A Compact 5GHz Standing-Wave Resonator-based VCO in 0.13µm CMOS

Dan Shi, Jack East and Michael P. Flynn

University of Michigan, Ann Arbor, MI, 48109

***Abstract*— A novel on-chip capacitively-loaded, transmission-line-standing-wave resonator is employed in a low phase noise VCO, to achieve a measured phase noise of -117dBc/Hz at a 1MHz offset. The prototype 5GHz VCO, implemented in 0.13µm CMOS, dissipates 3mW from a 1.2V supply, and occupies a compact die area of 0.11mm^2.**

***Index Terms* — VCO, CMOS, transmission line, resonator.**

I. Introduction

The phase noise of integrated oscillators is limited by the low quality factor of on-chip inductors. At 5GHz, inductor Q typically ranges from 5 to 15. Transmission-line-based standing-wave resonators have been used as an alternative to inductor-based resonant tanks, but this approach has been limited to very high oscillation frequencies (i.e. >15GHz). Furthermore, these oscillators tend to be large because the transmission line must measure an integer multiple of a quarter-wavelength [1].

To achieve a compact 5GHz standing-wave VCO, in this work two techniques are applied to significantly reduce resonator length so that a transmission line, measuring just $0.04\lambda_0$, achieves a simulated resonator quality factor of 35. The predicted resonator Q is confirmed by phase noise measurements of a prototype VCO. Periodic capacitive-loading reduces wave-velocity and wavelength; while capacitive termination reduces the required length of the transmission line to a fraction of the already reduced wavelength. A high Q is achieved because a short transmission line has low substrate and Ohmic losses. Furthermore, the oscillator operates at the frequency of peak resonator Q, not at the resonator self-resonant frequency.

II. Resonator Design

In this work, the length of the transmission line is shortened to below a half wavelength by terminating the differential transmission line with capacitors. A single-ended standing-wave-oscillator can be formed with a quarter-wavelength transmission line, connected at one end to AC ground, and at the other end to a negative resistance. A differential standing-wave-oscillator is formed by connecting a half-wavelength transmission line to a differential negative resistance. The amplitude of a standing wave along a transmission line is position-dependent and the current distribution along a linear transmission line resonator can be expressed as:

$$I(z) = I_0 \cos\left(\frac{2\pi}{\lambda} z\right) \tag{1}$$

where, λ is the wavelength in the transmission line, and z is the position, normalized to λ. This distribution along $|z|<\lambda/4$ is shown in Figure 1. The current density falls to 0 at the ends of the transmission line, where the voltage amplitude is maximum, whereas, the current density is maximum at the center of the line, where the voltage amplitude is 0.

A shorter transmission line can be used to achieve the same resonance frequency if the ends of the shorter transmission line are terminated with capacitance. Figure 1 shows that the current density at any point along the length of the modified transmission line is maintained the same as in the same section of the original line. The current distribution along the shorter line is identical to that in the corresponding portion of the original transmission line, and thus the same resonance frequency is achieved.

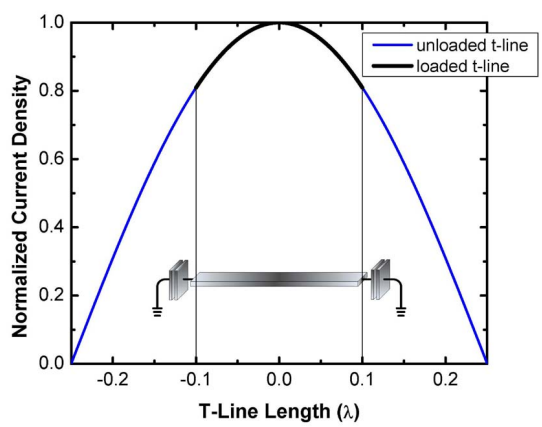
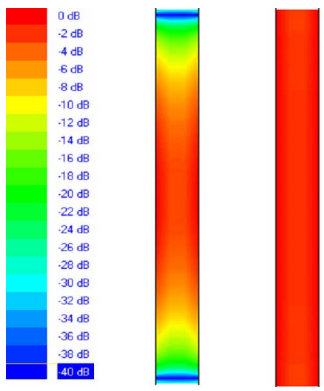


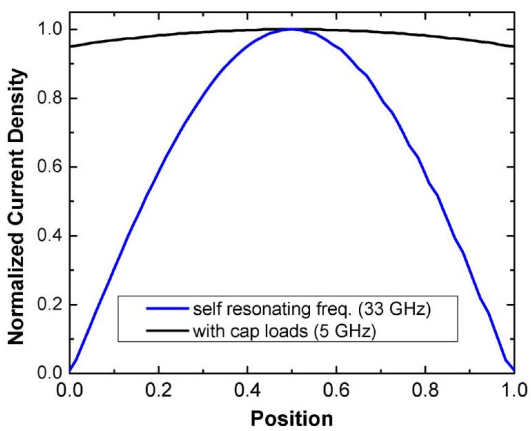
Figure 1: Current distributions on a half-wavelength and on a capacitively loaded transmission line.

