

A Low Phase Noise Quadrature VCO Using Symmetrical Tail Current-Shaping Technique

I-Shing Shen, Tze-Che Huang, and Christina F. Jou

Abstract—This letter presents a new symmetrical tail current-shaping technique to improve the phase noise of a quadrature voltage-controlled oscillator (QVCO). This proposed QVCO consists of two first-harmonic injection-locked oscillators (ILOs) and the outputs are injected back to the gates of the QVCO's tail transistors in order to shape the tail currents. A switching current path is provided between the two tail current sources in order to eliminate the asymmetric phenomenon of the tail currents. The measured phase noise can be improved by 4 dB using this technique. This CMOS LC-tank QVCO has been implemented using the TSMC 0.18 μm mixed-signal/RF CMOS 1P6M technology and the die area is $0.7 \times 1.1 \text{ mm}^2$. The total power consumption is 11.2 mW at the supply voltage of 1.4 V. The measured phase noise at 1 MHz offset is -119.3 dBc/Hz at the oscillation frequency of 5.28 GHz. The figure of merit (FOM) of the proposed QVCO is -183 dBc/Hz .

Index Terms—CMOS integrated circuits, injection-locked oscillators (ILO), LC oscillators, phase noise, quadrature VCO (QVCO), radio frequency (RF), tail current-shaping.

I. INTRODUCTION

QUADRATURE voltage-controlled oscillator (QVCO) plays a very important role in the phase-locked loop (PLL) circuit for the radio-frequency (RF) transceiver system. To generate a low phase noise local clock, the QVCO must be carefully designed. One of the popular methods to improve the phase noise of the QVCO is tail current-shaping technique [1]. By shaping the tail current of the QVCO, the thermal noise power spectral density, which was generated by the transistors, can be modulated in order to reduce the oscillator's phase noise.

There are many tail current-shaping techniques proposed to improve the performance of phase noise. One popular method is coupling the oscillating signal to the tail current source of the VCO through a transformer [2], however, it will cost large chip area. Another method is to inject an external pulse into the gate of the tail current transistor; although the phase noise reduction of this method had been mathematically proved [1], it is inconvenient to provide an extra external pulse signal for locking.

In our design, we propose a novel tail current-shaping technique to reduce the QVCO's phase noise. Instead of injecting an

external pulse signal into the gate of the tail transistors, the proposed QVCO is based on two first-harmonic injection locked oscillator (ILO) structures [3] and utilizes the QVCO's own output signals as self-injection signals to shape the tail currents of the proposed QVCO. To generate symmetrical tail currents in order to improve the phase noise, a switching line connecting between the two tail current sources is provided, which offers a switching current path in order to eliminate the asymmetric phenomenon of the tail currents. Additional capacitances are added in parallel with the cross-couple transistor pairs, which provide the negative differential resistance, this arrangement can increase the QVCO output amplitude, thus further improves the phase noise. Forward body bias (FBB) technique was used to reduce the supply voltage [4]. This novel QVCO circuit is implemented using the TSMC 0.18 μm CMOS 1P6M technology and oscillated at 5.3 GHz. The measured phase noise of -119 dBc/Hz @ 1 MHz was obtained.

II. CIRCUIT DESIGN

Fig. 1(a) shows a conventional first harmonic injection-locked oscillator (ILO) structure. The differential injection signals ($V_{\text{in}+}$ and $V_{\text{in}-}$) with frequency ω_o from external signal sources are injected to the gate of the tail transistors (M_{tail}). The tail transistors convert voltage of the injection signals into the tail current (I_{tail}) at the common source of cross-couple devices (M1 and M2). The output frequencies of the VCO are locked by the injection signals. As shown in Fig. 1(b), the differential injection signals ($V_{\text{in}+}$ and $V_{\text{in}-}$) with frequency of ω_o shape the tail current $I_{\text{tail}}(2\varphi)$, $\varphi = \omega_o t$, oscillating at frequency of $2\omega_o$. The outputs of the VCO oscillate at a frequency of ω_o . Based on the study of improving phase noise with shaping current methods [1], the more symmetrical shaping current shape, which have no additional current to result in undesired harmonic terms, can reduce the effective impulse sensitivity function (ISF) [5] of M1 and M2, therefore tail current-shaping VCO can achieve lower phase noise. However, according to Fig. 1(b), the simulation shows that $I_{\text{tail}}(2\varphi)$ is not really a symmetrical signal, and the asymmetric phenomenon is caused by the additional current from parasitic capacitances (C_p) of the tail transistors.

