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# A Waveform-Shaping Millimeter-Wave Oscillator with 184.7dBc/Hz FOM in 40nm Digital CMOS Process

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**Abstract**—In this paper, a topology for millimeter-wave (mm-wave) oscillator with a waveform-shaping operation is proposed with improved phase-noise. The 3<sup>rd</sup> Harmonic enhancement for enforcing a pseudo-square voltage waveform and adjustable tuning-banks for wide tuning range are simultaneously achieved, based on a multi-stage broadside-coupled transformer (MSBCT) with reconfigurable coupling factors at mm-wave. Meanwhile, to meet the high- $Q$ , high-resolution, and metal density limits, a novel 3D self-shielded capacitor is developed for implementation of tuning-banks operating at mm-wave. To verify the mechanism and structures above, a waveform-shaping mm-wave digitally-controlled oscillator (DCO) is fabricated. The proposed oscillator has a state-of-the-art figure-of-merit (FoM) of 184.7dBc/Hz at 58.1 GHz under 110°C, despite being realized in a digital CMOS 40nm process without customary ultra-thick metal option. The resolution for this DCO is about 2.5MHz within the whole tuning range. The chip micrograph with core size of 315um by 110um.

**Index Terms**—3D self-shielded capacitor, digitally-controlled oscillator (DCO), multi-stage broadside-coupled transformer (MSBCT), waveform-shaping, millimeter-wave (mm-wave).

## I. INTRODUCTION

Millimeter-wave (mm-wave) oscillators for high-data-rate wireless communications in 60GHz and E-band require very low phase noise at preferably low power consumption [1], thus historically favoring SiGe technology. Recently, waveform-shaping has been explored at single-GHz frequencies in CMOS technology to create a square-like waveform (through clipping or harmonic shaping [2]) of the oscillation voltage across the tank, which results in a lower rms value of the impulse sensitivity function (ISF) and thus less circuit noise contribution to phase noise. At the mm-wave, however, an attempt at controlling odd harmonics of the square-like signal (see equation in Fig. 1) is utmost challenging due to parasitics. Furthermore, to overcome severe degradation of varactor- $Q$  at mm-wave, digitally controlled oscillators (DCOs) with digitally controlled artificial dielectric (DiCAD) were developed [3]. Nevertheless, the coupling among adjacent units of DiCAD degrades linearity of the tuning banks [4].

In this work, the phase noise and figure-of-merit (FoM) of a mm-wave oscillator are significantly improved in digital CMOS technology in order to make it competitive compared to SiGe. Two techniques are introduced: (1) tank of tri-coupled resonators for waveform-shaping through harmonic tuning to achieve low phase noise; and (2) high- $Q$  3D self-shielded capacitors for highly linear frequency tuning without the tanks  $Q$ -factor degradation.

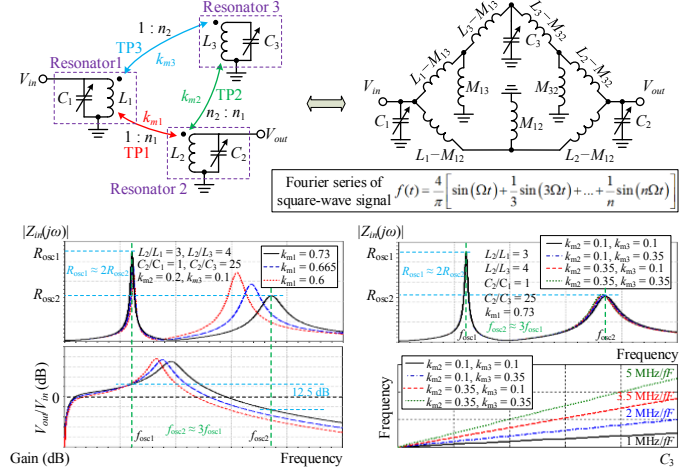


Fig. 1. Concept and topology of the tri-coupled resonator using multi-stage transformer.

