Current-mode quadrature oscillator based on CCCDTAs with noninteractive dual-current control for both condition of oscillation and frequency of oscillation

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Abstract: The realization of 2 current-mode quadrature oscillators using current-controlled current differencing transconductance amplifiers (CCCDTAs) and grounded capacitors is presented. The proposed oscillators can provide 2 sinusoidal output currents with a $90°$ phase difference. They enable noninteractive dual-current control for both the condition of oscillation and the frequency of oscillation. The high-output impedances of the configurations enable the circuit to be cascaded without additional current buffers. The use of only grounded capacitors is ideal for integration. The circuit performances are depicted through PSpice simulations; they show good agreement to theoretical anticipation.

Key words: Current-mode, CCCDTA, oscillator, condition of oscillation, condition of oscillator

1. Introduction

Controlled quadrature oscillators (QOs) are extremely useful circuits for various communication applications, wherein there is a requirement of multiple sinusoids that are $90°$ phase-shifted, e.g., in quadrature mixers and single sideband modulators [1]. Recently, current-mode circuits have been receiving considerable attention due to their potential advantages, such as inherently wide bandwidth, higher slew rate, greater linearity, wider dynamic range, simple circuitry, and low power consumption [2–5].

Recently, attention has turned to use of a new active building block, namely the current differencing transconductance amplifier (CDTA) [6], as a current-mode active element, since it has been shown that the CDTA seems to be a versatile component in the realization of a class of analog signal processing circuits, especially analog frequency filters [7–10]. The current-mode element's input and output signals are currents. In addition, the CDTA's output current can be electronically adjusted. Moreover, a modified version of the CDTA, which has parasitic resistances at 2 current input ports and can be electronically controlled, was proposed in [11]. This CDTA is called the current-controlled current differencing transconductance amplifier (CCCDTA).

From a literature survey, it is found that several implementations of oscillators employing CDTAs or CCCDTAs have been reported [12–25]. Unfortunately, these reported circuits suffer from one or more of the following weaknesses: they use more than 2 CDTAs or CCCDTAs and require excessive use of the passive elements, which is not convenient to further fabricate the integrated circuits (ICs); and some reported circuits use multiple-output CDTAs or CCCDTAs. Consequently, the circuits become more complicated. The proposed

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QOs using CDTA or CCCDTA are compared with the previously published QOs in [12–25] and the results are shown in Table 1.

The aim of this paper is to introduce a high-output impedance current-mode QO, based on CCCDTAs. The condition of oscillation (CO) and frequency of oscillation (FO) can be independently adjusted electronically. The circuit constructions consist of 2 CCCDTAs and grounded capacitors. The PSpice simulation results are also shown, which are in correspondence with the theoretical analysis.

Table 1. Comparison among various QOs using CDTAs and CCCDTAs.

Ref.	Active element	Number of active elements	Noninteractive dual-current control for both the CO and the FO	Grounded C only	Number of R + C	Electronic tune of the CO and the FO	Current-mode QO output
[12]	CDTA	3	No	Yes	0 + 3	Yes	Yes
[13]	CDTA	3	No	Yes	0 + 3	Yes	Yes
[14]	CDTA	2	No	No	4 + 2	No	Yes
[15]	CDTA	2	No	Yes	1 + 2	No	Yes
[16]	CDTA	2	No	No	4 + 2	No	Yes
[17]	CDTA	3	No	Yes	0 + 2	Yes	Yes
[18]	CDTA	4	Yes	Yes	0 + 2	Yes	Yes
[19]	CDTA	3	No	Yes	0 + 2	Yes	Yes
[20]	CDTA	1	No	No	2 + 2	No	No
[21]	CDTA	1	No	No	1 + 2	No	Yes
[22]	MO-CCCDTA	1	No	Yes	0 + 2	Yes	No
[23]	CCCDTA	2	Yes	Yes	0 + 2	Yes	No
[24]	MO-CCCDTA	1	No	Yes	0 + 2	Yes	Yes
[25]	ZC-CDTA	1	No	Yes	2 + 2	No	No
Proposed QOs	CCCDTA	2	Yes	Yes	0 + 3 (circuit a) 0 + 2 (circuit b)	Yes Yes	Yes Yes

CO: condition of oscillation.
FO: frequency of oscillator.

