

A THREE-PHASE VOLTAGE-CONTROLLED OSCILLATOR USING A COMPOSITE LC TRANSMISSION-LINE RESONATOR

S.-L. Jang, Y.-S. Lin, C.-W. Chang^{*}, and M.-H. Juang

Department of Electronic Engineering, National Taiwan University of Science and Technology, 43, Keelung Road, Section 4, Taipei, Taiwan 106, China

Abstract—This paper presents a new three-phase *LC*-ring voltage controlled oscillator (VCO) using the TSMC 0.18 μm 1P6M CMOS process. The VCO consists of three single-ended complementary Colpitts VCOs coupled via a varactor ring. Tuning range of VCO is 0.59 GHz, from 8.22 GHz to 8.81 GHz, while the control voltage was tuned from 0 V to 1.1 V and the VCO core power consumption is 2.82 mW at the supply voltage of 1.1 V. The measured phase noise is -118.14 dBc/Hz at 1 MHz offset frequency from 8.40 GHz. The VCO occupies a chip area of 1.018×0.74 mm² and provides a figure of merit of -192.14 dBc/Hz.

1. INTRODUCTION

Voltage Controlled Oscillator (VCO) employing LC-resonators plays the most crucial role in the phase-lock-loops (PLLs), clock recovery circuits, frequency synthesizers, and communication systems, and many efforts in the past have been spent to understand the design of differential VCOs. However, multiphase VCOs are also essential parts of many electronic systems. Among the multiphase VCOs, the quadrature VCO has received a lot of attention because we are used to the binary system and the QVCO is used in a homodyne transceiver and can be easily derived from two differential VCOs with a coupling network. In contrast, three-phase VCOs have received rarely attention, and they are used to study the operation principle and physical mechanism of oscillator including the phase noise. A 3-phase VCO can be realized with 3-stage ring oscillators [1, 2] with wide tuning

Received 29 September 2011, Accepted 8 November 2011, Scheduled 14 November 2011

* Corresponding author: Chia-Wei Chang (d9702301@mail.ntust.edu.tw).

range, small die area, or with LC oscillators with higher frequency operation, low power and low phase noise. An inductor-less three-stage ring oscillator suffers from high phase noise and the traditional 3-phase LC -ring oscillator is composed of a series of 3 cascaded unit LC oscillators with active coupling networks [3].

A three-phase VCO also can be formed with 3 single-ended Colpitts VCOs with coupling transistors in a ring and the coupling transistors substantially increase the capacitive loading of the tank and decrease the operating frequency. Recently, a three-phase LC VCO [4] has been studied, and it uses three single-ended VCOs coupled via wiring the inductors in the three single-ended VCOs to form a ring. This 3-phase VCO avoids the coupling transistors, however it suffers from higher phase noise than the proposed VCO in this paper, because varactors are AM modulated by current noise generated in all the active devices in a ring through the inductor ring.

The goal of this letter is to design a high-performance 3-phase VCO consisted of three single-ended complementary Colpitts VCOs [5, 6] coupled with a varactor-ring. The varactor can reduce the device current noise generated in other two single-ended VCOs on the phase noise performance of one single-ended VCO. This is an approach of passive coupling leading to less coupling injection device noise as compared with the transistor coupling method. The VCO also has no fixed capacitance parasitic in the active coupling devices, and this can lead to wider tuning range or higher operation frequency. They can be used to form a triple-push VCO [7] to provide a triple frequency source at 3ω by using a power combiner with three injection inputs from a three-phase VCO at the oscillation frequency ω . They can be used to form a differential triple-push VCO to provide a differential triple frequency source at 3ω by combining two triple-push VCOs, and also can be used as the core of a 3-phase divide-by-3 injection-locked frequency divider. Two 180° -coupled 3-phase oscillators can be used to form a 6-phase VCO and implemented in a phase-locked loop [8] and a multi-phase mixer [9]. In addition, the 3-phase VCO can be used to replace a single-ended VCO if the performance of the 3-phase VCO is better than a single-ended VCO.

