect of inductors reduces Q-factor of small inductance, especially limiting conventional double-turn class-F topologies from operating at high frequencies. As a result, the frequency of the reported quad-core dual-mode class-F VCO [1] [Fig. 1(a)] is limited to <20GHz. (2) Simple mode-switching electromagnetic (EM) coupling induces large Q variation of modes. The Q-factor degrades by a factor of (1-k) at HF, introducing large variation across modes, which degrades the performance of odd mode in [1] [Fig. 1(a)]. (3) Techniques for 2nd harmonic enhancement incur extra power and area. The reported dual-core dual-mode VCO in [2] employs an additional injection-locked oscillator (ILO) to double oscillation frequency at HF, causing high power consumption and large area [Fig. 1(b)]. Moreover, harmonic shaping techniques, which have been widely applied to reduce phase noise (PN) in a variety of VCOs [1-2, 9-15], show several issues for multi-mode VCO design. On the one hand, common-mode (CM) 2nd harmonic shaping with complex mode-switching EM coupling requires an outer common-mode resonator (CMR) and large area [1-2] [Fig. 1(a, b)], especially in CM tuning-free configurations. On the other hand, differential-mode (DM) 3rd harmonic shaping via conventional double-turn gate inductors limits oscillation frequency due to the degraded

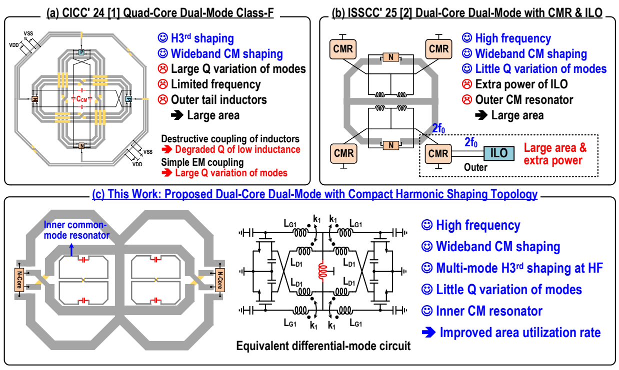

Fig. 1. Review of the prior-art multi-core multi-mode oscillators, and the proposed dual-core dual-mode oscillator

Q-factor of small inductance, as noted in bottleneck (1).

To surmount these challenges, this paper presents a HF dual-core dual-mode class-F VCO featuring compact harmonic shaping topology [Fig. 1(c)]. We propose a dual-mode single-turn class-F topology with gate-drain shared 8-shaped resonator toachieve multi-mode DM 3rd harmonic shaping, and maintaining high Q for both modes consistently with compact area. Furthermore, the proposed configuration realizes tuning-free wideband CM harmonic shaping via initial wideband CM shaping and CM band expansion method with an inner coupling CMR instead of occupying extra area. The proposed CM band expansion technique based on gate-drain CM coupling further expands the CM high impedance range without area penalty. Fabricated in 40nm CMOS process, the proposed VCO achieves a peak figure of merit (FoM) of -193.1dBc/Hz at 1MHz offset, a core area of 0.07mm², a 1MHz-offset FoM$_A$ of 204.6dBc/Hz, and a FTR of 18.7-to-28.5GHz (41.5%), together with wideband 1/f³ noise suppression which achieves a 1/f³ PN corner of 150-to-320kHz across the FTR.

II. Compact Harmonic Shaping Techniques

A. *Dual-Mode DM 3rd Harmonic Shaping*

Fig. 2 shows the DM operation of the proposed dual-core dual-mode class-F VCO using our devised dual-mode single-turn DM 3rd harmonic shaping topology with gate-drain shared 8-shaped resonator. The inner coupling CMR remains DM-transparent since DM magnetic flux excited by currents flowing through gate and drain inductors remains in the same direction across the series 8-shape CMR, thus inducing negligible current within it. In odd mode, the center inductor

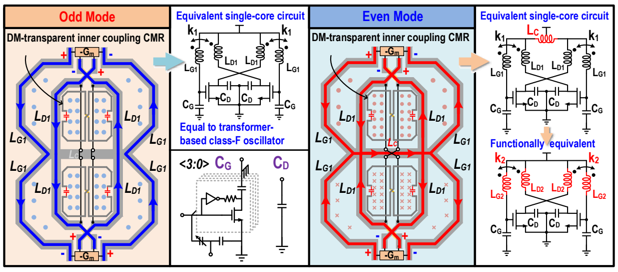

Fig. 2. The differential-mode operation of odd mode and even mode.

