RESEARCH HIGHLIGHTS

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The VCOs in ISSCC 2023 set the new performance frontier of silicon-based oscillators

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High-quality frequency generators are one of the fundamental building blocks in high-throughput wireless communication systems. Driven by the fast-growing demand for high data rate communications, the signal generator continues to be an active research topic. Efforts have been dedicated to improving the performance, including but not limited to phase noise, frequency tuning range, power consumption, and chip area, of voltage-controlled oscillators (VCO) from several GHz to millimeter wave frequency range. Among the proposed techniques in recent years, harmonic tuning technique such as tail filtering, class-F, and implicit common-mode resonance has been well acknowledged to be an effective method in improving the phase noise performance of single-core VCOs. To further improve the phase noise performance, multi-core and series-resonant techniques are proposed to absorb a larger amount of power from the source and trade for a better phase noise performance. As for the frequency tuning range, the mode-switching techniques can double or quadruple the frequency tuning range with less quality factor degradation compared with switched capacitors and switched inductors, by eliminating the influence of the switch's on-resistance when the mode is stable. Frequency generation at subterahertz (>100 GHz) is challenging due to the fast-degrading quality factor of variable inductors. Instead of oscillating at the fundamental harmonic frequency, a VCO working at sub-harmonic frequency followed by a harmonic extraction scheme would be a more practical solution for frequencies higher than 100 GHz. However, optimizing the efficiency, area, and power consumption of the harmonic extraction circuit including the necessary buffers is still challenging.

Four VCOs from several GHz to millimeter-wave frequency ranges with state-of-the-art performance have been reported in ISSCC 2023, setting the new frontier of silicon-based VCOs regarding the oscillation frequency, phase noise, and figure-of-merits (FoM). In Ref. [1], a dual-core VCO operating at 11.5 to 14.3 GHz achieving an excellent FoM of 192.8 dBc/Hz is reported. This work proposed a novel method to manipulate the common-mode impedance and thus the 2nd harmonic component. A novel power and ground routing arrangement is added to enhance the common-mode performance of conventional class-F topology. The drain inductor L_D is coupled to the source inductor L_S in the common mode while not affecting the differential mode, reducing the common-mode noise injected into the VCO's main tank. The power and ground routing arrangement also generates a high impedance at the 2nd harmonic frequency, helping suppress the flicker noise. In Refs. [2, 3], multi-core fundamental VCOs working at around 26 and 28 GHz employing the circular transformers are reported. Originally proposed in Ref. [4], the circular transformer multi-core topology is proven to be very effective for millimeter-wave oscillators. It improves the *Q* of inductors, while the area penalty for multi-core is insignificant in the millimeter-wave frequency range. Those two works further optimize the circular transformer topology, opening more possibilities. Fig. 1 shows the evolution of circular transformer based VCOs in recent years. In Ref. [4], each VCO core only couples to its two adjacent cores. In Ref. [3], additional coupling paths are added by introducing magnetic coupling between non-adjacent cores, therefore the multi-core is more robust against core frequency mismatches. It achieves 190.6 dBc/Hz at 1 MHz offset and 193.3 dBc/Hz FoM at 10 MHz offset. The VCO in Ref. [4] doesn't have a common-mode resonant feature for two reasons. First, the 120 GHz 2nd harmonic frequency is too high. Second, the original inductor topology doesn't provide the freedom to tune the common-mode inductance. In Ref. [3], common-mode resonance is added to the circular topology, lowering the flicker noise corner to less than 380 kHz. The proposed topology is also scalable. Quad-core and 20-core prototypes are reported, exhibiting state-of-the-art −115.6 dBc/Hz and −121.7 dBc/Hz phase noise performance, respectively. In Ref. [5], a quad-core quad-mode VCO working around 30 GHz together with a third-harmonic extraction output is proposed. Each VCO core has a class-F topology to generate a strong third-harmonic component. Two sets of mode capacitors are added, by switching the oscillating mode, each capacitor set can be added into the tank or not, creating different banks. Although four modes are used, the fractional tuning range is 20.9%, which is moderate compared with other recently reported mode-switching VCOs[6, 7]. With the third-harmonic extraction circuity, the FoM performance around 100 GHz is competitive, which is 180.2 dBc/Hz at 10 MHz offset from 104.7 GHz.

Those four works in ISSCC 2023 represent the current research interests in the area of VCOs from several GHz to millimeter-wave frequency ranges, such as harmonic component manipulation, circular fundamental millimeter-wave VCOs, and high-efficiency harmonic generation and extraction. The author believes that the path of pushing the performance of VCOs to its limitation has not ended yet. Critical design challenges still demand dedicated efforts from the industry and academia, such as octave frequency tuning range without degrading FoM, octave range flicker noise suppression, and tem-

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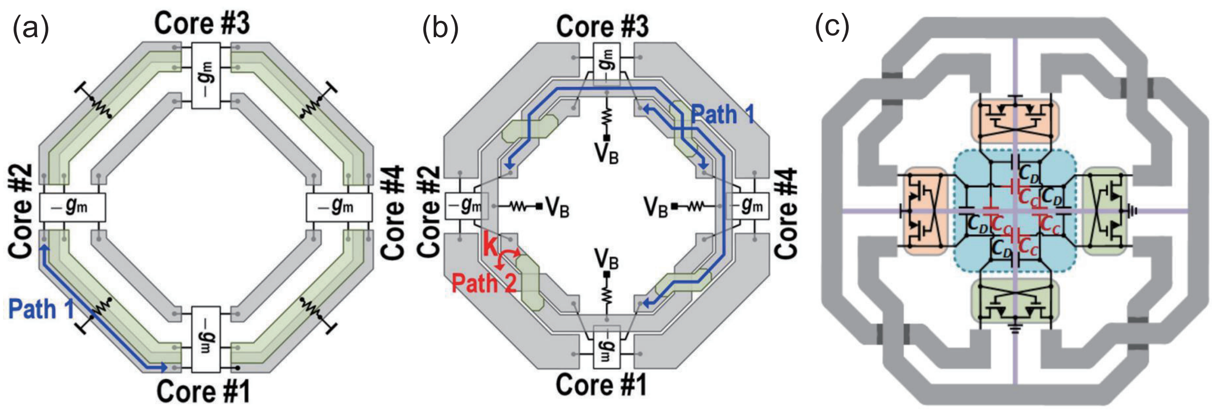

Fig. 1. (Color online) The evolution of circular-transformer-based VCOs: (a) original topology in Ref. [4], (b) adding additional synchronization paths in Ref. [2], and (c) adding implicit common-mode resonance in Ref. [3].

perature compensation features, just to name a few. Let's keep our eyes open and look forward to the next ISSCC conference.

References

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