2. Principle and operation

2.1. Basic concept of the CCCDTA

Since the proposed circuit is based on a CCCDTA, a brief review of the CCCDTA is given in this section. Generally, CCCDTA properties are similar to the conventional CDTA, except that the CCCDTA has finite input resistance (R_p and R_n) at the p and n input terminals. This parasitic resistance can be controlled by the bias current, as shown in the following equation:

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_x \end{bmatrix} = \begin{bmatrix} R_p & 0 & 0 & 0 \\ 0 & R_n & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_x \\ V_z \end{bmatrix}. \tag{1}$$

For the CCCDTA implemented by complementary metal-oxide semiconductor (CMOS) technology, the parasitic resistances (R_p and R_n) and transconductance g_m can be expressed as:

$$R_n = R_p = \frac{1}{\sqrt{8k_1 I_{B1}}}, \tag{2}$$

where $k_1 = \mu_p C_{ox} \left(\frac{W}{L}\right)_{9,10,11,12} = \mu_n C_{ox} \left(\frac{W}{L}\right)_{13,14,15,16}$, and

$$g_m = \frac{1}{\sqrt{k_2 I_{B2}}}, \tag{3}$$

where $k_2 = \mu_n C_{ox} \left(\frac{W}{L}\right)_{26,27}$.

Here, $k_i = \mu_n C_{ox} \left(\frac{W}{L}\right)$ is the physical parameter of the CMOS transistor. I_{B1} and I_{B2} are the bias current used to control the parasitic resistances and transconductance, respectively. The symbol and the equivalent circuit of the CCCDTA are illustrated in Figures 1a and 1b, respectively. In general, a CCCDTA can contain an arbitrary number of z terminals, called z_c (z-copy) terminals [18]. The internal current mirror provides a copy of the current flowing out of the z terminal to the z_c terminal.
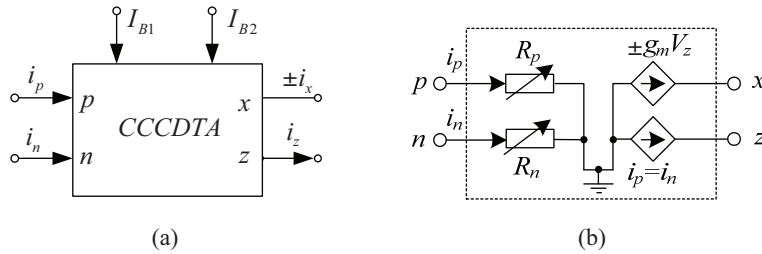

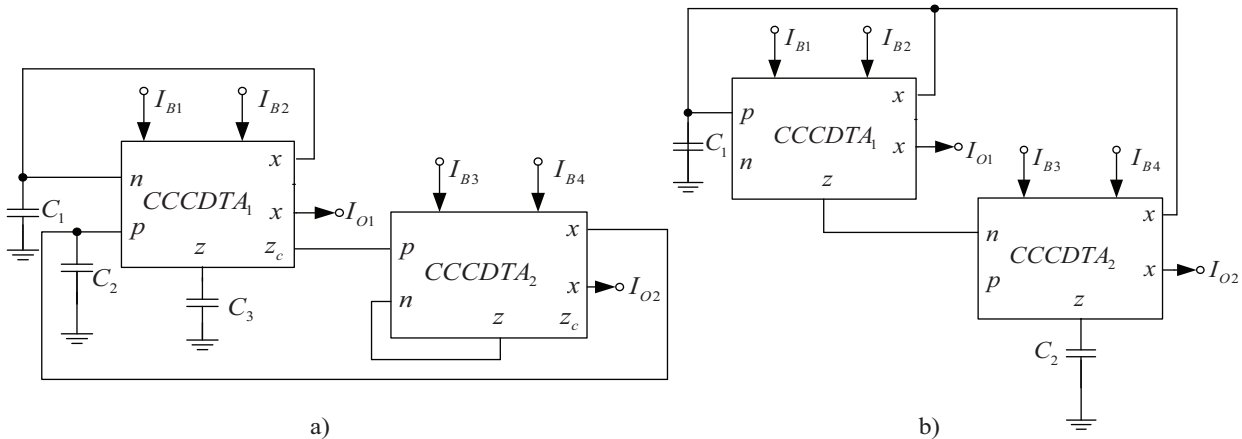Figure 1. CCCDTA: a) symbol, b) equivalent circuit.

