A Low EM Susceptibility VCO with Four-leaf-clover-shaped Inductor Verified via Chip-level 3D Near-field Measurement Technique

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***Abstract*—A low electromagnetic susceptibility voltage-controlled oscillator (VCO) utilizing a four-leaf-clover-shaped inductor is demonstrated at 5 GHz by 0.18-µm CMOS. A novel chip-level near-field coupling measurement setup resembling the modern 3D stacked packaging scheme is proposed using the integrated passive device (IPD) technology. The IPD coil embedded in the test carrier can generate EM interference on the flip-chip bonded VCO to verify the proposed high EMI immunity VCO. Compared to a VCO with the conventional spiral inductor, a significant improvement over 30 dB in a wide frequency range (maximum of 32.2 dB) in susceptibility is demonstrated by the VCO with the four-leaf-clover-shaped inductor.**

***Keywords*—electromagnetic susceptibility, inductor, near-field, voltage-controlled oscillator (VCO).**

I. Introduction

The voltage-controlled oscillator (VCO) is one of the most sensitive components in the RF front-end blocks. The transmitted signal may leak back from power amplifier to the local oscillator and causes unexpected errors in the RF transceiver [1]. The twisted inductor was reported to improve ASK modulated transmission signal asymmetry by suppressing the interference between the driver amplifier and VCO [2]. Also, the twisted winding scheme of inductor was demonstrated to increase the localization of magnetic field and thus reduce the parasitic coupling from a nearby inductor [3]. The 8-shaped inductor [4] could suppress EM induced magnetic flux by the two constitutive loops with an equal magnetic field but opposite polarization [5]. With the property of minimizing EMI related couplings and interferences, the 8-shaped topology and the similar configurations were adopted in the designs of inductor, transformer, and VCO [6]-[9]. Note that the previously published papers only used the side-by-side coupling for verification of EM susceptibility. The coupling effects were estimated with different spacing between the twisted inductor and the aggressor. However, the advanced 3D packaging technologies nowadays, such as InFO (Integrated Fan-out), CoWoS (Chip-on-Wafer-on-Substrate), and WoW (Wafer-on-wafer), make the practical EM interference becomes more complicated and unpredictable. The coupling varies upon the distance, orientation, and the field strength between the aggressor and victim. Therefore, a new approach for interference evaluation which can closely resemble the advanced 3D packaging condition rather than a relative simple side-by-side coupling test is highly desired.

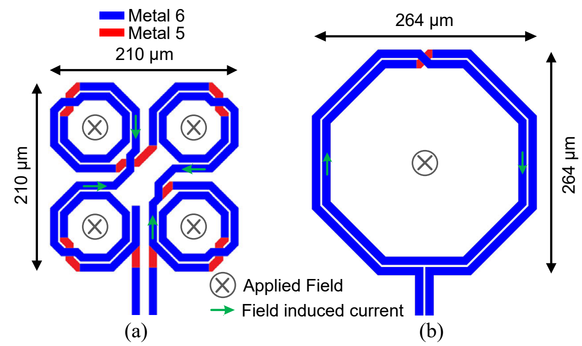

Fig. 1. Inductor topologies: (a) four-leaf-clover-shaped inductor and (b) conventional inductor.

In this work, the four-leaf-clover-shaped inductor based on the twisted layout scheme is employed to achieve a low susceptibility VCO design. Also, a novel chip-level near-field test setup is proposed to investigate the face-to-face 3D coupling effect for the first time. The susceptibility of the proposed VCO exhibits a significant improvement compared to the VCO built with the conventional spiral inductor.

II. VCO Design for Low EM Susceptibility

A. Four-leaf-clover-shaped Inductor

The four-leaf-clover-shaped inductor as shown in Fig. 1(a) produces equal but opposite magnetic fields which make the inductor be more immune to EM interference. From another point of view, assuming a field is applied on the inductor and the field-induced current is generated, the current in each lobe will flow along with the trace of inductor. As a result, the induced currents will cancel each other out because of the twisted layout. That means the inductance of the inductor will not be influenced by the applied field. In contrast, the conventional spiral inductor as shown in Fig. 1(b) will induce excess current that increases or decreases the effective inductance and further change the oscillation frequency of VCO.