A 3D EM simulator (Zeland IE3D) is used to compare the current density along a transmission line under two

different conditions. Without capacitive loading at the ends of the transmission line, $\lambda/2$ becomes equal to the length of the line, and the resonance frequency is 32GHz. With the addition of capacitive loading at the ends of the line, $\lambda/2$ becomes much larger than the length of the transmission line and the resonance frequency falls to 5GHz (Fig. 2(b) and 2(c)).



(a) (b)

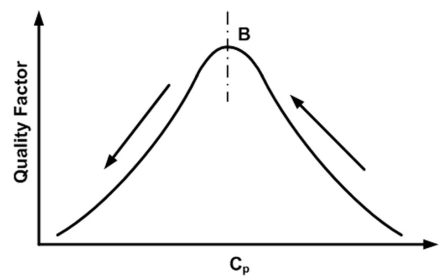


(c)

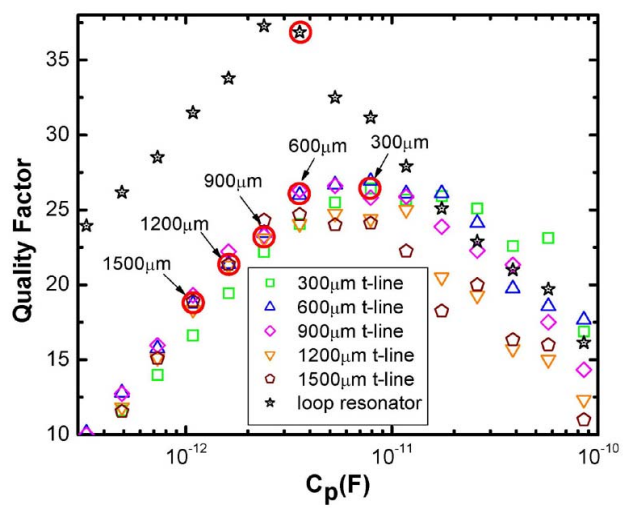
Figure 2: Simulated current distribution along a shortened transmission line; (a) at the self resonating frequency (32GHz), (b) with capacitive loads at the ends of the line (at 5GHz), and (c) simulated normalized current density along the transmission line for both cases

At the lower frequency, since the standing wave mimics that part of the standing wave in the central portion of a much longer transmission line, the current distribution is much more uniform. This is advantageous since because of the uniform distribution tapering is not required and a transmission line with a uniform width can be used.

In this work, we tradeoff transmission line length and termination capacitance, to achieve an optimum total resonator Q at a given frequency. This tradeoff is introduced qualitatively in Figure 3(a). The figure shows the variation in quality factor versus loading capacitance C_p. (It should be noted that since the line length is fixed the resonance frequency also changes with loading capacitance.) There are two distinct regions in the curve: a high capacitance (low frequency) region on the right side of line B, where metal resistance mainly determines the Q; and low capacitance (high frequency) region on the left, where the skin effect and energy coupling to the lossy substrate introduce more losses and the Q ceases to increase with frequency. To achieve best performance, the resonator should be loaded with capacitance to resonate around line B and achieve the peak quality factor.



(a)



(b)

Figure 3: (a) Qualitative variation in Q with load capacitance for a given transmission line length (b) Simulated quality factor versus loading capacitance for various transmission line lengths. The circles identify the capacitance values that achieve a 5GHz resonance frequency for each line length.

To achieve an optimum Q for a given resonance frequency, the tradeoff between line length and capacitance is examined. Five straight transmission line resonators, ranging in length from 300μm to 1500μm, and with various capacitive loadings are simulated. The simulation results are shown Figure 3(b), and for each line length a circle identifies the capacitance loading value that

achieves a 5GHz resonant frequency. The characteristic described in Figure 3(a) is apparent. We see that as predicted by [5], shorter transmission lines have larger Q at a certain frequency. This agrees with the equation describing the Q of an ideal half-wavelength transmission line:

$$Q = \frac{\pi}{2\alpha l} \qquad (2),$$

where α is the attenuation constant, l is the length.