Figure 2. The proposed current-mode quadrature oscillators: a) first QO, b) second QO.

2.2. Proposed current-mode quadrature oscillators

The proposed oscillator circuits are shown in Figure 2.

2.2.1. First current-mode QO

The first QO is shown in Figure 2a. It consists of 2 CCCDTAs and 3 grounded capacitors. For easy consideration, we set $R_{p1} = R_{n1} = R_1$, $C_1 = C_2 = C_1$, and using routine circuit analysis, the characteristic equation for the QO shown in Figure 2a can be found as:

$$s^2 C_1 C_2 R_1 - s C_2 \left(\frac{g_{m2} R_{n2}}{2} - 1 \right) + g_{m1} = 0. \tag{4}$$

It is found from Eq. (4) that the proposed circuit is a second-order sinusoidal oscillator that generates a pair of complex conjugate poles with a small positive real part. If $a = C_1 C_2 R_1$, $b = C_2 \left(\frac{g_{m2} R_{n2}}{2} - 1 \right)$, and $c = g_{m1}$, these poles $\sigma_p \pm j\omega_p$ are written as [26]:

$$\sigma_p = \frac{b}{2a}, \tag{5}$$

and

$$\omega_p = \frac{\sqrt{4ac - b^2}}{2a}. \tag{6}$$

If $\sigma_p \geq 0$, the circuit can be a oscillator. From Eq. (5), it is required that:

$$g_{m2} R_{n2} \geq 2. \tag{7}$$

If the above CO is satisfied, the circuit produces oscillations with a frequency of:

$$\omega_{osc} = \omega_p = \sqrt{\frac{g_{m1}}{R_1 C_1 C_2}}. \tag{8}$$

From Eqs. (7) and (8), if $g_{mi} = \sqrt{k_i I_{Bi}}$ and $R_{n,pi} = 1/\sqrt{k_i I_{Bi}}$, it can be seen that the CO can be adjusted independently from the FO by varying I_{B3} and I_{B4}, while the oscillation frequency can be adjusted by I_{B1} and I_{B2}. Moreover, it should be remarked that the proposed circuit can provide an advantage over the circuits in [12–25], because it enables noninteractive dual-current control for both the CO and the FO (the CO is tuned by I_{B3} and I_{B4}, and the FO is tuned by I_{B1} and I_{B2}).

From the circuit in Figure 2a, the relationship between the explicit-current outputs can be found as:

$$\frac{I_{O1}(s)}{I_{O2}(s)} = \frac{g_{m1}}{g_{m2} R_{n2} C_2 s}. \tag{9}$$

For the sinusoidal steady state, Eq. (9) becomes:

$$\frac{I_{O1}(j\omega)}{I_{O2}(j\omega)} = \frac{g_{m1} e^{-j90}}{g_{m2}. R_{n2} C_2} \tag{10}$$

The phase ϕ difference between I_{O1} and I_{O2} is:

$$\phi = -90°, \tag{11}$$

ensuring that the currents I_{O1} and I_{O2} are in quadrature. It should be remarked that the proposed circuit in Figure 2a requires a capacitor matching condition (C_1). This is the drawback of the proposed circuit. To solve this disadvantage, the circuit in Figure 2b is proposed.