## II. OSCILLATOR TOPOLOGY AND OPERATION

The first proposed technique creates harmonics in the mm-wave oscillator tank, which uses the tri-coupled resonators consisting of primary, secondary, auxiliary windings and tuning capacitors. The multi-stage transformer (i.e., TP1, TP2, and TP3) as shown in Fig. 1 is introduced to realize windings in the resonator. Two main resonances (i.e.,  $f_{osc1}$  and  $f_{osc2}$ ) can arise and be adjusted to  $f_{osc2} = 3f_{osc1}$  with magnetic coupling around  $k_{m1}$  of 0.73, while  $k_{m1}$  is with a function of  $L_2/L_1$ ,  $L_2/L_3$ ,  $C_2/C_1$ , and  $C_2/C_3$ . The coupling factors  $k_{m2}$  and  $k_{m3}$  of TP2 and TP3 can affect the tuning step size, only with slight shift of  $f_{osc2}$  (i.e.,  $f_{osc2} \approx 3f_{osc1}$ ). Note that, the 1-dB bandwidth of  $\text{mag}(f_{osc2})$  in the transfer function from passive tank is about 15%, which affords a wideband tolerance of frequency shifting to meet the  $f_{osc2}$  magnitude limits of equation in Fig. 1 with proper loop gain. Therefore, the fundamental frequency and third-order harmonic can coexist in the tank, thus meeting the requirements to implement a square-like waveform. Considering that the coupling factors are the key issue to control the resonances for waveform-shaping, the multi-stage broadside-coupled transformer (MSBCT) is introduced as depicted in Fig. 2. The primary, secondary, and third windings of the MSBCT are implemented on different metal layers (M7, M8, and AP). The primary and secondary windings are broadside-coupled with an overlap of  $d$ , which can enhance the magnetic coupling for improved coupling

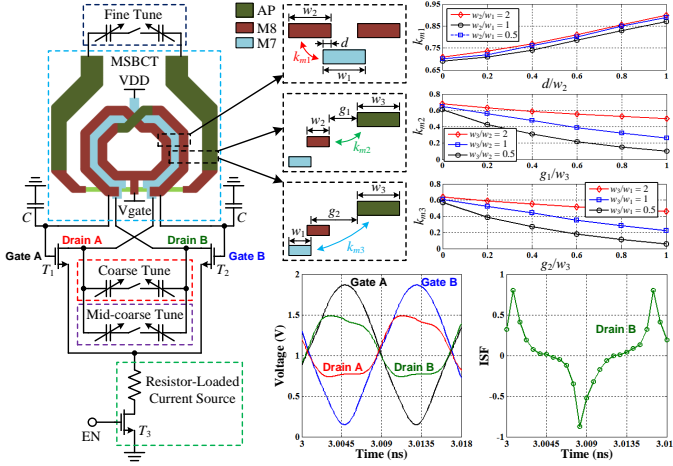


Fig. 2. Schematic and transformer layout of the mm-wave waveform-shaping oscillator.

factor  $k_{m1}$ . Considering the substrate height among the metal layers, the third winding is located on the AP layer with relative large gaps ( $g_1$  and  $g_2$ ) to the former two windings for decreasing the coupling. Therefore, to properly adjust the ratios of width ( $w_2/w_1$ ,  $w_3/w_2$ , and  $w_3/w_1$ ) under various cases of overlap/gap to width ratios ( $d/w_2$ ,  $g_1/w_3$ , and  $g_2/w_3$ ), respectively, the coupling factors of  $k_{m1}$ ,  $k_{m2}$ , and  $k_{m3}$  can be precisely controlled. To introduce enough loop gain of the tank, transistors  $T_{1,2}$  operate in the triode-region. The resistor-loaded tail is used to fix the oscillator current. Once powered up, the oscillator starts fluctuating at fundamental frequency since it needs lower loop gain. Then, as the oscillation amplitude grows, the current and loop gain increase. Therefore, the second resonance is excited. With a limited current from the source tail, the magnitude of the dual resonances go to a steady state of  $\text{mag}(f_{osc1}) \approx 3\text{mag}(f_{osc2})$ . Thus, the waveform-shaping of the oscillator at mm-wave is achieved with ISF of lower rms (enhanced flatness in the oscillator period), which further improves the phase noise and power efficiency compared to the conventional mm-wave oscillators.

The capacitor design in the resonant-tank is also the key issue affecting the final oscillator performance (i.e., phase noise and tuning step with good linearity). In order to further reduce the losses and improve the  $Q$ -factor, a 3D self-shielded capacitor is proposed, as shown in Fig. 3. There are two main contributions to the capacitance. The first part is due to the horizontal surrounding coupling, which is denoted by  $C_h$  (red); the second part is the vertical surface-to-surface coupling through the substrate, which is denoted by  $C_v$  (blue). The goal is to maximize  $C_h$ , while minimizing  $C_v$ , in order to avoid the capacitive coupling through the substrate with lossy dielectric. Especially in mm-wave operation, this implementation (i.e.,  $C_h > C_v$ ) effectively reduces the substrate loss and greatly improves the  $Q$ -factor. Under limits of the 40nm CMOS DRC rules, the smallest unit cell operating at 60 GHz can introduce a capacitance around 2fF and  $Q > 40$ . Note that, the value of the horizontal capacitors  $C_h$  can be properly adjusted by

