Research Article

Third-Order Quadrature Oscillator Circuit with Current and Voltage Outputs

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The paper presents a new quadrature oscillator of third order which can provide four quadrature current outputs and two quadrature voltage outputs. The new circuit employs three differential voltage current conveyors and six passive components, most of which are in grounded form. Circuit operation at high frequencies is verified along with nonideality and parasitic study. The circuit enhancement for generation of four phase clock waveforms is also given. The proposed circuit is a novel addition to the oscillator family.

1. Introduction

Realization of quadrature oscillators using current mode active building blocks has received continuous attention ever since the advent of current conveyors. The literature has thus witnessed voluminous works which may run into an equally voluminous bibliography, which is beyond the scope of the present discussion and hence limited to some selected works of the last few decades [1–10]. Differential voltage current conveyor became popular in the late 1990s and continued to find applications in realizing oscillators till recently [11–17]. Besides the realization of multiphase oscillators, third-order quadrature oscillators found special attention owing to their low-distortion output generation capability [18–24]. As a result, numerous high performance oscillator circuits continue to find most recent space in the literature [25–29].

In this paper a new third-order quadrature oscillator based on DVCCs is proposed. The proposed circuit requires three DVCCs, three grounded capacitors, and three resistors, of which two are grounded. The circuit generates four quadrature current outputs at high impedance nodes and two quadrature voltage outputs. The circuit usability at high frequencies with low THD is demonstrated. The nonideal analysis as well as parasitic analysis is included to study the

real world performance of the proposed circuit. The new proposal further enriches the subject area. Section 2 presents the actual circuit description. Section 3 is devoted to the nonideal analysis. Parasitics considerations are given in Section 4. Simulation results are given in Section 5. Application of the proposed circuit is further explored in Section 6. Lastly, Section 7 presents conclusion of the paper.

2. Proposed Circuit

2.1. Circuits' Description. The symbol and CMOS implementation of differential voltage current conveyor (DVCC) are shown in Figure 1. DVCC is a five-port building block and is characterized by the following port relationship:

$$\begin{aligned} V_X &= V_{Y_1} - V_{Y_2}, \\ I_{Y_1} &= I_{Y_2} = 0, \\ I_{Z+} &= +I_X, \\ I_{Z-} &= -I_X. \end{aligned} \quad (1)$$

In a DVCC, terminals Y_1, Y_2 exhibit infinite input impedance. Thus no current flows in terminal Y_1, Y_2 . The terminal X

FIGURE 1: (a) Symbol of DVCC. (b) CMOS implementation of DVCC.

FIGURE 2: Proposed circuit of third-order voltage/current mode quadrature oscillator.

FIGURE 3: (a) Phasor diagram depicting quadrature current outputs. (b) Phasor diagram depicting quadrature voltage outputs.

FIGURE 4: Parasitic model of DVCC.

exhibits zero input impedance. The Z_+ and Z_- terminals exhibit high output impedance. The proposed circuit of third order quadrature oscillator is shown in Figure 2. It is composed of three DVCCs, three grounded capacitors, and three resistors.

The characteristic equation of the circuit can be expressed as

$$s^3 + s^2 \frac{(C_2 R_2 + C_1 R_1 - C_1 R_2)}{C_1 C_2 R_1 R_2} + s \frac{1}{C_1 C_2 R_1 R_2} + \frac{1}{C_1 C_2 C_3 R_1 R_2 R_3} = 0. \quad (2)$$

Replacing s with $j\omega$ and equating real and imaginary terms, the above equation yields the frequency of oscillation (FO) and condition of oscillation (CO) as

$$\text{FO: } f_0 = \frac{1}{2\pi \sqrt{C_1 C_2 R_1 R_2}}, \quad (3)$$

$$\text{CO: } C_1 C_2 R_1 R_2 = C_3 R_3 (C_2 R_2 + C_1 R_1 - C_1 R_2). \quad (4)$$

FIGURE 5: Quadrature current output waveforms.

Assuming equal value resistors ($R_1 = R_2 = R$) and capacitors ($C_1 = C_2 = C$), the expressions of (3) and (4) are simplified to

$$\begin{aligned} \text{FO: } f_0 &= \frac{1}{2\pi RC}, \\ \text{CO: } CR &= C_3 R_3. \end{aligned} \quad (5)$$

The various voltage and current outputs depicted in Figure 3 are related as

$$\begin{aligned} V_2 &= -(j\omega C_2 R_1) V_1, \\ I_1 &= (j\omega C_3 R_3) I_3, \\ I_2 &= (j\omega C_3 R_3) I_4, \\ I_1 &= -I_2, \\ I_3 &= -I_4. \end{aligned} \quad (6)$$

FIGURE 6: Frequency spectrum of current outputs.