2.2.2. Second current-mode QO

The second QO in Figure 2b consists of 2 CCCDTAs and 2 grounded capacitors. Using Eq. (1) and doing routine analysis, the characteristic equation for the QO shown in Figure 2b is:

$$s^2 R_{p1} C_1 C_2 - C_2 s \left(g_{m1} R_{n2} - 1 \right) + g_{m2} = 0. \tag{12}$$

With the same consideration to the above section, the CO and FO are given as:

$$g_{m1} R_{n2} \geq 1 \tag{13}$$

and

$$\omega_{osc} = \sqrt{\frac{g_{m2}}{R_{p1} C_1 C_2}}. \tag{14}$$

Hence, the CO can be controllable by the bias currents I_{B2} and I_{B3} and the FO can be independently controlled by I_{B1} and I_{B4}. From the circuit in Figure 2b, the relationship between the explicit-current outputs for can be found as:

$$\frac{I_{O1}(s)}{I_{O2}(s)} = -\frac{g_{m2}}{g_{m1} R_{n2} C_2 s}. \tag{15}$$

For the sinusoidal steady state, Eq. (15) becomes:

$$\frac{I_{O1}(j\omega)}{I_{O2}(j\omega)} = \frac{g_{m2} e^{j90}}{g_{m1} R_{n2} C_2}. \tag{16}$$

The phase ϕ difference between I_{O1} and I_{O2} is:

$$\phi = 90°, \tag{17}$$

ensuring that the currents I_{O1} and I_{O2} are in quadrature. It is found that the proposed circuit in Figure 2b can provide the same abilities to the circuit in Figure 2a without the capacitor matching condition.

2.3. Analysis of a nonideal case

For a nonideal case, the CCCDTA can be characterized with the following equation:

$$I_z = \alpha_p i_p - \alpha_n I_n, I_{z_c} = \beta I_z, I_x = \pm \gamma g_m V_z, \tag{18}$$

where α_p, α_n, and β are the frequency dependent current gains and γ is the frequency dependent voltage gain. These gains are ideally equal to unity. Practically, they depend on the frequency of operation, temperature, and transistor parameters of the CCCDTA.In a nonideal case, the CO and FO of the QO in Figure 2a are as follows:

$$\frac{\alpha_{n1} \alpha_{p2} \beta_1 \gamma_2 g_{m2} R_{n2}}{1 + \alpha_{n2}} \geq 1 \tag{19}$$

and

$$\omega_{osc} = \sqrt{\frac{\alpha_{n1} \gamma_1 g_{m1}}{R_{n1} C_1 C_2}}. \tag{20}$$

The CO and FO of the QO in Figure 2b are given as:

$$\alpha_{p1}\gamma_1 g_{m1} R_2 \geq 1 \tag{21}$$

and

$$\omega_{osc} = \sqrt{\frac{\alpha_{p1}\gamma_2 g_{m2}}{R_{n1}C_1 C_2}}. \tag{22}$$

Actually, α_p, α_n, β, and γ originate from the intrinsic resistances and stray capacitances in the CCCDTA. These errors affect the sensitivity to temperature and the high-frequency response of the proposed circuits; hence, the CCCDTA should be carefully designed to minimize these errors. Consequently, these deviations are very small and can be ignored in ideal consideration.