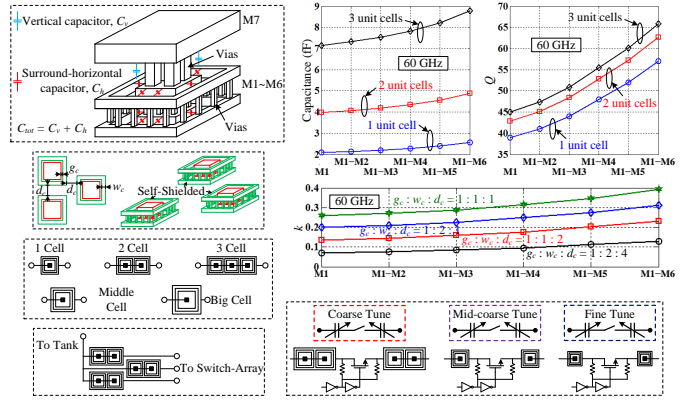


Fig. 3. Characteristics, layout, and implementation of the proposed 3D self-shielded capacitor.

the stacked metal layers (i.e., M1–M6), which make a good enough flexibility to achieve specific design requirements. Considering the stacked structure of the capacitor, it is easy to meet the limits of metal-density in the nanoscale CMOS technology. Meanwhile, the self-shielding of the proposed capacitor can decrease the coupling effect to the adjacent cells under a proper ratio of dimensions (i.e.,  $g_c : w_c : d_c$ ), which can further improve the linearity of switched-capacitor array. In addition, the proposed capacitor is flexible to achieve different capacitance (i.e., large, middle, and small) with various composition of unit cells, as shown in Fig. 3. Based on the proposed 3D self-shielded capacitor, the switch-cap arrays (coarse-, middle-, and fine-bank) in the tank with high linearity and high- $Q$  are achieved, simultaneously.

### III. IMPLEMENTATION AND EXPERIMENTAL RESULTS

The prototype oscillator is fabricated in 40nm 1P8M digital CMOS without ultra-thick-metal. The core transistors  $T_{1,2}$  are 22.5um/40nm. The positive feedback is realized by a 1:2 step-up broadside-coupled transformer (TP1) with primary and secondary  $Q$  factors of 10 and 16, respectively. The  $Q$  of the third winding in the additional transformer is about 18. 34 switched loaded self-shield capacitors (C0-C17 and M0-M15) across secondary winding form the coarse tune and mid-coarse tune banks. Meanwhile, a pair of fixed capacitors adjust the  $f_{osc2}$  near  $3f_{osc1}$  for specific frequency tuning range (about 15%) with the improved phase noise. Besides, 25 and 7 switched loaded self-shield capacitors (F0-F24 and P0-P6) located on the third winding are used to achieve fine-tune banks with PVT tolerance.

Measured characteristics of the proposed waveform-shaping mm-wave oscillator are obtained by a test setup, as shown in Fig. 4. The phase noise is tested using the external fundamental down-converter and R&S signal source analyzer with a PLL-mode. The oscillator spectrum is directly measured using the R&S spectrum analyzer. The results in Fig. 4 are tested in a temperature chamber at 110°C. The phase noise of -99.5dBc/Hz at 1MHz offset with a 58.1 GHz carrier is achieved with an output power of -5.41 dBm. Figure 5 shows

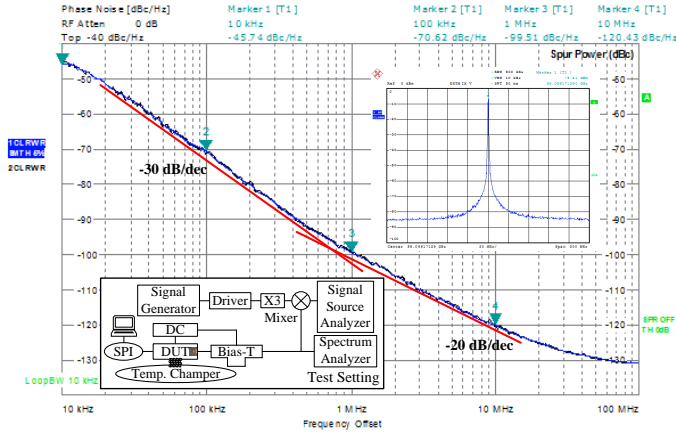


Fig. 4. Measured phase noise and spectrum with a 58.1 GHz carrier at 110°C temperature.