FIGURE 7: Quadrature voltage output waveforms.

It is evident from (6) that two quadrature voltages in the forms of V_1 and V_2 with a phase shift of 90° are obtained. It is quite worth noting that the voltage outputs unlike the available current outputs do not appear at appropriate (low) impedance level. The four current outputs are available at desired high impedance level and also exhibit a quadrature relationship. Four quadrature current outputs in the forms of I_1 , I_2 , I_3 and I_4 with a progressive phase shift of 90° are obtained. The various outputs generated have equal amplitudes. The sensitivity figures of FO with respect to passive components are low and given in

$$s_{C_1, C_2, R_1, R_2}^{f_0} = -\frac{1}{2}. \quad (7)$$

Equation (7) shows that the sensitivity figures for the proposed circuit are found to be less than unity, which implies good sensitivity performance.

FIGURE 8: Frequency spectrum of voltage outputs.

FIGURE 9: Frequency of oscillation variation with R (for $R_1 = R_2 = R$).

3. Nonideal Analysis

Taking the nonidealities of the DVCC into account, the relationship between the terminal voltages and currents of the DVCC can be rewritten as:

$$\begin{aligned} V_X &= \beta_1 V_{Y_1} - \beta_2 V_{Y_2}, \\ I_{Y_1} &= I_{Y_2} = 0, \\ I_{Z+} &= +\alpha I_X, \\ I_{Z-} &= -\alpha I_X. \end{aligned} \quad (8)$$

Here, β_1 and β_2 are the voltage transfer gains from Y_1 and Y_2 terminals, respectively, to the X terminal. And α is the current transfer gain from X terminal to $Z+$ and $Z-$ terminals. The above transfer gains deviate unity by the voltage and current transfer errors, which are quite small and technology dependent. Moreover, the transfer gains, instead of being real, are actually frequency dependent with an upper bound on the usable frequency.

TABLE 1: Model parameters used for simulation.

NMOS
LEVEL = 3; UO = 460.5; TOX = 1.0E - 8; TPG = 1; VTO = 0.62; KP = 159E - 6; JS = 1.8E - 6; XJ = 0.15E - 6
RS = 417; RSH = 2.73; LD = 0.04E - 6; ETA = 0; VMAX = 130E3; NSUB = 1.71E17; PB = 0.761
PHI = 0.905; THETA = 0.129; GAMMA = 0.69; KAPPA = 0.1; AF = 1; WD = 0.11E - 6; CJ = 76.4E - 5
MJ = 0.357; CJSW = 5.68E - 10; MJSW = 0.302; CGSO = 1.38E - 10; CGDO = 1.38E - 10
CGBO = 3.45E - 10; KF = 3.07E - 28; DELTA = 0.42; NFS = 1.2E11
PMOS
LEVEL = 3; UO = 100; TOX = 1.0E - 8; TPG = 1; VTO = -0.58; KP = 34.5E - 6; JS = 0.38E - 6; XJ = 0.1E - 6
RS = 866; RSH = 1.81; LD = 0.03E - 6; ETA = 0; VMAX = 113E3; NSUB = 2.08E17; PB = 0.991
PHI = 0.905; THETA = 0.120; GAMMA = 0.76; KAPPA = 2; AF = 1; WD = 0.14E - 6; CJ = 85E - 5
MJ = 0.429; CJSW = 4.67E - 10; MJSW = 0.631; CGSO = 1.38E - 10; CGDO = 1.38E - 10
CGBO = 3.45E - 10; KF = 1.08E - 29; DELTA = 0.81; NFS = 0.52E11

FIGURE 10: Proposed circuit as sine/clock generator.

The third-order quadrature oscillator of Figure 2 is re-analyzed using (8) so as to obtain the characteristic equation as:

$$s^3 + s^2 \frac{(\alpha_1 \beta_{12} C_2 R_2 + C_1 R_1 - \alpha_1 \beta_{11} C_1 R_2)}{C_1 C_2 R_1 R_2} + s \frac{\alpha_1 \beta_{12}}{C_1 C_2 R_1 R_2} + \frac{\alpha_1 \alpha_2 \alpha_3 \beta_{12} \beta_{31}}{C_1 C_2 C_3 R_1 R_2 R_3} = 0. \quad (9)$$