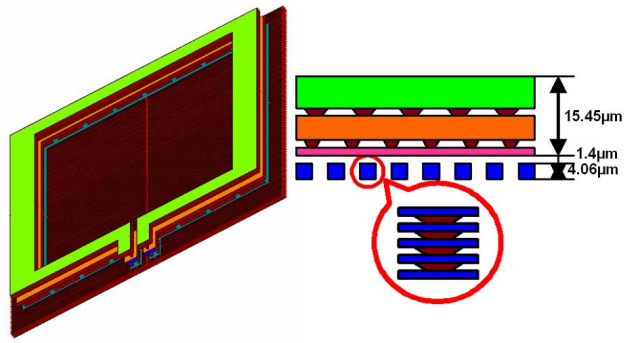


Figure 4: Capacitively-loaded slow-wave transmission line resonator.

As shown in Figure 4, the prototype resonator consists of a thick metal rectangular loop over a thin floating metal shield. To reduce Ohmic losses, the metal conductor of the resonator is formed with the top three metal layers, connected in parallel. The floating metal shield is formed with floating metal strips, with each strip formed with the lower five metal layers connected in parallel. This use of parallel strips not only helps reduce the strip resistance but also helps meet the stringent metal fill requirements of the 0.13μm process. Unlike the case with a conventional inductor, the top of the floating metal shield is relatively close to the conductor (only 1.4μm away), so that the shield deliberately loads the resonator with capacitances. Periodic capacitive loading introduces the slow-wave effect [2, 3]. The slow wave effect was demonstrated by H.M. Barlow [4], by placing an array of uniformly spaced parallel wires along a rectangular waveguide. Since the wave-velocity and wavelength are reduced, the slow wave effect allows size to be reduced, and the quality factor to be increased. (The predicted Q versus capacitive loading is over-laid on Figure 3(b).) The combination of the slow-wave-effect and capacitive loading at the ends reduces the length of the transmission line to only $0.04\lambda_0$ (λ_0 is the wavelength in free space).

III. Prototype Oscillator

A schematic of the prototype oscillator is shown in Figure 5. As in most LC oscillators, cross-coupled FETs introduce negative resistance. Current reuse due to the use of NMOS and PMOS cross coupled FETs improves power efficiency. Two 0.83pF capacitances are connected at the ends to the transmission line. Varactors are used to achieve 22% tuning range. Two common-source output buffers drive 50Ω loads. The prototype is fabricated in an 8-level-metal 0.13μm CMOS process with a 4μm thick top aluminum layer. A die micrograph is shown in Figure 6. The VCO occupies 0.11mm^2 and the total die area including pads is 0.29mm^2.

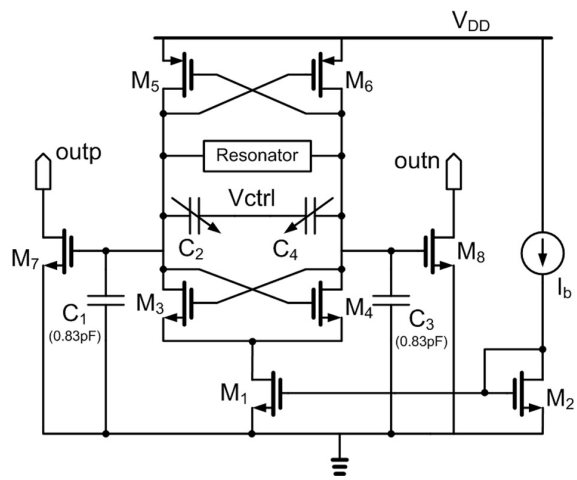


Figure 5: VCO schematic.

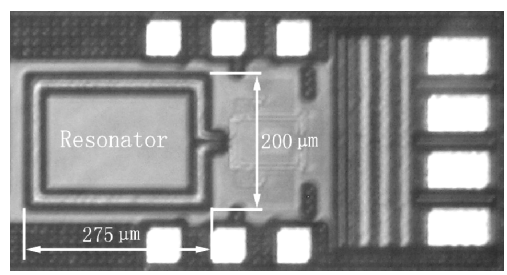


Figure 6: Die micrograph.

