A V-band Voltage Controlled Oscillator with Greater than 18GHz of Continuous Tuning-Range Based on Orthogonal E mode and H mode Control

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***Abstract* — A technique to achieve an extended continuous tuning range for Voltage Controlled Oscillators (VCO) is presented. The technique is scalable and the theory could be applied to achieve wide tuning range VCOs operating at arbitrary center frequency; however, it is more desirable at mm-wave regime (V-Band in this case) as it alleviates the need for switches and big varactor banks. The technique incorporated here relies on separate E and H mode excitation of the resonator, while avoiding the Q-degrading switches. The standing-wave V-band VCO reported here is implemented in 65-nm CMOS technology and achieves a continuous tuning range from 58 GHz to 76.2 GHz, with an average phase noise of -89.5 dBc/Hz at 1 MHz offset across the entire band, consumes an average of 5.8 mW (excluding the output buffers), and thus achieves a record FoM.**

***Index Terms* — mm-wave, multi-band, continuous-tuning, wide-band, E-mode, H-mode, oscillator, VCO, V-Band, software-defined radio, CMOS.**

I. Introduction

Driven by the goal of achieving a multi-band, multi-standard, as well as a reconfigurable radio or one that can adjust and optimize its performance under any operating condition, many different tuning and reference signal generation schemes have been envisioned and implemented in the lower GHz regime (below the Ku band). There is a growing interest in implementing similar ideas in the higher GHz band. For example, there is the unlicensed 57-64 GHz band, applicable for wide-band communication, as well as the three licensed 71-76 GHz, 81-86 GHz, and 92-95 GHz applicable for point-to-point fixed wireless communication such as last-mile access bottlenecks. There is also an interest in wireless chip-chip communication.

Wide-band tuning techniques commonly implemented in the lower GHz regime are in the form of varactor/capacitor-bank sizing, inductor switching [1], or transistor core size switching [2]. In case of capacitor switching variously sized varactors/capacitors are connected to the resonator and enabled with switches. In case of inductor switching [1], either variously sized inductors are switched and connected to the resonator, or various inductors' coupling is switched and controlled [1] so that the effective total inductance is changed. These techniques, however, are not as readily applicable to higher GHz bands for the reason that the switches are along the path of the signal oscillation and as a result themselves as well as their parasitic deteriorates the loaded Q-factor. As a result, various techniques have been proposed to address the problem and attain a wider frequency range.

Multiplexing multiple VCOs has been proposed, and implemented in a PLL [3]; the disadvantage is in added area for multiple VCOs and power consumption for the multiplexer, as well as the loss introduced. In order to minimize the effect of the switches in the signal path, [4,5] mode selection/capacitor control switches have been implemented so that they are not enabled during the whole cycle of oscillation. In [4], due to the dynamics of the system two resonances are possible, and the switches control which tone to oscillate at; once a tone is selected that is the only stable oscillation frequency for the circuit, the switches are not needed anymore, and they are opened. The timing for the switch control (enabling/disabling) has to be well controlled/modeled, otherwise the tone could drift to the other resonance condition and create confusion. Moreover, the asymmetry of the oscillation could cause flicker noise up-conversion and thus poor phase noise performance. In [5], a technique has been introduced to exploit the capacitance in differential mode vs. common mode, to create two different discrete oscillation frequencies, and also ideally minimize the effect of the switches. However, to get more discrete tones, and produce 2^N tones, many inductors are still needed. Transmission lines could be exploited for higher frequency and bandwidth operation due to their distributed nature. In [6] a standing-wave VCO is implemented with coplanar-stripline (CPS), and oscillation tuning is achieved by shorting different lengths of the transmission line, as well as varactors. Since the switches are used to short the length of the transmission line their parasitic and series resistance directly affects the Q-factor of the resonator and to mitigate it the switches are made very big. The parasitic capacitance thus introduced as well as

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the poor R_{on}/R_{off} ratio of the switches affects the center frequency, as well as bandwidth, power consumption, and phase noise.

In order to address the aforementioned problems, a technique based on E and H mode excitation of a transmission line resonator configured in a standing-wave VCO topology is proposed in this paper, that is able to achieve very wide bandwidth, high frequency, as well as good phase noise with low power consumption, while occupying a small die area, since only one resonator is required for the entire frequency band.