Our designed QVCO using a symmetrical tail current-shaping technique as shown in Fig. 2(a), 2 ILO structures are combined to form a QVCO in which two PMOS pairs (M_{p1} , M_{p2} , and M_{p3} , M_{p4}) at the top of the circuit are used to couple the two ILOs in quadrature phase. Bias voltage V_{bb} is used to bias the body of the cross-coupled NMOS (M_{n1} , M_{n2} , M_{n3} and M_{n4}) in order to increase the currents without increasing supply voltage V_{dd} . The tail current transistors (M_{tail}) are dc biased at

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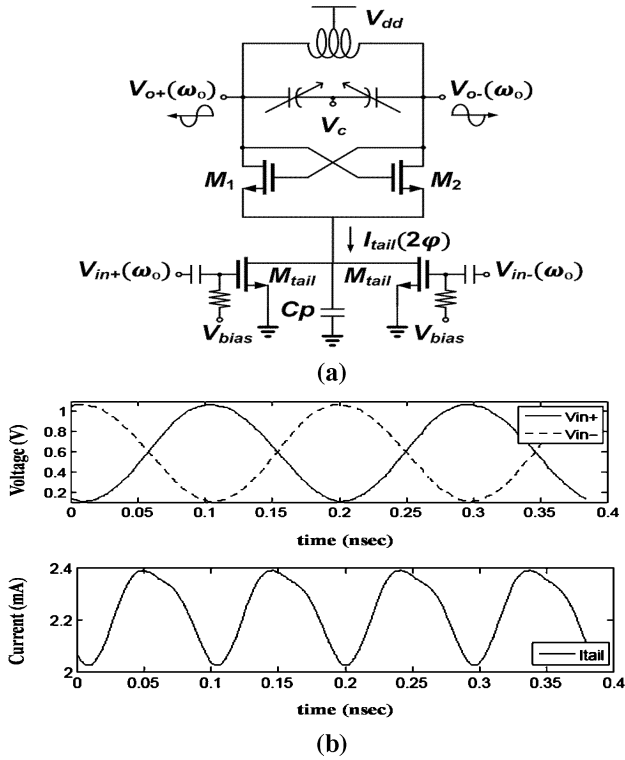


Fig. 1. (a) Conventional first-harmonic injection locked structure. (b) waveforms of V_{in+} , V_{in-} and I_{tail} .

the voltage V_{bias} . The C_{p1} and C_{p2} are parasitic capacitance of M_{tail1} . In order to shape the tail currents (I_{tail1} and I_{tail2}), the QVCO's own output signals ($Q+$, $Q-$, $I+$ and $I-$) are injected back into the gates of the tail current transistors directly rather than using injecting signals through external source. In order to improve the phase noise, we can eliminate the asymmetric phenomenon of tail currents by adding a switching path I_3 between the two tail transistor pairs. Fig. 2(b) shows the simulated currents waveform of tail transistor pairs (I_1 and I_2) and switching path I_3 . The asymmetric phenomenon of I_1 and I_2 in Fig. 2(b) is caused by the additional current from the C_{p1} and C_{p2} . The additional current resulting from C_{p1} directly flow to C_{p2} through path I_3 and has no impact on $I_{tail1}(2\varphi)$ waveform. Fig. 2(c) shows the simulated tail currents waveform ($I_{tail1}(2\varphi)$ and $I_{tail2}(2\varphi)$). Comparing Fig. 1(b) and Fig. 2(c), we can obviously find the shaped tail currents waveform of our proposed QVCO in Fig. 2(c) is much more symmetrical than the tail currents waveform of the conventional ILO shown in Fig. 1(b). Thus, by using switching path I_3 the phase noise can be improved.

Additional capacitances C_1 – C_4 in parallel with cross-couple devices (M_{n1} and M_{n2} , M_{n3} and M_{n4}) are used to increase the amplitude of the oscillator outputs waveform. These cross-couple devices are used to provide the negative differential resistance. Fig. 3 shows the simulated result of the outputs amplitude of the proposed QVCO with and without the additional capacitances C_1 – C_4 . We can see that the amplitude with C_1 – C_4 is 26% larger than the one without the additional capacitances, therefore, the phase noise of the proposed QVCO can further be improved.