2. CIRCUIT DESIGN

In Fig. 1(a), an ordinary single-ended (SE) complementary LC -tank VCO [5, 6] is illustrated. The inductor L_1 and accumulation-mode MOS varactor C_{var1} and parasitic active capacitors form the LC resonator. The pMOSFET M_1 and nMOSFET M_2 are used to restore the energy loss from the parasitic resistors in the tank. The

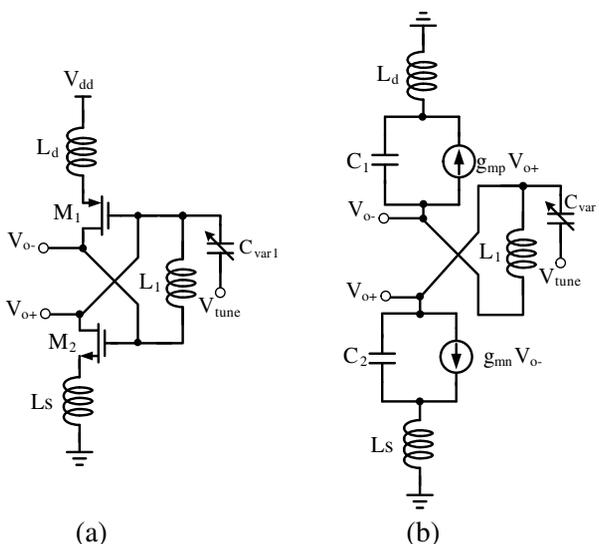


Figure 1. (a) Schematic of a single-ended complementary Colpitts VCO and (b) its small-signal equivalent circuit (right plot).

pMOSFET and nMOSFET uses the same dc current to save dc power consumption. Fig. 1(b) shows the small-signal equivalent circuit. The g_{mp} (g_{mn}) is the transconductance of M_1 (M_2). The capacitors are given by $C_1 (= C_{gsn} + C_{dsp})$ and $C_2 (= C_{gsp} + C_{dsn})$ and the symbols (C_{gsp} , C_{dsp}) and (C_{gsn} , C_{dsn}) stand for the parasitic (gate-source, drain-source) capacitor of pMOSFET M_1 and the parasitic (gate-source, drain-source) capacitor of nMOSFET M_2 respectively. The ac source currents of M_1 and M_2 develop ac voltages across the bonding wire inductors L_d and L_s . These ac voltages can delay the oscillation and degrade the performance of oscillator. If L_d and L_s are zero, the VCO is a Colpitts VCO, and the output signal is fed back to the sources of transistors through the parasitic capacitors (C_{dsn} , C_{dsp}). The circuit is a Colpitts VCO because it uses the capacitive feedback to form an oscillator. The proposed 3-phase complementary Colpitts VCO is shown in Fig. 2, and it consists of three identical single-ended (SE) VCOs shown in Fig. 1(a) with shared common bonding wires L_d and L_s . In the first SE VCO circuit nMOSFET M_2 and pMOSFET M_1 , inductor L_1 , and varactor C_{var1} form a single-ended VCO. V_{tune} is the control voltage used for tuning frequency. The second SE VCO circuit uses nMOSFET M_4 and pMOSFET M_3 , inductor L_2 , and varactor C_{var3} . The third SE VCO circuit uses nMOSFET M_6 and pMOSFET M_5 , inductor L_3 , and varactor C_{var5} . The varactors C_{var2} , C_{var4} and