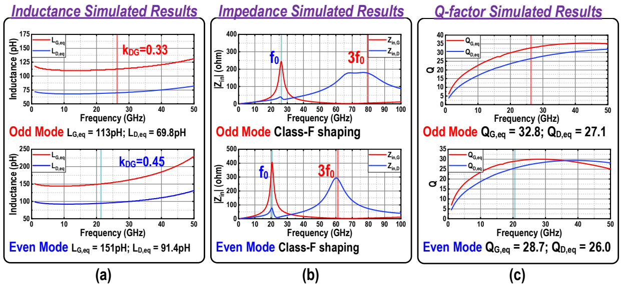

Fig. 3. Simulated results of inductance (a), impedance (b) and Q-factor (c) in both modes

L_C is transparent due to the opposite current direction of each core controlled by the mode switch. DM current flows circularly through the DM-coupled effective gate inductor L_{G1} and drain inductor L_{D1}. As a result, the equivalent single-core circuit corresponds to a classic transformer-based class-F oscillator topology [14-15]. The gate capacitor C_G including a switched capacitor array and a varactor is adjustable for the oscillation frequency, and C_D is fixed to improve the Q-factor. In even mode, with two cores having in-phase currents, current flows through the center inductor L_C, enabling a shared gate-drain inductor and an equivalent single-core circuit analogous to the previously reported single-core single-turn class-F VCO [9] without area penalty. The equivalent circuit can be further transformed into the same class-F topology as in odd mode, but with enlarged effective gate and drain inductances, L_{G2} and L_{D2}. As shown in Fig. 3(a), the equivalent gate/drain inductances are 113pH/69.8pH in odd mode, and 151pH/91.4pH in even mode, respectively. The equivalent DM gate-drain coupling factors are 0.33 in odd mode, and 0.45 in even mode. Consequently, the proposed configuration achieves HF multi-mode single-turn DM 3rd harmonic shaping, validated by the simulated results of impedance in Fig. 3(b), in which the frequency of the second impedance peak reaches desired 3 times that of the frequency of the first impedance peak in both modes. Additionally, Fig. 3(c) demonstrates consistently high Q-factor of relatively small inductances across both modes achieved by the 8-shaped tank [2, 8] and single-turn structure, with a Q of 32.8 in odd mode and a Q of 28.7 in even mode, respectively. Moreover, the drain-connected mode switch minimizes FTR degradation owing to the low sensitivity of drain capacitance, unlike prior gate-connected configuration [1].

B. Tuning-free Wideband CM 2nd Harmonic Shaping

Fig. 4 illustrates the CM operation of proposed tuning-free wideband CM shaping achieved with initial wideband shaping and our developed CM band expansion method along with the detailed floorplan of our dual-core class-F

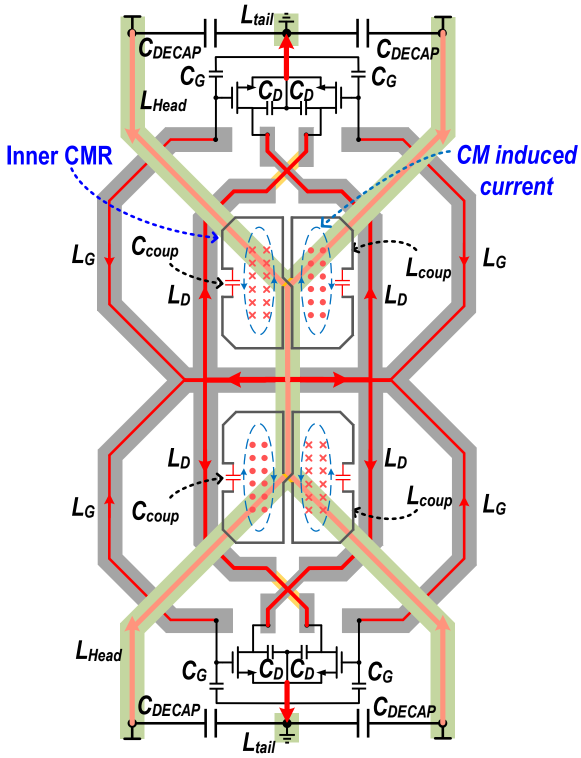

Fig. 4. The common-mode operation

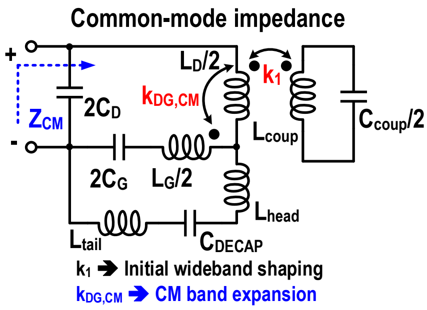

Fig. 5. Impedance of the common-mode path.

