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CMOS RF Quadrature Voltage-Controlled Oscillator Design: a Current-mode Approach

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Abstract. The paper presents a new method to realize quadrature oscillators (QO) for the radio frequency (RF) applications. The current-mode circuits which have been developed for decades are mature to be used in designing oscillators. However, as the frequency of the current-mode oscillators is very low (less than 10MHz), they do not meet the demands of the modern communication systems. An attempt is being made to use the current-mode method in designing the RF QOs as the current-mode theory developed for designing the low-frequency oscillators can be efficiently used in designing the RF QOs. A quadrature ring voltage-controlled oscillator (QRVCO) using the classical current-mode block called the current conveyor II (CCII) is designed to explain the convenience of using the current-mode method in the RF oscillator design.

Keywords: CMOS, Radio frequency, Quadrature oscillator, Current-mode, Voltage-Controlled Oscillator.

CMOS RF-kvadraturni napetostno krmiljeni oscillator: načrtovanje s tokovnim vezjem

V članku je predstavljena nova metoda za izvedbo kvadraturnega oscilatorja za področje RF v tehnologiji CMOS. Tokovna vezja so bila že uporabljena pri načrtovanju oscilatorjev, vendar zaradi nizke zgornje frekvenčne meje ne ustrezajo zahtevam sodobnih komunikacijskim sistemov. V članku je predstavljena zasnova in način uporabe tokovnih vezij za izvedbo kvadraturnih oscilatorjev tehnologiji CMOS. Opisan je kvadaturni napetostno krmiljeni oscillator v zanki z uporabo klasičnega tokovnega bloka CCII. Eksperimentalni rezultati potrjujejo prednosti predlaganega pristopa.

1 INTRODUCTION

During the past decades, the current-mode approach has become more popular in the analog integrated-circuit design due to its advantages of providing a larger dynamic range, wider bandwidth, lower power consumption over the voltage-mode counterparts [1], and various of active current mode blocks (such as CCII, OTA, CDBA, CDTA) are proposed for the analog-integrated circuit design. The current-mode method is actually a modular design method, and the current-mode QOs consist of two integrator-loop QOs (second-order QO) [Ref. [2] and the references cited therein, 3-5] and three or more integrator-loop QOs (ring QO) [6-7]. All these QOs are completely inductor-less and the current-mode theory is more mature to be used in designing the oscillators. However, because of these QQs are very low frequency (less than 10MHz), they can not to be used for the modern communication systems.

Several RF ring oscillators are presented in [8-11]. The techniques of realizing these ring oscillators use the connected phase delay stages forming a loop, but without providing quadrature sinusoidal output waveforms. Actually, in the current-mode circuit design, a phase delay stage for a lossy-integrator or a first-order low-pass filter is used. It is not only the first-order low-pass filter, but also the first-order all-pass, high-pass and band-pass filters, that can realize the phase delay stages, and these blocks are easy to be realized thanks to the current-mode modular design method. Using the current-mode modular-design method in the RF oscillators design makes the integrated RF oscillator design easier and more convenient.

A new method to realize QOs for RF applications is presented. The emphasis is not on the current-mode circuits, but on using the method in designing RF QOs. Though these have already been mature, and many QOs are realized by using this method, they operate in low-frequency band, and as such they can't meet the demands of the modern communication systems. However, an attempt is made to use the current-mode modular-design method in a quadrature second-order and ring RF oscillator design. A quadrature ring voltage-controlled oscillator (QVCO) using the classical current-mode block CCII is designed in this paper to explain the convenience of the current-mode method in the RF oscillator design. QRVCO operates at 700MHz, its frequency tuning range is about 80MHz by changing bias voltage V_b, and it consists of two lossy-integrators and one lossless-integrator. The QRVCO theoretical

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analysis is based on the current-mode modular-design method and the feasibility and convenience of the RF QRVCO design using this new method is shown.

2 CIRCUIT DESCRIPTION

2.1 CCII and its sub-circuits

CCII is a classical current-mode block. A CMOS realization of CCII is shown in Fig.1. X and Y are the voltage and current input terminals. Z+ and Z- are the positive and negative terminals, that can be added arbitrarily by using current mirrors. V_b is the bias voltage.