The modified frequency of oscillation and condition of oscillation are

$$\text{FO: } f_0 = \frac{1}{2\pi} \sqrt{\frac{\alpha_1 \beta_{12}}{C_1 C_2 R_1 R_2}}, \quad (10)$$

$$\text{CO: } \alpha_2 \alpha_3 \beta_{31} C_1 C_2 R_1 R_2 = C_3 R_3 (\alpha_1 \beta_{12} C_2 R_2 + C_1 R_1 - \alpha_1 \beta_{11} C_1 R_2). \quad (11)$$

Here, β_{11} , β_{12} are the voltage transfer gains from Y_1 , Y_2 terminals, respectively to the X terminal of DVCC₁, and β_{31} is the voltage transfer gain from Y_1 terminal to the X terminal of DVCC₃. α_1 is the current transfer gain from the X terminal to Z_+ terminal of DVCC₁, α_2 is the current transfer gain from the X terminal to Z_- terminal of DVCC₂ and α_3 is the current transfer gain from the X terminal to Z_+ terminal of DVCC₃.

TABLE 2: Dimensions of MOS transistors used in DVCC of Figure 1(b).

Transistors	W (μm)/L (μm)
M_1, M_2, M_3, M_4	1.6/1
M_5, M_6	8/1
M_{13}, M_{14}	29/1
M_7, M_8	20/1
M_{15}, M_{16}	90/1
$M_9, M_{10}, M_{11}, M_{12}$	60/1
$M_{17}, M_{18}, M_{19}, M_{20}$	270/1

It is to be noted that (10) reduces to (3) and (11) reduces to (4) for the ideal value of the transfer gains, which is equal to unity. The active and passive sensitivities are given in

$$S_{\alpha_1, \beta_{12}}^{f_0} = -S_{C_1, C_2, R_1, R_2}^{f_0} = \frac{1}{2}. \quad (12)$$

The sensitivities of active and passive components are within unity in magnitude. Thus, the new circuit of third-order quadrature oscillator enjoys attractive active and passive sensitivity performances. It can be further observed from (10) and (11) that the non-idealities slightly change the frequency of oscillation and condition of oscillation.

4. Parasitic Considerations

The various parasitics involved with a typical current conveyor [30] are well known. Like the second-generation current conveyor (CCII), the DVCC has a small parasitic resistance R_X at port X , high input impedance ($R_Y // C_Y$) at port Y , and high input impedance ($R_{Z+} // C_{Z+}$) at $Z+$ terminal. The parasitic model of DVCC is shown in Figure 4. As the X terminal of the DVCC₁, DVCC₂, and DVCC₃ is connected to a resistor, the parasitic resistance at the X terminal of the DVCC (R_X) can be absorbed as a part of the main resistance. As the value of R_{X_1} , R_{X_2} , and R_{X_3} is much smaller than that of, the external resistors, frequency of oscillation of the proposed circuit of third-order quadrature oscillator will be slightly affected. The effects of the capacitors at ports Y and Z of the DVCC are also negligible because these capacitors

TABLE 3: % THD for current and voltage outputs.

Outputs	I_1	I_2	I_3	I_4	V_1	V_2
% THD	1.82	1.16	0.53	0.58	1.34	0.84

FIGURE 11: Four phase clock wave shapes.

are quite small (and process dependent) as compared to the external capacitors. However, the proposed circuit of quadrature oscillator is reanalyzed taking into account the above parasitic effects. A reanalysis of the proposed circuit of quadrature oscillator yields

$$s^3 a + s^2 b + s c + d = 0, \quad (13)$$

where

$$\begin{aligned}
 a &= R' R'' R''' R_1^2 R_2' R_3' (C_1 + C') (C_2 + C'') (C_3 + C''') \\
 b &= R_1' R_2' R_3' \\
 &\quad \times [R' R'' R_1' (C_1 + C') (C_2 + C'') \\
 &\quad \quad + R'' R''' R_1' (C_2 + C'') (C_3 + C''') + R' R''' R_1' \\
 &\quad \quad \times (C_1 + C') (C_3 + C''') + R' R'' R''' \\
 &\quad \quad \times (C_2 + C'') (C_3 + C''')] \\
 &\quad + R' R''' R_3' [R'' R_1^2 (C_1 + C') (C_3 + C''') \\
 &\quad \quad + R_2' (C_1 + C') (C_3 + C''')] \\
 c &= R_1' R_2' R_3' \\
 &\quad \times [R' R_1' (C_1 + C') + R'' R_1' (C_2 + C'') \\
 &\quad \quad + R''' R_1' (C_3 + C''') + R' R'' (C_1 + C') \\
 &\quad \quad + R' R'' (C_2 + C'') + R' R''' (C_3 + C''') \\
 &\quad \quad + R'' R''' (C_3 + C''')] \\
 &\quad + R'' R_1' R_3' [R' R_1' (C_1 + C') R''' R_1' \\
 &\quad \quad \times (C_3 + C''') + R' R''' (C_3 + C''')]
 \end{aligned}$$