VCO. In CM operation, the current flowing through the drain inductor excites magnetic flux in opposing directions across the horizontally separated sections of the inner coupling CMR. The magnetic flux induces coupling current in the CMR, thereby establishing a coupling factor k_1 between L_D and L_{coup} [10]. According to the equivalent schematic for CM impedance estimation shown in Fig.5, where L_{head} and L_{tail} represent the parts that overlap with the core circuit area, occupying negligible additional area. The double-coil transformer consisting of L_D and L_{coup} forms the initial wideband shaping by properly setting the coupling capacitor C_{coup}. Employing our inner CM double-coil transformer, the initial wideband shaping is realized across a wide frequency range with compact area and a relatively large CM coupling factor k_1. Maintaining a constant gate capacitor C_G, the spectrum of CM impedance exhibits a stable high impedance range and resistive path range over a 16.5GHz bandwidth (35%), demonstrating effective tuning-free CM wideband shaping (Fig. 6). Furthermore, tuning the DM resonant frequency via the C_G shifts the CM impedance in

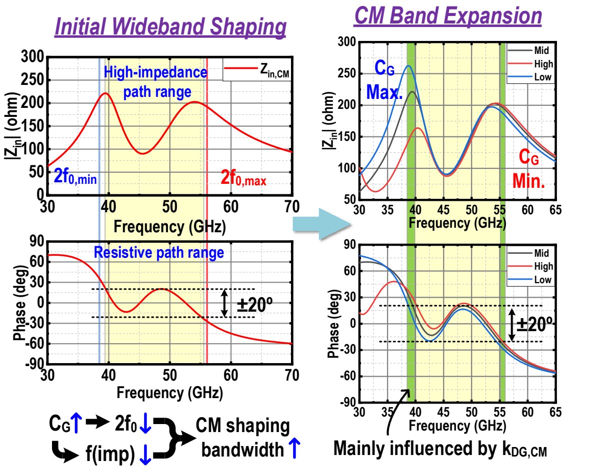

Fig. 6. The initial wideband shaping and the implementation of the proposed CM band expansion.

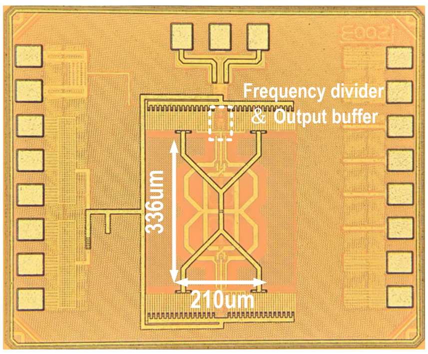

Fig. 7. Chip micrograph in 40nm prototype.

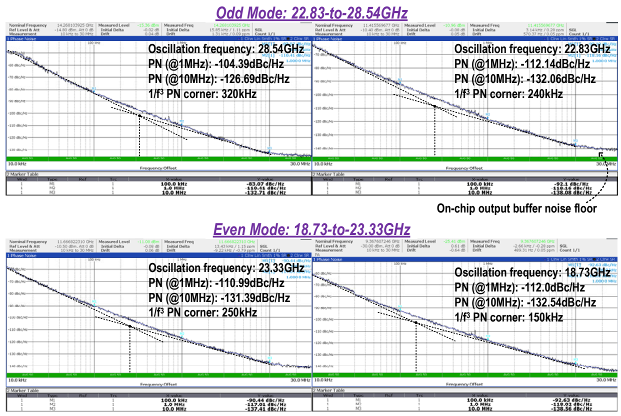

Fig. 8. Measured phase-noise profiles from divide-by-2 output.