IV. Measurement Results

Figure 7 shows the measured performance of the oscillator. A phase noise of -117dBc/Hz at 1MHz offset is achieved. Over a 10% tuning range the phase noise at a 1MHz offset is less than -106dBc/Hz. The VCO core draws 2.5mA from a 1.2V supply. To compare the performance of our design with other published work, the figure of merit:

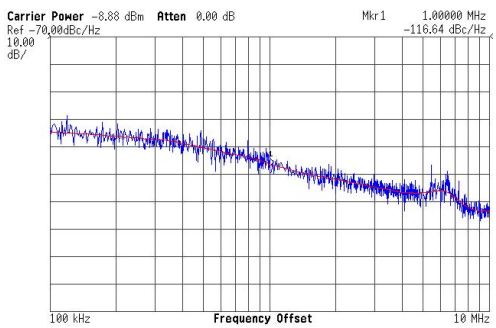
$$FOM = L(f_0) + 10 \cdot \log\left({P_{DC}}/{1mW} \right) - 20 \cdot \log\left({f_0}/{f_{offset}} \right) \qquad (3),$$

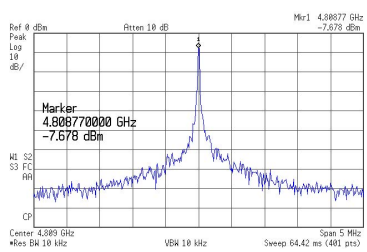
is used. This prototype is compared with other recently published VCOs that operate in the 5GHz frequency range

TABLE I: FOM COMPARISON.

Reference	Technology	f_0 (GHz)	Power Supply (V)	P_{DC} (mW)	PN (dBc/Hz at 1MHz)	Die area (mm^2)	Tuning (%)	FOM (dBc/Hz)
This work	CMOS 0.13μm	4.81	1.1 to 1.3	3	-117	0.11	22	-186
[6]	BiCMOS SiGe 0.18μm	5.67	1.5	2.4	-119	0.49	15	-191
[7]	BiCMOS SiGe 0.35μm	5.6	2.7	13.5	-117	0.20	10	-180
[8]	CMOS 0.18μm	5.5	1.8	3.6	-115	0.84	20	-184

in Table 1. This prototype on-chip resonator based outperforms most recently published CMOS VCOs in terms of phase noise, tuning range and die area.





Phase Noise	-117dBc/Hz at a 1MHz offset
Figure of Merit	-186dBc/Hz
Operating Frequency	4.81 GHz
Frequency Tuning Range	22%
Supply Voltage	1.2 V
Power Consumption	3mW
Die Area	0.11mm^2

Figure 7: Measured phase noise and VCO performance summary.

V. CONCLUSION

One of the most efficient methods to lower the phase noise of an oscillator is to increase resonator quality factor. However, the quality factor of an on-chip inductor is usually low due to substrate losses and metal interconnect losses. A compact standing-wave transmission-line resonator is utilized to achieve higher quality factor, and hence reduce phase noise and power consumption.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of Zeland and MOSIS. This work was supported by the WIMS-ERC, Engineering Research Centers program of the NSF under Award Number EEC-9986866.

REFERENCES

[1] W. F. Andress and D. Ham, "Standing wave oscillators utilizing wave-adaptive tapered transmission lines," *IEEE J. Solid State Circuits*, vol. 40, pp. 638-651, 2005.

[2] T. S. D. Cheung, J. R. Long, K. Vaed, R. Volant, A. Chinthakindi, C. M. Schnabel, J. Florkey, and K. Stein, "On-chip interconnect for mm-wave applications using an all-copper technology and wavelength reduction," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, 2003, pp. 396-501 vol.1.

[3] H. Jia-Sheng and M. J. Lancaster, "Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filters," *IEEE Trans. Microw. Theory Tech.*, vol. 44, pp. 2099-2109, 1996.

[4] H. M. Barlow, "Dipole-type-mode propagation in a rectangular waveguide," *Proc. IEE*, vol. 121, pp. 1363-1366, 1974.

[5] D. M. Pozar, *Microwave engineering*, 2nd ed. New York: Wiley, 1997.

[6] H. Ainspan and J. O. Plouchart, "A comparison of MOS varactors in fully-integrated CMOS LC VCO's at 5 and 7 GHz," in *Proc. ESSCIRC*, 2000, pp. 447-450.

[7] G. De Astis, D. Cordeau, J. M. Paillot, and L. Dascalescu, "A 5-GHz fully integrated full PMOS low-phase-noise LC VCO," *IEEE J. Solid State Circuits*, vol. 40, pp. 2087-2091, 2005.

[8] C. Jae-Hong, Y. Yong-Sik, P. Mun-Yang, and K. Choong-Ki, "A new 6 GHz fully integrated low power low phase noise CMOS LC quadrature VCO," in *IEEE RFIC Symp. Dig.*, 2003, pp. 295-298.