$$\begin{aligned}
 d &= R_1' [R'' R_1' R_3' + R_1' R_2' R_3' \\
 &\quad + R' R'' R_3' + R' R_2' R_3' \\
 &\quad + R' R'' R''' + R'' R_2' R_3'] , \quad (14)
 \end{aligned}$$

where $R' = R_{Z_{1+}} + R_{Y_{12}} + R_{Z_{3+}}$, $R'' = R_{Z_{1+}} + R_{Y_{11}}$, $R''' = R_{Z_{2-}} + R_{Y_{31}}$ and $R_1' = R_1 + R_{X_1}$, $R_2' = R_2 + R_{X_2}$, $R_3' = R_3 + R_{X_3}$, and $C' = C_{Z_{1+}} + C_{Y_{12}} + C_{Z_{3+}}$, $C'' = C_{Z_{1+}} + C_{Y_{11}}$, $C''' = C_{Z_{2-}} + C_{Y_{31}}$.

From (13) it is clear that the parasitic resistances and capacitances appear in shunt with external capacitors, which are connected at Z terminals, thus ensuring a possibility of predistorting the designed values. Therefore it is to be concluded that the circuits are not adversely affected by the parasitic resistances and capacitances. Moreover, from (13), it can be further observed that the parasitic resistances/capacitances merge with the external value. Such a merge does cause slight deviation in circuit's parameters, which can be eliminated by predistorting the element values to be used in the circuit.

5. Simulation Results

The proposed third-order quadrature oscillator was next simulated using PSPICE, an industry standard tool for evaluating the performance of circuits. The CMOS implementation of DVCC in Figure 1(b) was used with 0.5 μm CMOS parameters and aspect ratios as listed in Tables 1 and 2, respectively, and the supply voltages were $V_{DD} = -V_{SS} = 2.5\text{ V}$. The biasing voltage V_{BB} was taken as -1.4 V . The circuit was designed using equal capacitors and resistors of values $C_1 = C_2 = C_3 = 5\text{ pF}$ and $R_1 = R_2 = R_3 = 4\text{ k}\Omega$. The theoretical FO using this design was 796 MHz. The simulated FO was found to be 794 MHz, which is very close to the theoretical value and only

0.25% in error. The results for the four current outputs and two voltage outputs are shown in Figures 5 and 7 respectively. The Fourier spectrum of the outputs of Figures 5 and 7, are shown in Figures 6 and 8, respectively. The THD at various outputs is listed in Table 3. A low THD along with good accuracy of the FO is a justifying feature for the third-order oscillator. To further support the circuit's practical utility, R (for $R_1 = R_2 = R$) was varied so as to vary the FO. The FO tuning through R is shown in Figure 9. The FO is found to vary from 3.18 MHz to 10.62 MHz for variation of R from 10 K Ω to 3 K Ω , respectively. Both theoretical and simulated FO are found to be closely matched; the discrepancy in simulated frequency being the result of various nonidealities and parasitics as discussed in Sections 3 and 4.

6. Circuit Enhancement

Next, a new application of the proposed third-order quadrature oscillator in clock generation is given. A four phase clock ($V_{ac\text{clk}}$, $V_{bc\text{clk}}$, $V_{cc\text{clk}}$ and $V_{dc\text{clk}}$) along with two sine waveforms ($V_{1\text{sin}}$ and $V_{2\text{sin}}$) is generated by using the proposed circuit of oscillator (Figure 2). The block diagram representation is shown in Figure 10. For generation of four phase clocks, four voltage outputs are taken instead of four current outputs (as shown in Figure 2) at the Z terminals of DVCC₂ and DVCC₃. The four phase clock voltage outputs are at a progressive phase shift of 90°. Note that the Z terminals exhibit a high output resistance, sufficient to saturate the DVCCs. The output levels depend on the supply voltage (V_{DD} and V_{SS}). No additional resistors are being used, and thus the new scheme is compatible with monolithic implementation. The results of the four phase clock are shown in Figure 11 and very well justify this new application.

7. Conclusion

A new third-order quadrature oscillator circuit based on three DVCCs as active element, three grounded capacitors, and three resistors is presented. The circuit provides both quadrature voltage and current outputs. The circuit exhibits good high frequency performance. The enhancement of the proposed circuit as sine/clock generator is further given. PSPICE simulations using 0.5 μm CMOS parameters support the validity and practical utility of the proposed circuit.

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