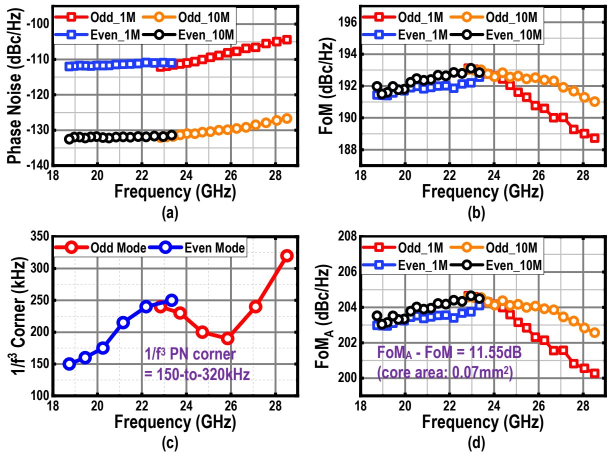

Fig. 9. Measured PN (a) and FoM (b), measured $1/f^3$ PN corner (c) and measured FoM_A (d) across the frequency tuning range.

the same direction through the CM coupling factor $k_{DG,CM}$ of drain and gate. Therefore, to further expand the tuning-free CM shaping frequency range, we propose the CM band expansion method based on the equivalent triple-coil transformer comprising L_G, L_D and L_{coup}, in which C_G influences the frequency of the CM impedance peak along with f_0, effectively broadening the existing CM resonance range and ensuring tuning-free operation across the entire FTR. For example, as C_G increases, the CM frequency $2f_0$ decreases, while the spectrum of CM impedance shifts towards lower frequencies, resulting in an equivalent CM shaping band expansion. C_G simultaneously adjusts both the DM and common-mode CM impedances, thereby eliminating the need for additional CM tuning capacitors. As depicted in Fig. 6, the maximum C_G causes the impedance peak to shift towards lower frequencies, while minimum C_G shifts it towards higher frequencies. The equivalent high-impedance range increases by 20%, covering a 20GHz bandwidth (42%) after the CM band expansion with a magnitude of >90Ω and a phase staying within ±20°, demonstrating a wideband resistive path across the FTR. In summary, the CM shaping and CM band expansion technique realize tuning-free wideband 2nd harmonic shaping in a multi-mode VCO without any outer CMR, suppressing $1/f^3$ PN sensitivity and reducing the core area.

III. Measurement Results

The proposed VCO is fabricated in 40nm CMOS process with a core area of only 0.07mm², as shown in the die micrograph in Fig. 7. Fig. 8 shows the measured FTRs and PN of each mode, with an on-chip divide-by-2 circuit for testing. The proposed VCO achieves a FTR of 18.7-to-28.5GHz, which consists of a FTR of 18.7-to-23.3GHz in even mode and a FTR of 22.8-to-28.5GHz in odd mode, with an overlap of 0.5GHz. The top of Fig. 9 shows the measured PN and FoM across the FTR. The measured PN varies from -112.1 to -104.4dBc/Hz at 1MHz offset and from -132.5 to -126.7dBc/Hz at 10MHz offset, respectively. With a power supply of 0.45V and consuming 3-to-4.2mW, the corresponding FoM varies from 188.7 to 193.1dBc/Hz at 1MHz offset and from 191.0 to 193.2dBc/Hz at 10MHz offset, respectively. With the measured FoM and a core area of 0.07mm², the FoM_A varies from 200.3 to 204.6dBc/Hz at 1MHz offset and from 202.5 to 204.8dBc/Hz at 10MHz offset, respectively [Fig. 9(c)]. Fig. 9(d) depicts the $1/f^3$ PN corner across two modes, which is 150-to-320kHz.

TABLE I and Fig. 10 present a summary and comparison between the proposed oscillator and other prior-art multi-core multi-mode oscillators operating over 20GHz. This work is the first reported multi-mode VCO that achieves DM 3rd and wideband CM 2nd harmonic shaping concurrently with an oscillation frequency over 20GHz. Thanks to the compact harmonic shaping topology comprising the proposed multi-mode single-turn class-F structure with gate-drain shared 8-shaped resonator, the initial CM wideband shaping, and CM band expansion with gate-drain CM

TABLE I. PERFORMANCE COMPARISON WITH PRIOR-ART MULTI-MODE OSCILLATORS OPERATING OVER 20GHZ.