A VCO using the 2-turn four-leaf-clover-shaped inductor is implemented by the TSMC 0.18-µm 1P6M CMOS technology. The inductor is with a width of 9 µm and a spacing of 2 µm. The radius of each lobe is 30 µm. For comparison, a conventional 2-turn inductor with the identical width and spacing is designed as shown in Fig. 1(b), while the radius is 112 µm to obtain a similar inductance as the four-leaf-clover-shaped inductor. The extracted quality factor (Q) and

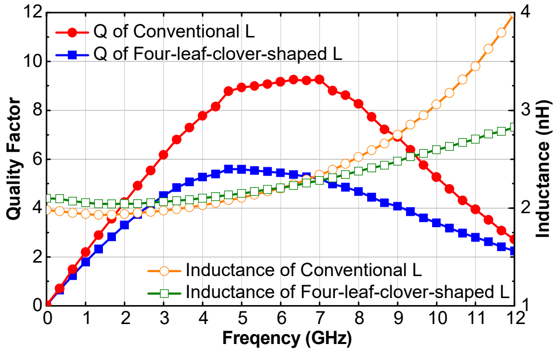

Fig. 2. Measured quality factor and inductance.

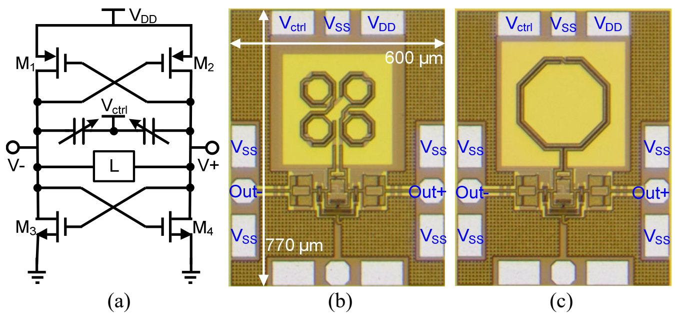

Fig. 3. VCO under test: (a) circuit topology (buffers not included), (b) VCO with the proposed four-leaf-clover-shaped inductor, and (c) VCO with conventional spiral inductor.

inductance are shown in Fig. 2. The Q of four-leaf-clover-shaped inductor and conventional inductor are 5.6 and 9.1 at 5.5 GHz, respectively. The lower Q of four-leaf-clover-shaped inductor is caused by the longer trace and more underpasses which add extra loss, but the impact on phase noise of VCO are not very obvious as shown in the measured results later. The inductances of four-leaf-clover-shaped inductor and conventional inductor are 2.18 nH and 2.15 nH at 5.5 GHz, respectively.

B. *VCO circuit*

The cross-coupled pair topology is adopted in the VCO design as shown in Fig. 3(a). The negative resistance used to replenish the tank loss and sustain periodic oscillation is formed by the cross-coupled pairs (M_1−M_4). The sizes of M_1 (or M_2) and M_3 (or M_4) are 49.5 μm/0.18 μm and 13.5 μm/0.18 μm, respectively. The varactor is implemented by the accumulation-mode MOS with the gate length of 0.5 μm and finger number of 10. Under a 1.8 V supply voltage, the dc power consumption of the core circuit and buffers are 6.5 mW and 6.1 mW, respectively. The measured output power with buffer is −5.5 dBm (cable loss included). A chip size of 0.6 mm×0.7 mm including the RF and dc bias pads is implemented.