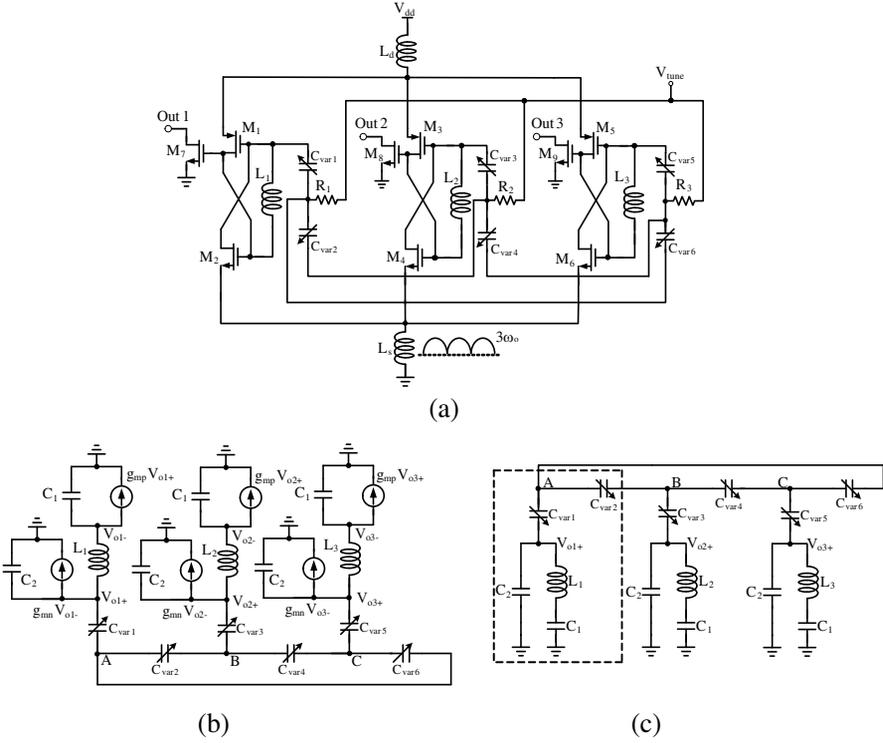


Figure 2. (a) Schematic of the proposed 3-phase VCO. (b) Simplified small-signal equivalent circuit. (c) The composite transmission line resonator.

C_{var6} form a ring to ensure a 3-phase VCO. The resistors R_1 , R_2 and R_3 are used for varactor bias and frequency tuning. The sources of nMOSFETs (M_2 , M_4 , M_6) are connected to the ground through a bonding wire inductor L_s , and the sources of pMOSFETs (M_1 , M_3 , M_5) are connected to the supply through a bonding wire inductor L_d . The open drain buffers M_7 , M_8 and M_9 have been designed in the implemented chip for measurement. The operation principle of the 3-phase VCO is as follows. The three source currents from pMOSFETs (I_{p1} , I_{p2} , I_{p3}) develop a net voltage given by $sL_d I_p$ at the output of inductor L_d , where $I_p = I_{p1} + I_{p2} + I_{p3}$, and the three source currents from nMOSFETs (I_{n1} , I_{n2} , I_{n3}) develop a net voltage given by $sL_s I_n$ at the output of inductor L_s , where $I_n = I_{n1} + I_{n2} + I_{n3}$. The ac voltages tend to degrade the performance of VCO if the fundamental I_n and I_p are not equal to zero as the single-ended VCO shown in Fig. 1(a). The even-mode oscillation requires $I_{p1} = I_{p2} = I_{p3}$, and

$I_{n1} = I_{n2} = I_{n3}$, so the odd mode prevails leading to $I_{p1} + I_{p2} + I_{p3} = 0$, and $I_{n1} + I_{n2} + I_{n3} = 0$. The VCO in Fig. 2 has higher figure of merit than that in Fig. 1(a), because the virtual ground at the common node of transistors and bonding wire is found in Fig. 2 but not in Fig. 1(a). The 3-phase VCO is a better option for VCO design than the single-ended VCO.

In the previous complementary VCOs, the VCO output voltage amplitude is limited by supply and ground level, this nonlinear behavior leads to fundamental and high-order harmonics at the common node of bonding wire and MOSFETs. In the odd mode, the fundamental source current $I_{pi}(\omega_o)$ of M_{pi} ($i = 1-3$) cancels out at the inductor output node due to the 120° phase shift among $I_{pi}(\omega_o)$, and the second harmonic signal currents with 240° phase shift among $I_{pi}(2\omega_o)$ also cancel themselves out. The third harmonics at $3\omega_o$ are in phase and the bonding wire outputs have the signal at $3\omega_o$ with small amplitude.

When the varactors C_{var2} , C_{var4} and C_{var6} are eliminated from Fig. 2, the circuit uses the triple-push coupling technique, with $I_{p1} + I_{p2} + I_{p3} = 0$, and $I_{n1} + I_{n2} + I_{n3} = 0$, to provide 3-phase output and this doesn't give output phase directivity. The varactor ring provides the phase directivity and enhances the phase accuracy as the triple-push coupling relies on the signal strength at the bonding wire terminals. The anode and cathode dc biases of C_{var2} , C_{var4} and C_{var6} are the same; however, the anode and cathode ac voltages of C_{var2} , C_{var4} and C_{var6} are different. The current flow through varactors C_{var2} , C_{var4} and C_{var6} are used to establish the unidirectional phases (A, B, C) by utilizing the monotonic tuning curve of accumulation-mode MOS varactor. Fig. 2(b) shows the small-signal equivalent circuit. From Fig. 2(b), the ideal oscillation frequency can be derived as

$$\omega = \sqrt{\frac{C_{v1}(C_1 + C_2) + 3C_{v2}(C_{v1} + C_1 + C_2)}{L_1C_1C_2C_{v1} + 3C_{v2}(L_1C_1C_{v1} + L_1C_1C_2)}} \quad (1)$$