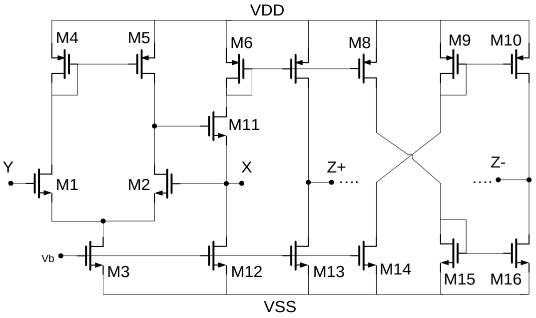

Figure1. CMOS realization of CCII

The terminal relations of CCII are:

$$V_x = V_y, \quad I_y = 0, \quad I_z = \pm I_x \qquad (1)$$

So, CCII can be described using an ideal modular element shown in Fig.2.

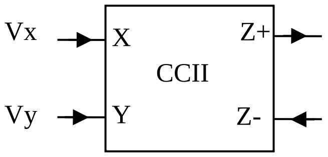

Figure 2. CCII symbol

CCII can be used to realize several phase-delay stages. The lossless and lossy-integrator are shown in Figures 3 and 4.The transfer function of Figure 3 is:

$$\frac{I_{o+}(s)}{I_{in}(s)} = -\frac{I_{o-}(s)}{I_{in}(s)} = \frac{1}{sRC} = \frac{I_{o+}(j\omega)}{I_{in}(j\omega)} = -\frac{I_{o-}(j\omega)}{I_{in}(j\omega)} = \frac{1}{\omega RC} e^{-j90^o} \qquad (2)$$

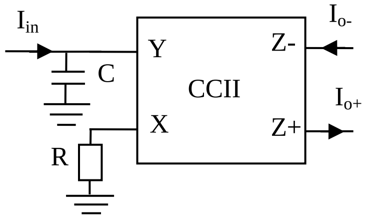

Figure 3. CCII-based lossless-integrator

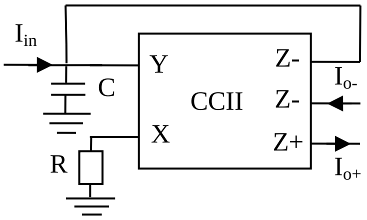

Figure 4. CCII-based lossy–integrator

As seen from equation (2), the lossless-integrator can provide a 90° phase shift. The transfer function in Figure 4 is:

$$\frac{I_{o+}(s)}{I_{in}(s)} = -\frac{I_{o-}(s)}{I_{in}(s)} = \frac{1}{1+sRC} = \frac{I_{o+}(j\omega)}{I_{in}(j\omega)} = -\frac{I_{o-}(j\omega)}{I_{in}(j\omega)} = \frac{1}{1+j\omega RC} \qquad (3)$$

This circuit provides a phase shift of

$$\varphi(\omega) = -\arctan(\omega RC) \qquad (4)$$

2.2 The CCII-based RF QVCO

Using the CCII-based lossless and lossy-integrator as the phase delay stages, QRVCO can be easily obtained. An example of a three-stage QRVCO is shown in Figure 5.

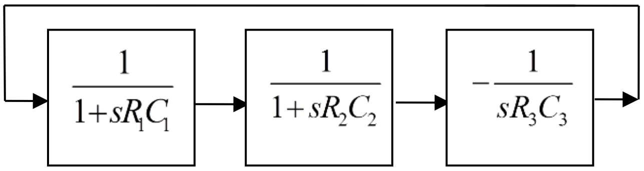

Figure 6. QVCO block diagram

This circuit will be very easily analized by using the current-mode method. Figure 6 shows a block diagram of QVCO. From Figure 6, it is easy to get the characteristic equation of QVCO:

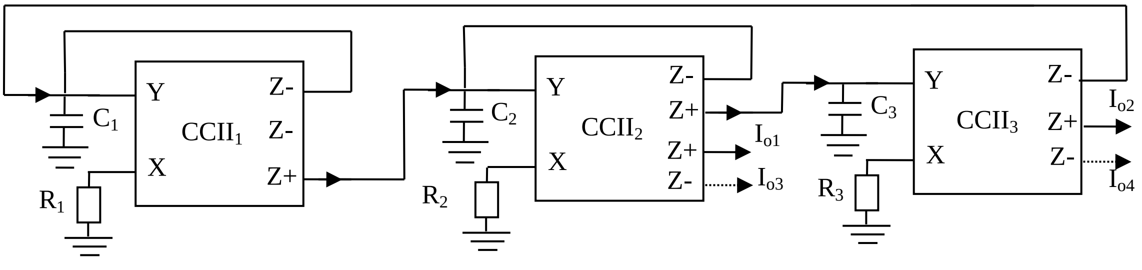

Figure 5. CCII-based RF QVCO

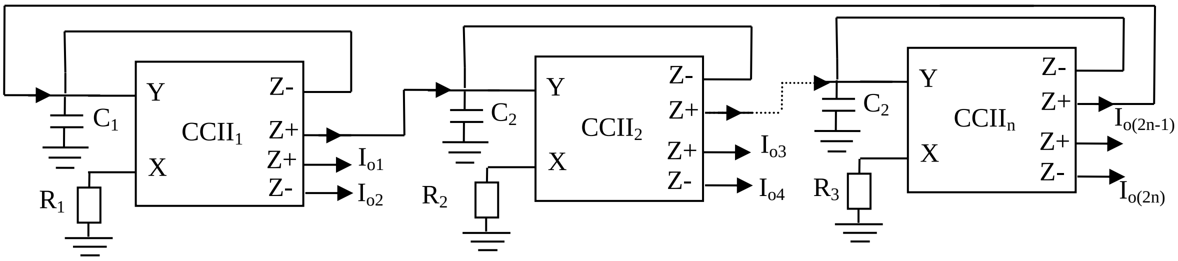

Figure7. CCII-based multi-phase RF oscillator

$$\frac{1}{1+sR_1C_1}\times\frac{1}{1+sR_2C_2}\times\left(-\frac{1}{sR_3C_3}\right)=1 \qquad (5)$$

By rearranging equation (5), we get:

$$s^3R_1R_2R_3C_1C_2C_3+s^2R_3C_3\left(R_1C_1+R_2C_2\right)+sR_3C_3+1=0 \qquad (6)$$

The condition of oscillation (CO) and its frequency (FO) are expressed as:

$$\text{CO:}\quad R_1R_2C_1C_2=R_3C_3\left(R_1C_1+R_2C_2\right) \qquad (7)$$

$$\text{FO:}\qquad \omega_0=\sqrt{\frac{1}{R_1R_2C_1C_2}} \qquad (8)$$

As seen from Figure 5, the relationship between I_{o1} and I_{o2} is:

$$\frac{I_{o2}}{I_{o1}}=\frac{1}{sR_3C_3}=\frac{I_{o2}(j\omega)}{I_{o1}(j\omega)}=\frac{1}{\omega R_3C_3}e^{-j90^o} \qquad (9)$$

It is clear that I_{o1} and I_{o2} are quadrature. To get four quadrature outputs, the Z- terminals at $CCII_2$ and $CCII_3$, respectively, are added.

$$I_{o1}=-I_{o3} \text{ and } I_{o2}=-I_{o4} \qquad (10)$$

This means that the circuit can provide four-quadrature current outputs.

When the oscillator works in a sinusoidal steady-state, equation (8) is put into equation (9):

$$\frac{I_{o2}(j\omega_o)}{I_{o1}(j\omega_o)}=\frac{\sqrt{R_1R_2C_1C_2}}{R_3C_3}e^{-j90^o} \qquad (11)$$

The magnitude ratio of I_{o1} and I_{o2} is:

$$\left|\frac{I_{o2}(j\omega_o)}{I_{o1}(j\omega_o)}\right|=\left|\frac{\sqrt{R_1R_2C_1C_2}}{R_3C_3}\right| \qquad (12)$$

From equations (9), (10) and (12), it is shown that the RF oscillator provides four phase quadrature current outputs, but current outputs I_{o1}, I_{o3} and I_{o2}, I_{o4} are generally not of the same magnitudes.

Also, we can use this method to get multi-phase RF oscillator, and it is shown in Fig.7.

The characteristic equation of the multi-phase RF oscillator is:

$$\frac{1}{\left(1+sR_1C_1\right)^n}=1 \qquad (13)$$

This oscillator provides 2n multi-phase outputs. The analysis method is similar to QVCO. Using this method, many other two integrator-loop RF QOs in [Ref. [2] and the references cited therein].

3 SIMULATION RESULTS

RF QRVCO in Figure 5 has been designed by a standard TSMC 0.18 μm RF CMOS process [12]. The supply voltage is ±1.8 V; the transistor sizes W/L with μm/μm are M_1, M_2 = (17/0.18), M_3 = (10/0.18), M_4, M_5 = (19/0.18), M_6 = (5/0.18), M_7 = (26/0.25), M_8, M_9, M_{10}, M_{11} = (20/0.25), M_{12}, M_{13}, M_{14}, M_{15}, M_{16} = (10/1); the values of the passive elements are C_1 = C_2 = 0.1 pF, C_3 = 2 pF, R_1 = R_2 = 2 kΩ, R_3 = 400 Ω. The output resistors of I_{o1} and I_{o2} are 50 Ω.