II. THE RESONATOR DESIGN CONCEPT, E-MODE H-MODE

A. The Resonator

Transmission lines in various configurations, in particular the quarter wave resonator, and their various applications have been discussed extensively in the literature. Moreover, the wave propagation on transmission lines with both open, and short ended configurations have also been elaborated on. In this work the loaded transmission lines is excited under both open and short termination, via the E-mode or H-mode excitation, as means of mode selection, in order to achieve a wide tuning range while avoiding the detrimental switches. When a transmission line is excited to be shorted at one end, any capacitor at that end would be ineffective, whereas the capacitor at the open-end will be effective at determining the resonance frequency.

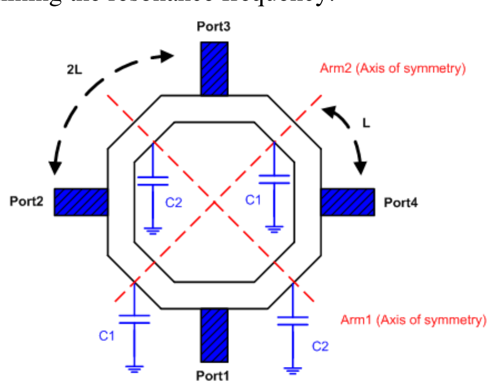
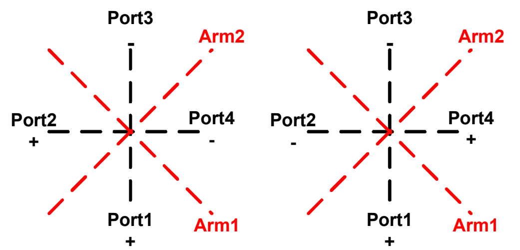


Fig. 1. The resonator structure, illustrating the transmission line, capacitor banks, axis of symmetry, as well as the excitation ports.

Figure 1, illustrates the structure of the resonator, with the capacitor/varactor bank, axis of symmetry, and the four excitation ports highlighted. Cross-coupled pairs control the excitation ports in the way that ports 1 and 3 are connected to one complementary (NMOS and PMOS) set, whereas ports 2 and 4 to another. In this way, ports 1 and 3 are always 180 degrees out of phase, as well as ports 2 and 4. Ports 1 and 2, and 3 and 4 are controlled to be either in phase, or 180 degrees out of phase, as pictured in Figure 2. When ports 1 and 2 are in phase, ports 3 and 4 are also symmetrically in phase, whereas when ports 1 and 2 are 180 degrees out of phase, ports 3 and 4 are also 180 degrees out of phase.



(a) (b)

Fig. 2. Resonator excitation ports polarity. 1 and 3 (2 and 4) always 180 degrees out of phase, whereas in (a) 1 and 2 (3 and 4) are in phase, and in (b) 1 and 2 (3 and 4) are 180 degrees out of phase.

Depending on how the ports are excited, when ports 1 and 2 (3 and 4) are in phase, as in Fig. 2(a) Arm2 is an H field boundary, forming an open circuit, and Arm1is an E field boundary, forming a virtual ground, Fig. 3. On the other hand, when ports 1 and 2 (3 and 4) are out of phase, as in Fig. 2(b), Arm2 is an E field boundary and Arm1 is an H field boundary, Fig. 4. The in-phase control is implemented with switches, as explained later. When the switch is turned on ports 1 and 2 (3 and 4) are in phase, and when it's open, ports 1 and 2 (3 and 4) are out of phase by 180 degrees and instead 1 and 4 (2 and 3) are switched to be in phase. As the resonator has only two degrees of freedom, only one of the modes is favored at any time. The significant point is that the switch is only turned-on to inhibit one unwanted mode, and does not degrade the other desirable mode. The resonance condition corresponding to each case is discussed below. Due to the symmetry of the design only one pair of ports are taken into analysis.

The resonance condition corresponding to the configuration in Figure 3 can be stated as in (1).

$$\omega \cdot C_1 \cdot Zline = 2 \cdot \cot(2 \cdot \theta) \qquad (1)$$

The resonance condition corresponding to Figure 4 can be stated in (2).

$$\omega \cdot C_2 \cdot Zline = 2 \cdot \cot(2 \cdot \theta) \qquad (2)$$

As can be seen in (1) and (2) the resonance frequency depends on four designable variables, C_1 and C_2

capacitance/varactor banks, Z_{line} the characteristic impedance of the transmission line, and the electrical length of the transmission line. As a result an optimization scheme is required to fit the frequency range while achieving the best performance from the VCO.