By changing V_{tune} the capacitance C_{v1} (C_{v3} , C_{v5}) of varactor C_{var1} (C_{var3} , C_{var5}) and the oscillation frequency can be tuned. Fig. 2(c) shows the LC-ring resonator redrawn from Fig. 2(b), and the resonator consists of three unit composite LC cells and is in a form of the composite transmission line [10] in a loop. The design concept of the three-phase VCO can be extended to design a quadrature VCO by using four unit composite LC cells shown in Fig. 2(c) to form a loop.

A noise current source is generated in each active transistor and pMOSFET tends to have small low-frequency noise. The noise currents associated with each complementary MOSFET pair are independent. The low-frequency noise current charges the capacitors and modulates

the ac bias voltage applied to the anodes of varactors C_{var1} , C_{var3} and C_{var5} leading to AM-PM noise [11] upconversion via the varactors $C_{var1} \sim C_{var6}$.

3. RESULTS AND DISCUSSION

The proposed circuits were fabricated in TSMC 0.18 μm CMOS process. The die micrograph of the 3-phase VCO is shown in Fig. 3. Including pads, the chip area is $1.018 \times 0.74 \text{ mm}^2$. The simulation tools-Spectre RF and ADS Momentum were used to simulate circuits and calculate the inductance and quality factor of the 3-turn octagonal inductors. Compared with the conventional single differential VCO, the occupied area of the 3-phase VCO is larger because the VCO uses three separated inductors. However the three inductors may be designed as a 6-port transformer to save die area. The VCO was measured on printed circuit board tested with an Agilent E4446A spectrum analyzer. The measurement shows the VCO can be tuned from 8.22 GHz to 8.81 GHz as shown in Fig. 4 when the tuning voltage varies from 0 V to 2 V. The capacitance of varactor is a function of the voltage V_{tune} , the oscillation frequency increases with V_{tune} . The circuit is biased at $V_{dd} = 1.1 \text{ V}$. Without buffers, the current and power consumption of the 3-phase VCO core are 2.56 mA and 2.82 mW, respectively.

Figure 5 shows the measured output spectrum at the center oscillation frequency of 8.40 GHz. The output power is -4.11 dBm . Fig. 6 shows the measured time-domain output waveforms from three output buffers by using the Agilent 54855A Infiniium oscilloscope. The output phase error is about 1.36° . The measured phase noise is shown

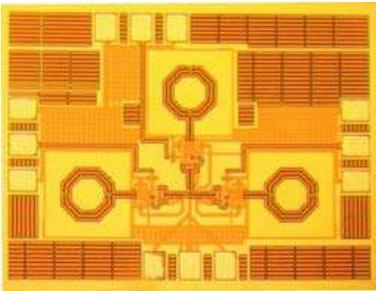


Figure 3. Chip photograph of the implemented 3-phase VCO.

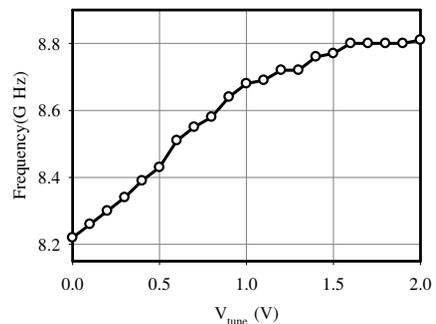


Figure 4. Frequency tuning range of the proposed 3-phase VCO.

Table 1. Performance comparison of VCO performance.

Ref.	Tech (μm).	Freq. (Tun. Rang) (GHz)	V_{dd} (V)	P_{DC} (mW)	FOM (dBc/Hz)	Phase No.
[16]	0.18	11.0 (9.95 ~ 11.0)	0.6	4.1	-185.2	2
[15]	0.18	7.91 (8.08 ~ 7.83)	3	24.0	-181.0	4
[14]	0.18	7.13 (7.03 ~ 7.36)	1.0	2.2	-184.8	4
[4]	0.18	6.25 (6.22 ~ 7.27)	1.5	11.47	-184.1	3
This	0.18	8.40 (8.22 ~ 8.81)	1.1	2.82	-192.1	3