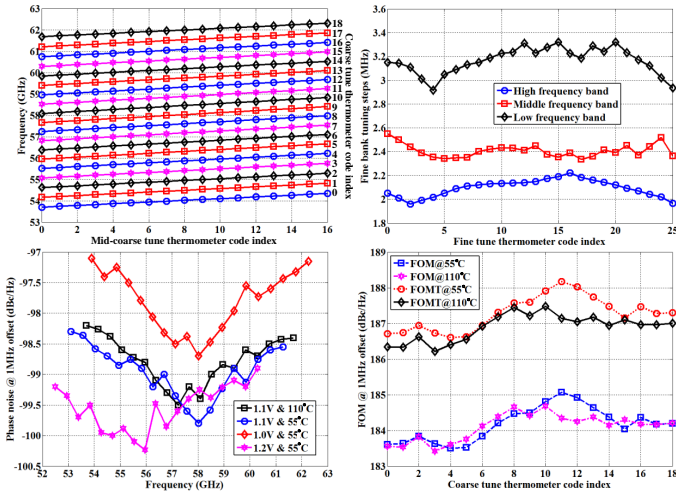


Fig. 5. Measured results of the frequency range and step sizes for coarse, mid-coarse, and fine tuning banks; phase noise at 1MHz offset at different carriers; FOM and FOMT at different coarse-band settings.

the tuning-bank characteristics of the oscillator with good linearity. The fine-tuning steps of 2.1, 2.4, and 3.2 MHz are achieved at lower, middle, and high operating frequencies, respectively. The phase noise, FOM, and FOMT under different temperature conditions demonstrate that the proposed waveform-shaping mm-wave oscillator has a competitive performance, covering the whole operation frequency bands with tuning ranges around 14.8%.

Experimental results are summarized and compared to recently reported mm-wave oscillators (i.e., VCOs and DCOs in various CMOS and SiGe processes) in Fig. 6. The proposed waveform-shaping oscillator has a state-of-the-art FOM of 184.7dBc/Hz at 58.1 GHz under 110°C, despite being realized in a digital CMOS 40nm process without the customary ultra-thick metal option. The chip micrograph with core size of 315um by 110um is shown in Fig. 7.

	This Work	ISSCC 2009 [1]	IMS 2009 [3]	JSSC 2013 [4]	ISSCC 2011 [5]	ISSCC 2013 [6]
Process Technology	CMOS 40nm	SiGe	CMOS 90nm	CMOS 90nm	CMOS 65nm	SiGe N/A
Supply Voltage (V)	1.1	3	1.2	1.2	1	1.5
Center Frequency (GHz)	58.1	52.9	61.05	60.86	58.2	32.9
Tuning Range (GHz)	53.7-62.3	45.5-59.4	58.3-63.8	55.8-61.6	56-60.35	28-37.8
Tuning Range (%)	14.8	26.5	9.3	9.89	7.48	29.8
Phase noise (dBc/Hz)	100 kHz	-70.6	-81	-66	N/A	-65.9
	1 MHz	-99.5	-108	-97	-90.1	-94
	10 MHz	-120.4	-130	-118	N/A	N/A
Phase noise (dBc/Hz) Norm. to 60GHz	100 kHz	-72.3	-79.9	-65.7	N/A	-65.8
	1 MHz	-99.2	-106.9	-96.7	-90.25	-93.9
Power consumption (mW)	10	132	10.6	14	22	10.5
FoM at 1 MHz (dBc/Hz)	184.7	181.1	175.6	178.1	179	183.9
FoM <sub>T</sub> at 1 MHz (dBc/Hz)	188.9	189.6	174.9	177.9	171.8	193.5
Oscillator core area (mm <sup>2</sup> )	0.035	0.168	0.01	0.068	0.075	0.03
Oscillator type	DCO	VCO	DCO	DCO	VCO	VCO
Oscillator description	Waveform-Shaping	Push-Push	DICAD	Passive Resonator	Quadrature	Current-Redistribute

$$\text{FoM} = 20 \log(f_0/\Delta f) - \text{PN} - 10 \log(P_{DC}/\text{mW})$$

$$\text{FoM}_T = 20 \log(f_0/\Delta f \cdot \text{FTR}/10) - \text{PN} - 10 \log(P_{DC}/\text{mW})$$

Fig. 6. Performance summary and comparison with state-of-the-art mm-wave oscillators.

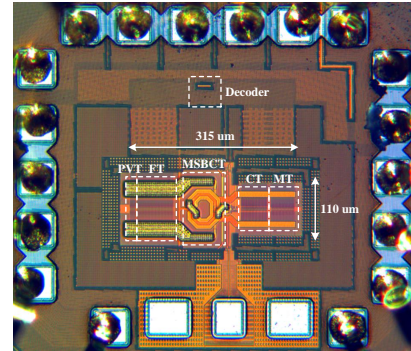


Fig. 7. Chip micrograph of the proposed mm-wave waveform-shaping oscillator.

## IV. CONCLUSION

In this paper, the novel MSBCT and 3D self-shielded capacitor are utilized to design mm-wave DCO, which can achieve waveform-shaping and high-resolution tuning, simultaneously. Phase noises in the whole tuning-band is specifically optimized for improved performance. The state-of-the-art measured results of the mm-wave DCO around 60GHz is first achieved.

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