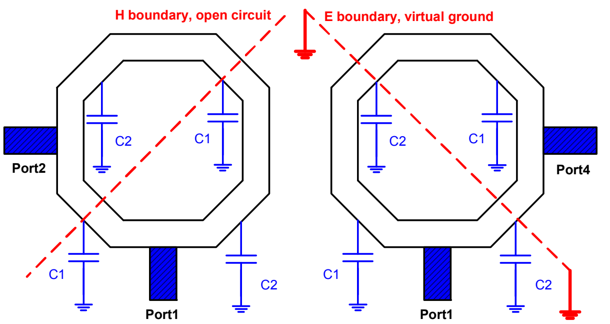


Fig. 3. Resonator structure analysis when ports 1 and 2 are in phase and 1 and 4 are 180 degrees out of phase.

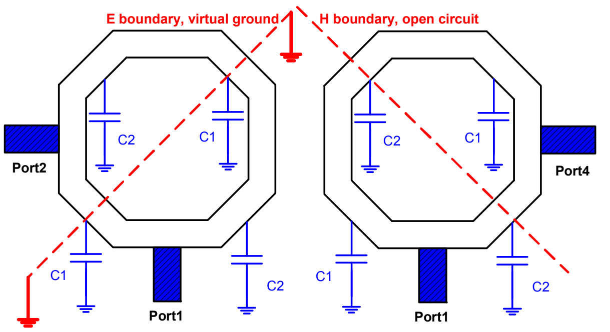


Fig. 4. Resonator structure analysis when ports 1 and 2 are 180 degrees out of phase and 1 and 4 are in phase.

A design curve is presented in Figure 5, where the sweep of characteristic impedance vs. the capacitance bank for Arm1 is studied for the higher V-Band coverage.

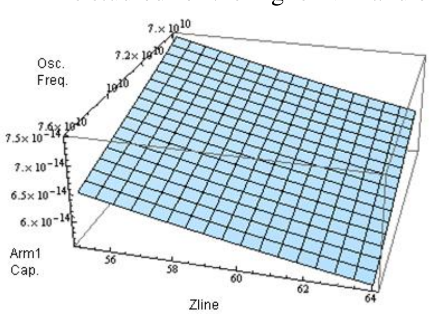


Fig. 5. Sample design curve for high V-band coverage.

B. Mode selection switches

A mode selection switch exists between port 1 and 2, 1 and 4, as well as port 3 and 2, 3 and 4. The switches are a single small NMOS device (4 um/0.065 um) and their only purpose is to separate the two modes (E and H). Since the two modes are orthogonal and could co-exist, the switches parasitic and Ron inserted in one mode does not degrade the performance in the other mode. Their only goal is to provide a higher loss for the undesired mode, so that the undesired mode doesn't resonate as readily as the desired one. For example, in case of H-mode (Fig. 3), the switch is short between ports 1 and 2, and 3 and 4 to force them in phase, thus making 1 and 4, and 2 and 3 out of phase inhibiting the E-field oscillation.

C. Cross coupled pairs

Two identical cross coupled pairs are connected to the resonator at the excitation ports as shown in Figure 6.

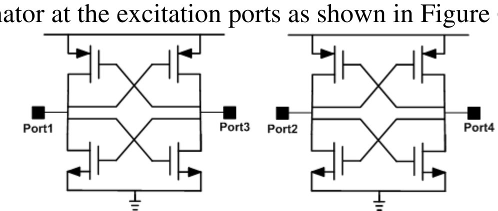


Fig. 6. Cross coupled pairs connection at the excitation ports

A complementary (NMOS and PMOS) style is chosen to lower the power consumption (taking advantage of negative trans-conductance from PMOS and NMOS with the same current), as well as improve the flicker noise performance in the close-in phase noise spectrum due the symmetrical waveforms of the structure.

D. Capacitors and varactors

The only two identical small varactors (not degrading the Q) are inserted across the cross-coupled pairs, ports 1 and 3 (2 and 4), controlled with same voltage. Fixed MoM capacitors are used for C_1 and C_2, with C_1 being smaller, thus providing the higher V band. To fully exploit the symmetry of the structure for finer controls, fixed MoM capacitors are also implemented between ports 1 and 2 (3 and 4), and 1 and 4 (2 and 3). When the ports are in phase the capacitor is open and in-effective, where as when 180 degrees out of phase the effective capacitance is doubled.

III. IMPLEMENTATION AND MEASUREMENT

The VCO is implemented in 65 nm CMOS technology, and the die picture is presented in Figure 7. In order to create contact points for the excitation ports and minimize the routing, the transmission line is bent in-ward at the ports. The area is 177 μm x 177 μm.

The VCO is measured using a harmonic mixer on the spectrum analyzer. Two sample tones are presented in

Figure 8, where the right most tone is the signal and the left one is the image. The loss in the harmonic mixer is de-embedded, but the loss in the cable is not and amounts to about -15 dB.