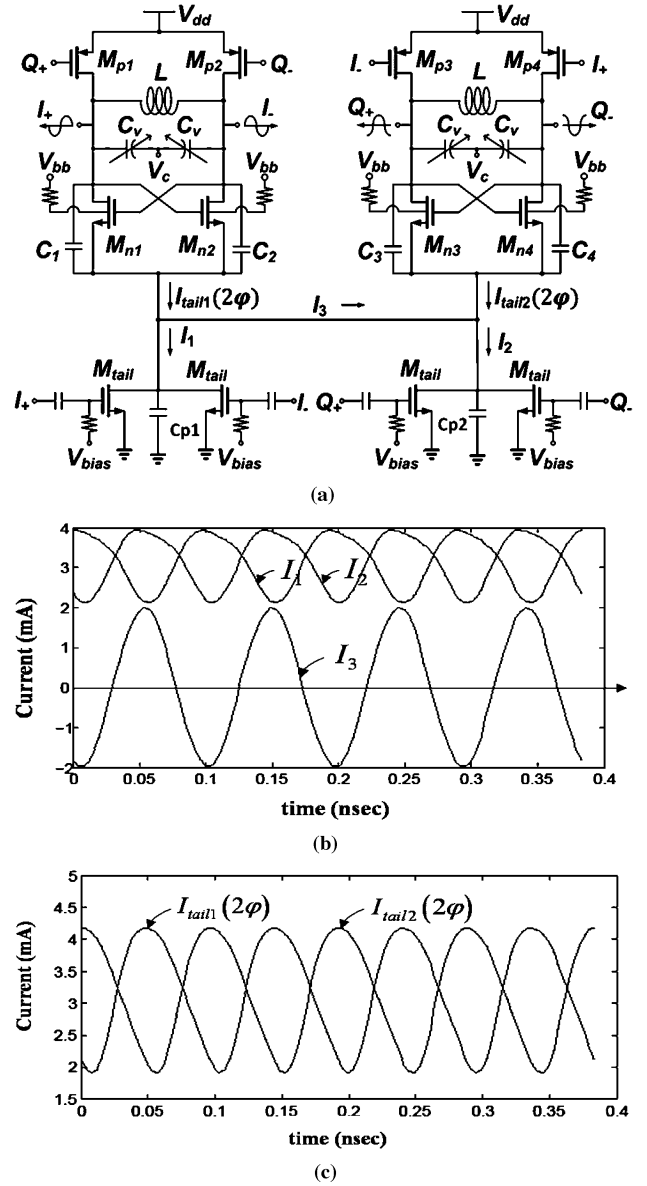


Fig. 2. (a) Proposed QVCO using symmetrical tail current-shaping technique. (b) the simulated currents waveform of tail transistor pairs (I_1 and I_2) and switching path I_3 . (c) the simulated tail currents waveform ($I_{tail1}(2\varphi)$ and $I_{tail2}(2\varphi)$).

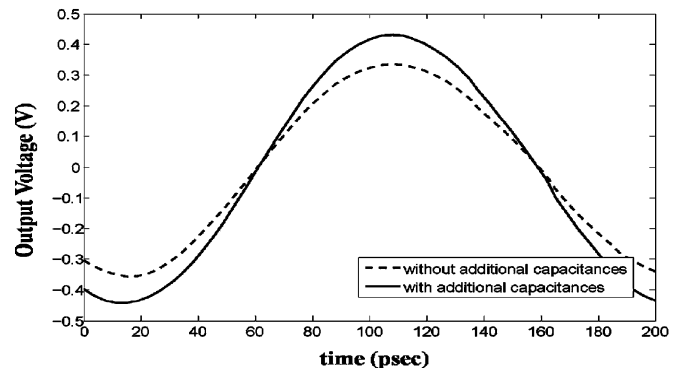


Fig. 3. Simulated result of the outputs amplitude of the proposed QVCO with and without the additional capacitances C_1 – C_4 .

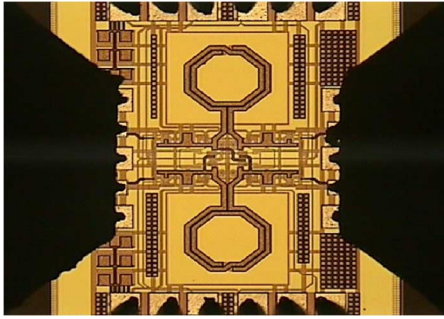
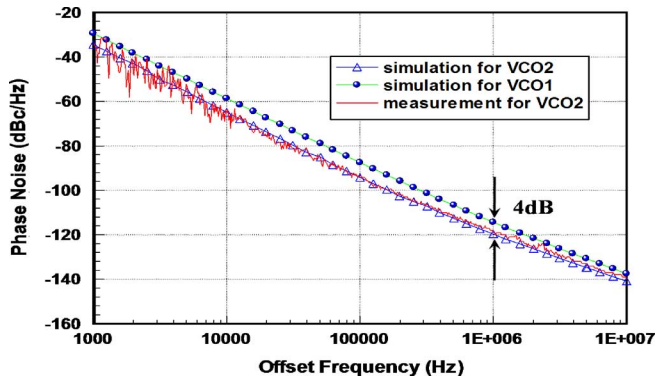


Fig. 4. Chip photograph of the fabricated QVCO.

Fig. 5. VCO1 is the simulated phase noise of the proposed QVCO without the switching path I_3 . VCO2 is the measured and simulated results of the QVCO with path I_3 at the oscillation frequency of 5.3 GHz.