In order to compare the performance, another VCO with the aforementioned conventional spiral inductor is implemented. The only difference in the design is the inductor in the LC tank. The chip micrographs are shown in Fig. 3(b) and 3(c), respectively. The tuning sensitivity and phase noise were measured by using the Agilent E5052B signal source analyser. Fig. 4 shows the measured frequency tuning range of 5.66−5.20 GHz with four-leaf-clover-shaped inductor and 5.69−5.26 GHz

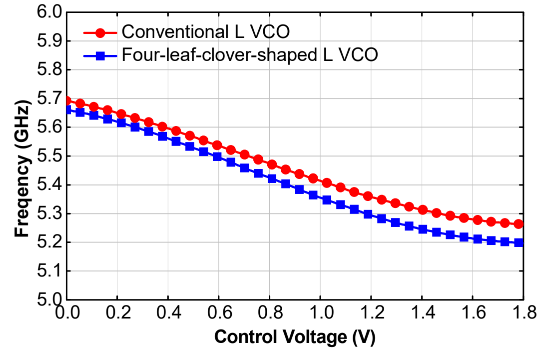

Fig. 4. Measured output frequency versus tuning voltage.

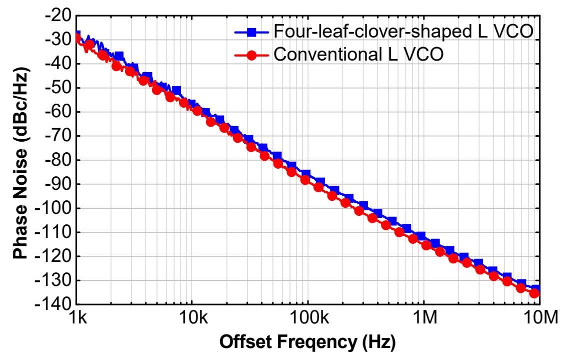

Fig. 5. Measured phase noise at 5.5 GHz.

with conventional inductor. The slight discrepancies between the two VCOs on tuning range and oscillation frequency could be attributed to the difference of inductance. Fig. 5 shows the measured 5.5 GHz phase noise of −134.19 dBc/Hz with four-leaf-clover-shaped inductor and −136.26 dBc/Hz with conventional inductor at a 10-MHz offset frequency. The discrepancies of two VCOs are considered to be negligible for the demonstration of the EM susceptibility measurement in the following section. It should be mentioned that the FoM for both designs exceed -180 dBc/Hz (-180.87 and -182.94 dBc/Hz for the proposed and reference designs respectively). The FoM could be further improved by optimizing the quality factor of inductor.

III. Chip-level Near Field Measurement and Results

In order to demonstrate the chip-level susceptibility measurement, a novel test configuration is proposed. Different from other reported evaluations which place the coupling coil beside the inductor of the VCO on the same die, the coupling coil in this work is set face-to-face the inductor of VCO as depicted in Fig. 6(a). This testing configuration can resemble the 3D packaging situation in modern multiple-chip stacking technology, which has not been reported before to the best of our knowledge. The coupling coil is realized by the integrated passive device (IPD) technology, which has three metal layers with a low loss tangent dielectric material of benzocyclobutene (BCB). The top metallic Cu layer of IPD with the thicknesses of 10 μm is deployed for the 1.5 turn coil with both trace width and spacing of 10 μm, and the radius of 105 μm as shown in Fig. 6(b). The size of coil is designed to have a similar size of inductor in VCO. Therefore, the generated magnetic flux from

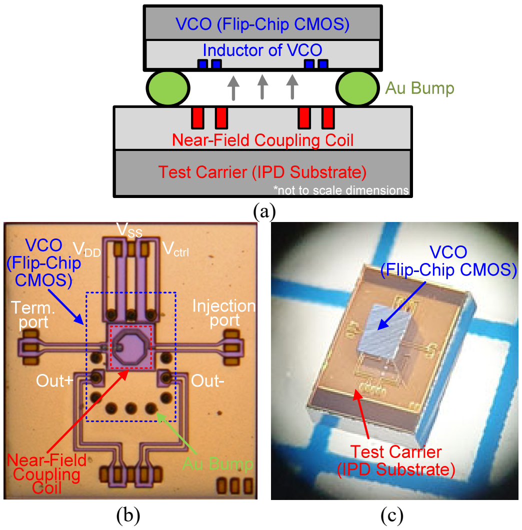

Fig. 6. Proposed chip-level test solution: (a) near field coupling test setup, and photographs of (b) IPD substrate, and (c) test carrier with VCO.

the injected signal can be coupled to the VCO effectively. The proposed face-to-face coupling could provide more uniform and stronger magnetic flux than the side-by-side coupling. With the flip-chip technology, the VCO under test was flipped and bonded on the IPD substrate as a test carrier as shown in Fig. 6(c). The Au bumps with the diameter of 70 µm and height of 30 µm not only support VCO above the test carrier, but also serve as the interconnects to supply dc voltage to VCO and carry out the oscillation signal from VCO to test carrier for observation.