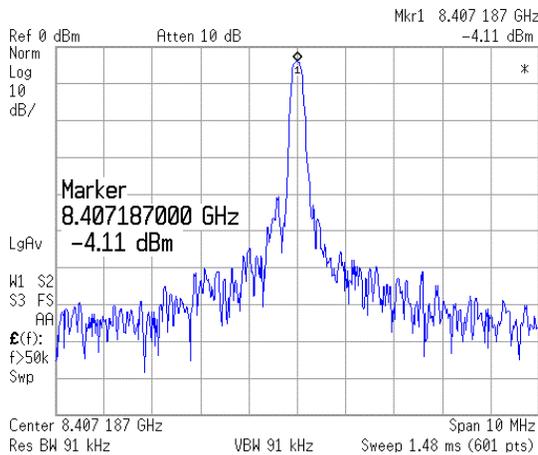


Figure 5. Measured output spectrum of the proposed VCO at 8.40 GHz. The output power is -4.11 dBm. $V_{dd} = 1.1$ V, $V_{tune} = 0.55$ V, and $V_b = 0.7$ V.

in Fig. 7, and the low-frequency offset phase noise may be caused by the frequency drift [12]. The slope of phase noise in the offset frequency range 100 Kz-1 MHz is -30 dB/dec, and the measured phase noise is -118.14 dBc/Hz at 1 MHz offset frequency from the center oscillation frequency of 8.40 GHz. The figure of merit (FOM) of the proposed 3-phase VCO is -192.13 dBc/Hz, it is calculated using the FOM defined as [13]

$$\text{FOM} = L\{\Delta\omega\} + 10 \cdot \log(P_{DC}) - 20 \cdot \log\left(\frac{\omega_o}{\Delta\omega}\right) \quad (2)$$

where $L\{\Delta\omega\}$ is the SSB phase noise measured at $\Delta\omega$ offset from ω_o carrier frequency and P_{DC} is DC power consumption in mW. Table 1 lists the performance comparison of the proposed VCO and other VCOs.

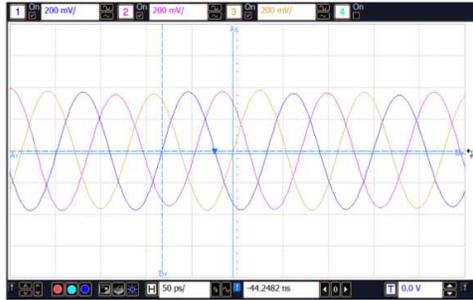


Figure 6. Measured output waveforms of the 3-phase VCO buffers. $V_{dd} = 1.1$ V, $V_{tune} = 1.1$ V. $f_{osc} = 8.69$ GHz.

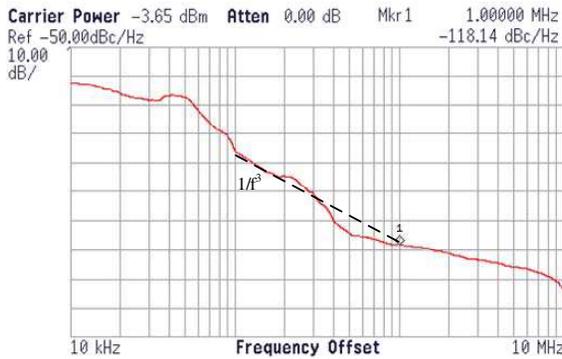


Figure 7. Measured phase noise of the VCO. $V_{dd} = 1.1$ V, $V_{tune} = 0.55$ V, and V_b (buffer's drain bias) = 0.7 V.

4. CONCLUSION

A novel 3-phase complementary Colpitts VCO using the composite transmission-line resonator has been designed and successfully implemented in the 0.18 μm CMOS process. The 3-phase VCO provides three signals phase-shifted by 120° and the common nodes of bonding wires and switching transistors are used as a virtual ground, so that the 3-phase VCO can have better performance than the single-ended sub-VCO circuit. The use of varactor-ring coupling provides phase directivity and also enhances the phase accuracy. The VCO can be tunable from 8.22 GHz to 8.81 GHz, while the control voltage varies from 0 V to 1.1 V and the figure of merit of the VCO is -192.13 dBc/Hz. This work proves that the proposed transmission-line resonator can be used to design a high-performance radio-frequency three-phase VCO.

ACKNOWLEDGMENT

The authors would like to thank the Staff of the Nation Chip Implementation Center (CIC) for the chip fabrication and technical supports.

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