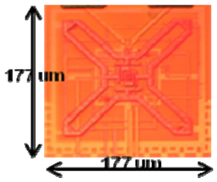


Fig. 7. Die area picture, 177 um x 177 um

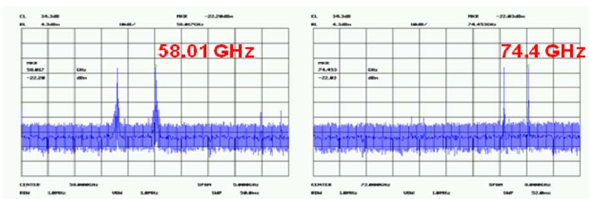


Fig. 8. Output spectrum from the VCO.

A sample phase noise plot is presented in Figure 9. It is widely known that measuring phase noise at mm-wave is challenging. The VCO is free-running, and the phase noise is averaged out over 10 measurements to improve accuracy.

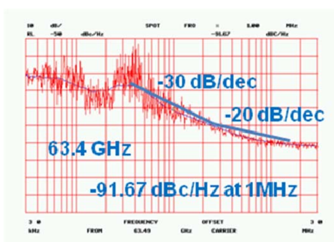


Fig. 9. Phase noise spectrum.

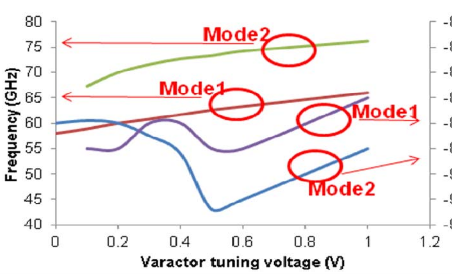


Fig. 10. Tuning frequency and phase noise vs. varactor tuning voltage for mode1 (E-mode) and mode2 (H-mode)

$$FoM(\Delta f) = L\{\Delta f\} - 20\log\left(\frac{f_0}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1mW}\right) - 20\log\left(\frac{TR}{10}\right)$$

For proof of concept, and to demonstrate range, in this design only one varactor is used. Varactors could be included along with C_1 and C_2 to further fine tune the range. A comparison with previously published continuous tuning VCO is conducted in Figure 11 according to the figure of merit (FoM).

Reference	F_0 (GHz)	TR (%)	Phase noise (dBc/Hz 1MHz)	Pdc (mW)	FoM (dB)
Y. Lin, VLSI, 2009	47.9	1.59	-102.5	5.6	-172.7
L. Li, JSSC, 2009	58.4	9.32	-91	8.1	-176.7
K. Scheir, ISSCC, 2008	49.9	12	-87	10.4	-172.4
B. Cath, CICC, 2009	60	16.7	-97.1	30	-182.3
M. Nariman, RFIC, 2010	39.9	15.1	-98.1	14.4	-182.1
This work	**67.1**	**27**	**-89.5**	**5.8**	**-187**

Fig. 11. State of the art FoM comparison table

IV. CONCLUSION

A V-Band VCO with greater than 18 GHz continuous tuning range is presented based on E and H mode excitation of a transmission line standing wave VCO, avoiding the switches degradation, and achieving a new record figure of merit (FoM). Figure 11 summarizes the results. The size is 177 µm x 177 µm.

REFERENCES

[1] M. Demirkan, et. al., "Design of wide tuning-range CMOS VCOs using switched coupled-inductors", IEEE JSSC, pp. 1156-1163, Vol. 43, No. 5, May 2008

[2] D. Hauspie, et. al., "Wideband VCO with simultaneous switching of frequency band, active core, and varactor size", IEEE JSSC, pp. 1472-1480, Vol. 42, No. 7., July2007.

[3] V. Jain, et. al., "A BiCMOS dual-band millimeter-wave frequency synthesizer for automotive radars", IEEE JSSC, pp. 2100-2113, Vol. 44, No. 8, Aug. 2009

[4] A. Goel, et. al., "Frequency switching in dual resonance oscillators", IEEE JSSC, pp. 571-582, Vol. 42, No. 3, March 2007.

[5] A. H-T. Yu, et. al., "a mm-wave arbitrary 2^N band oscillator based on even-odd mode technique", IEEE RFIC, pp. 141-144, June 2010

[6] J-C. Chien, et. al., "Design of wide-tuning-range millimeter-wave CMOS VCO with a standing-wave architecture", IEEE JSSC, pp.1942-1952, Vol. 42, No. 9, Sept.2007