Figure 8 shows the simulated output signals of I_{o1} and I_{o2} for V_b = 570 mV. The simulated frequency is 700 MHz. Its peak-to-peak current amplitudes are 410 uA and 110 uA for I_{o1} and I_{o2}, respectively. From equation (12), when C_1 = C_2 =0.1 pF, C_3 = 2 pF, R_3 = 400 Ω, the magnitude ratio of I_{o2} and I_{o1} is about 0.25 and the simulation results confirm the theory.

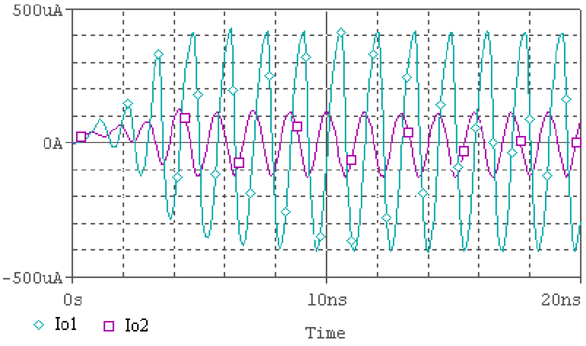

Figure 8. Simulated output signals of I_{o1} and I_{o2}

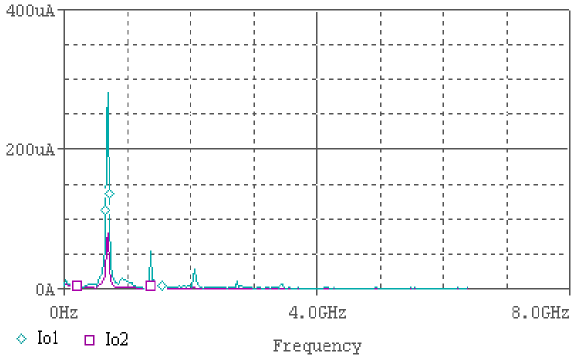

Figure 9. Simulated output frequency spectrum of I_{o1} and I_{O2}

Figure 9 shows the simulated output frequency spectras of I_{o1} and I_{o2} for $V_b = 550$ mV, and the total harmonic distortion (THD) of I_{o1} and I_{o2} are 5.490% and 1.759%, respectively. It is clear that the simulated frequency is 700 MHz. From equation (8), when $C_1 = C_2 = 0.1$ pF, $R_1 = R_2 = 2$ kΩ, the frequency $f_o = \omega_0/2\pi = 796$ MHz. The frequency deviation is about 12%. Obviously, because of some impacts, the frequency deviates from theoretical value.

Figure 10 shows a simulated tuning range with different V_b. RF QRVCO works when V_b is between 0.55 V to 0.8 V and the tuning frequency range is from 620 MHz to 700 MHz by changing bias voltage V_b.

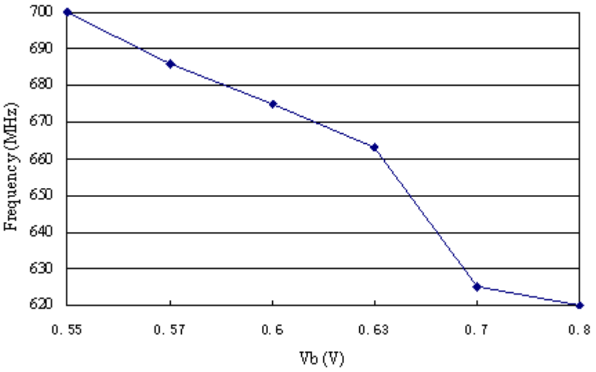

Figure 10. Tuning range of QRVCO with different V_b

4 CONCLUSION

A new method to realize the quadrature oscillators (QOs) for the radio frequency (RF) applications is presented. The current-mode circuits, which have been developed for decades are more mature for being used in designing oscillators. However, as the frequency of the current-mode oscillators is very low (less than 10 MHz), they do not meet the demands of the modern communication systems. The advantages of using the current-mode oscillator design method in the RF QO design has are: 1) the theory of designing the quadrature current-mode oscillators has reached the stage when it could be used in designing the RF oscillators in a more easier and theoretical way; 2) as all the current-mode QOs are completely inductor-less and the resistors and capacitors used in them are grounded, they are suitable for a monolithic integration; 3) as most of the current-mode QOs are quadrature and able to provide two or four quadrature outputs, they are suitable for modern communication systems.

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