		This Work	ISSCC' 25 H. Guo [2]	ISSCC' 24 H. Ge [3]	CICC' 23 P. Guan [4]	ISSCC' 20 Y. Shu [5]	ISSCC' 19 A. Baht [6]
Technology		40nm CMOS	65nm CMOS	65nm CMOS	65nm CMOS	40nm CMOS	65nm CMOS
VCO Topology		Dual-core Dual-mode	Dual-core Dual-mode**	Quad-core Quad-mode	Quad-core Dual-mode	Quad-core Quad-mode	Dual-core Dual-mode
Harmonic Shaping		CM 2nd & DM 3rd	CM 2nd	N/A	CM 2nd	CM 2nd	CM 2nd
Power (mW)		3 to 4.2	14.8 to 30.1	2 to 8.8	10.6 to 13.8	9 to 15	17.5 to 21.6
Tuning Range (GHz)		18.7 to 28.5 (41.5%)	9.06 to 37.0** (121%)	13.7 to 41.5 (101%)	25.0 to 35.9 (35.8%)	18.6 to 40.1 (73.2)	25 to 38 (41.2%)
PN (dBc/Hz)	@1MHz	-112.1 to -104.4	-126.3* to -110*	-110.0* to -97.8*	-111.3 to -106.2	-108.5 to -100.3	-109.3* to -99.7*
	@10MHz	-132.5 to -126.7	-147.6 to -132.2	-133.2 to -124.4	-131.9 to -127.4	-130.3 to -122.7	-130* to -120*
FoM(1) (dBc/Hz)	@1MHz	188.7 to 193.1	188.1 to 192.2	177.8 to 190.8	186.5 to 189.1	181.4 to 184.4	177.6 to 184.8
	@10MHz	191.0 to 193.2	190.7 to 193.1	184.4 to 194.0	187.8 to 189.6	183.0 to 186.3	180.3 to 185.5
$1/f^3$ PN Corner (kHz)		150 to 320	170 to 720	<2000*	200 to 700	220 to 620	750* to 1800*
FoM_T(2) @10MHz (dBc/Hz)		203.4 to 205.6	212.3 to 214.7	204.5 to 214.1	198.8 to 200.7	200.3 to 203.6	192.5 to 197.8
Core Area (mm^2)		0.07	0.15	0.14	0.19	0.08	0.08
FoM_A(3) (dBc/Hz)	@1MHz	200.3 to 204.6	196.3 to 200.4	186.3 to 199.3	193.7 to 196.3	192.4 to 195.4	188.6 to 195.8
	@10MHz	202.5 to 204.8	198.9 to 201.3	192.9 to 202.5	195.0 to 196.8	194.0 to 197.3	191.3 to 196.5

(1) $FoM = |PN| + 20\log_{10}(f_0/\Delta f) - 10\log_{10}(P_{DC}/1mW)$ (2) $FoM_T = FoM + 20\log_{10}(FTR/10)$ (3) $FoM_A = FoM + 10\log_{10}(1mm^2/A)$
*Estimated from plots
**Low frequency oscillator + injection-locked oscillator

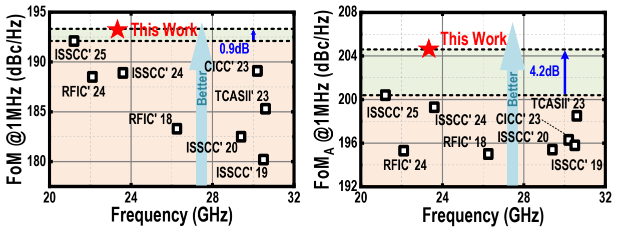

Fig. 10. Comparison of 1MHz-offset FoM and 1MHz-offset FoM_A with prior-art multi-mode oscillators operating over 20GHz.

coupling, our VCO achieves the highest FoM at 1MHz offset with an improvement of 0.9dB, and the highest FoM_A at 1MHz offset with an improvement of 4.2dB, along with a compact core area of 0.07mm^2. In contrast, the design in [2] degrades the FoM when operating over 20GHz due to the ILO, and occupy twice the core area of the proposed VCO. Additionally, the proposed topology simultaneously realizes DM 3rd and CM 2nd harmonic shaping at HF without a frequency multiplier or an extra ILO as in [2]. Both the FoM and FoM_A at 10MHz offset are also among the best reported to date. Moreover, with the tuning-free wideband CM 2nd harmonic shaping, the proposed VCO achieves the lowest $1/f^3$ PN corner among compared oscillators, ranging from 150 to 320kHz without tuning, which is realized by the initial wideband shaping and CM band expansion method.

IV. CONCLUSION

This paper proposes a dual-core dual-mode class-F VCO with 2nd and 3rd harmonic shaping. A dual-mode single-turn 8-shaped class-F topology is employed to realize dual-mode 3rd harmonic shaping with small Q variation and compact area. An inner CMR with gate-drain coupling is adopted to achieve wideband tuning-free 2nd harmonic shaping to suppress flicker noise without occupying extra area. Fabricated in 40nm CMOS process, the proposed VCO operates over 20GHz, and achieves a 1MHz-offset FoM and FoM_A of 193.1dBc/Hz and 204.6dBc/Hz with a core area of 0.07mm^2, and wideband CM shaping which achieves a low $1/f^3$ PN corner of 150-to-320kHz.

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