The proposed method is defined to characterize the susceptibility of VCO in the presence of radiated RF disturbances. The whole measurement setup with instrumentations is illustrated in Fig. 7. The signal generated from signal generator was injected into the VCO through the cable harness, microwave probe, and coupling coil of test carrier. To observe the susceptibility, the output of VCO was connected to a spectrum analyzer. The susceptibility criterion of VCO is defined when injection locking is observed, and the injected power level which causes injection locking effect of VCO is recorded. The reference plane of the injected power was calibrated at the probe tip. In order to deliver enough power into the VCO, a power amplifier (Mini-Circuits ZVE-3W-83+) with a saturated output power of 3 W was added. The whole measurement was performed from 5.25 GHz to 5.75 GHz with a frequency step of 10 MHz. Fig. 8 shows the measured susceptibility results of two VCOs. As expected, the injected power to affect circuit operation becomes much higher with the four-leaf-clover-shaped inductor VCO. Also, the required power reduces at frequencies close to the self-resonant frequency of VCO. As can be seen, the susceptibility of VCO with the four-leaf-clover-shaped inductor achieves a significant improvement of over 30 dB in a wide frequency range (maximum of 32.2 dB and minimum of 26.3 dB) than that of VCO with conventional inductor. Based on the proposed novel 3D chip-level near-field measurement technique using IPD, the VCO with the four-leaf-clover- shaped inductor is proved to be much less susceptible to the radiated disturbance.

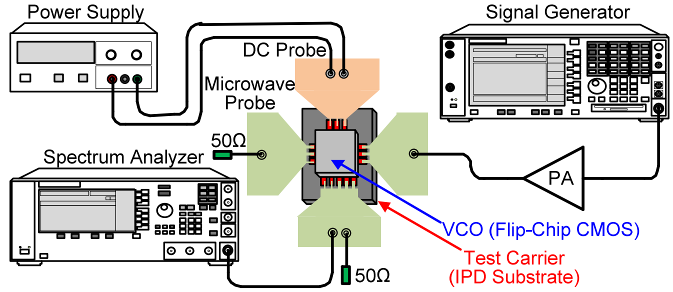

Fig. 7. Proposed chip-level near field measurement setup for evaluation of VCO susceptibility.

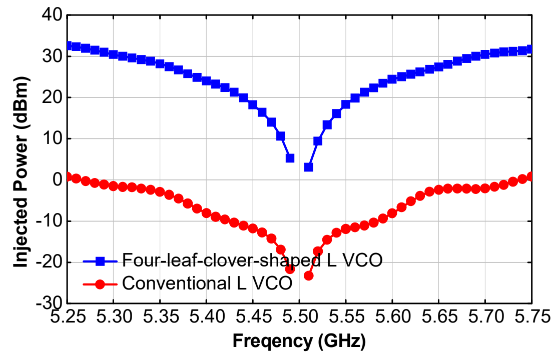

Fig. 8. Measured susceptibility results of VCOS.

IV. Conclusion

This paper demonstrated a voltage-controlled oscillator (VCO) realized by 0.18-µm CMOS with low EM susceptibility using a four-leaf-clover-shaped inductor. A new face-to-face testing scheme to resemble the modern 3D packaging was proposed by chip-level near-field coupling in IPD technology. The VCO with the four-leaf-clover-shaped inductor was verified by the proposed setup and exhibited a superior immunity than the conventional spiral inductor VCO. A significant improvement up to 32.2 dB in EM susceptibility was observed by the VCO with the four-leaf-clover-shaped inductor.

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