III. MEASUREMENT

The proposed QVCO was design and fabricated using the TSMC 0.18 μm mixed-signal/RF CMOS 1P6M technology. Fig. 4 shows the chip photograph of the fabricated QVCO with a chip area of $0.7 \times 1.1 \text{ mm}^2$. The bias-tee was adopted while doing measurement. The output spectrum and phase noise was measured using the Agilent E4440A spectrum analyzer and Agilent E5052A signal source analyzer, respectively.

Fig. 5 compares the measured phase noise of our proposed QVCO with switching path I_3 with the simulation result of the QVCO without path I_3 at the oscillation frequency of 5.3 GHz. The phase noise shows the trend of $1/f^2$ at offset frequency between 100 KHz to 10 MHz, and the measured phase noise of our proposed QVCO is -119.3 dBc/Hz at 1 MHz offset frequency, which is 4 dB lower than the simulated QVCO without path I_3 at 1 MHz offset frequency.

As shown in Fig. 6 the oscillation frequency can be tuned from 5.3 GHz to 5.44 GHz as the control voltage V_c is raised from 0 V to 3 V, and the total tuning range is 550 MHz. The power consumption of the QVCO core is measured to be 11.2 mW at the V_{dd} supply voltage of 1.4 V. The average output phase error is about 5° . Fig. 7 shows the measured frequency spectrum of the proposed QVCO. The output power is about -7 dBm at 5.3 GHz oscillating frequency.

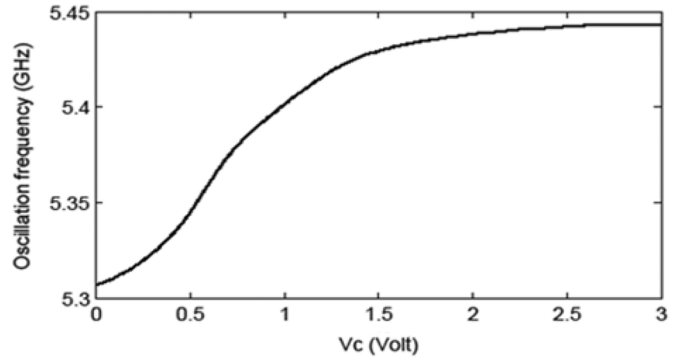


Fig. 6. Measured tuning range of the proposed QVCO.

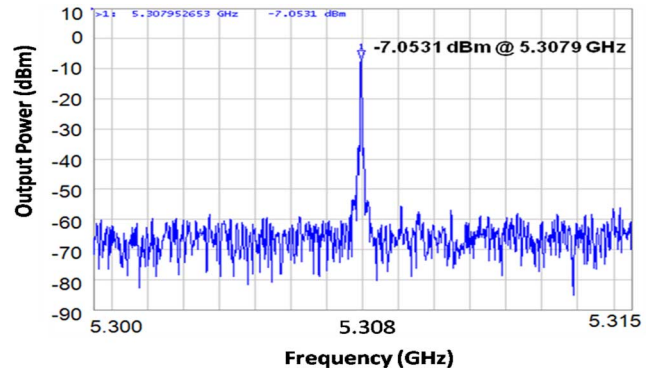


Fig. 7. Measured frequency spectrum of the proposed QVCO.

IV. CONCLUSION

A new technique to improve the phase noise of the first-harmonic injection-locking QVCO has been proposed and successfully demonstrated. The asymmetrical tail current can be eliminated with the additional switching path, and the phase noise thus can be improved by 4 dB. The measured phase noise is around -90 dBc/Hz and -119 dBc/Hz at 100 KHz and 1 MHz offset frequency, respectively. This low phase noise QVCO demonstrates a FOM of -183 dB at 5.28 GHz [1].

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REFERENCES

- [1] B. Soltanian and P. R. Kinget, "Tail current-shaping to improve phase noise in LC voltage-controlled oscillators," *IEEE J. Solid-State Circuits*, vol. 41, no. 8, pp. 1792–1802, Aug. 2006.
- [2] T. H. Huang and Y. R. Tseng, "A 1 V 2.2 mW 7 GHz CMOS quadrature VCO using current-reuse and cross-coupled transformer-feedback technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 10, pp. 698–700, Oct. 2008.
- [3] S. L. Jang, S. S. Huang, C. F. Lee, and M. H. Juang, "CMOS quadrature VCO implemented with two first-harmonic injection-locked oscillators," *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 10, pp. 695–697, Oct. 2008.
- [4] H. H. Hsieh and L. H. Lu, "A high-performance CMOS voltage-controlled oscillator for ultra-low-voltage operations," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 3, pp. 467–473, Mar. 2007.
- [5] A. Hajimiri and T. H. Lee, "A general theory of phase noise in electrical oscillator," *IEEE J. Solid-State Circuits*, vol. 33, no. 2, pp. 179–194, Feb. 1998.