3. Simulation results
To prove the performances of the proposed circuit, the PSpice simulation program was used for the examination. The p-type metal-oxide semiconductor (PMOS) and n-type metal-oxide semiconductor (NMOS) were simulated using the parameters of the Taiwan Semiconductor 0.25 μ m CMOS technology [27]. The first QO, as shown in Figure 2a, is chosen as the design example. The internal construction of the CCCDTA used in the simulation is shown in Figure 3. The aspect transistor ratios of the PMOS and NMOS are listed in Table 2. The circuit was biased with $\pm$ 1.25 V supply voltages, $C_1 = C_2 = C_3 = 15$ pF, $I_{B1} = 50 \mu$ A, $I_{B2} = 200 \mu$ A, $I_{B3} = 10 \mu$ A, and $I_{B4} = 32 \mu$ A. This yields an oscillation frequency of 10.4 MHz. The power consumption of the
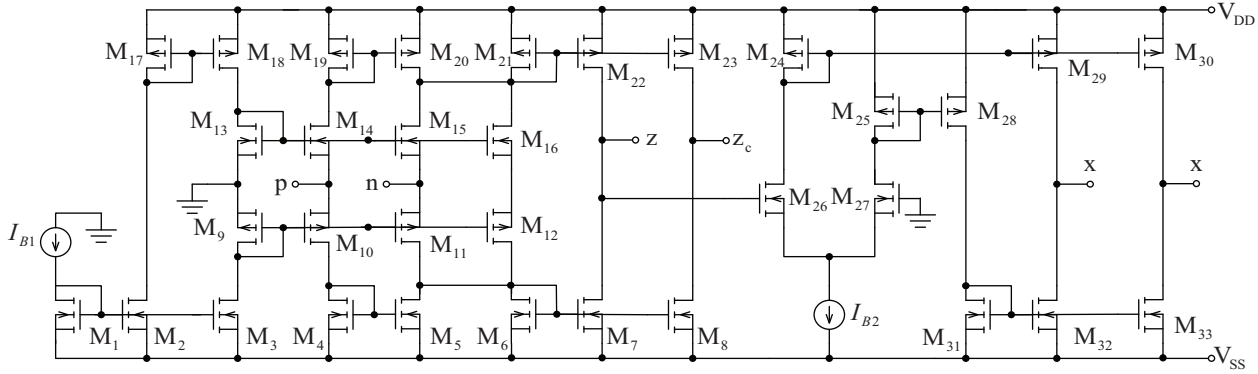
Figure 3. Internal construction of the CCCDTA.

Table 2. Dimensions of the CMOS transistor.

CMOS Transistors	W (μ m)/L (μ m)
M1–M3, M6–M9, M12	5/0.5
M4–M5, M24	5/0.25
M10–M11, M25	4.5/0.5
M12–M16	2/0.5
M17–M18, M21–M23	15/0.5
M19–M20	15/0.25
M26–M27	55/0.25
M28–M30	4/0.25
M31–M33	10/0.25

circuit is 2.45 mW. Figure 4 shows the simulated quadrature output waveforms for the transient response, and the steady state response is shown in Figure 5. Figure 6 shows the simulated output spectrum, where the total harmonic distortion of I_{O1} is about 0.98% and that of I_{O2} is about 2.80%. The electronic tunings of the FO with bias current I_{B1} and I_{B2} for different capacitor values are shown in Figures 7 and 8, respectively. It is seen that the simulation results are in accordance with the theoretical analysis as shown in Eq. (8)
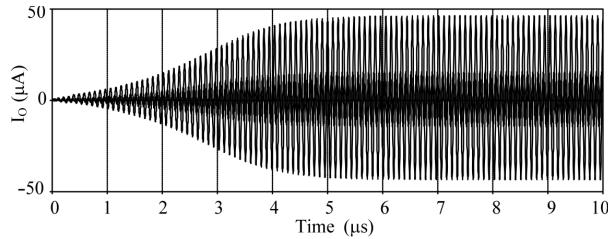
Figure 4. The simulation results of the quadrature outputs for transient response.
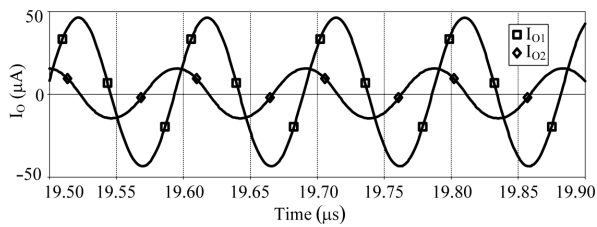
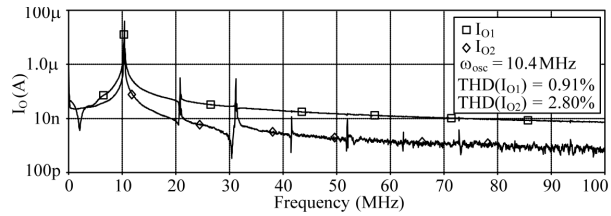**Figure 5.** The simulation results of the quadrature outputs for steady state response.

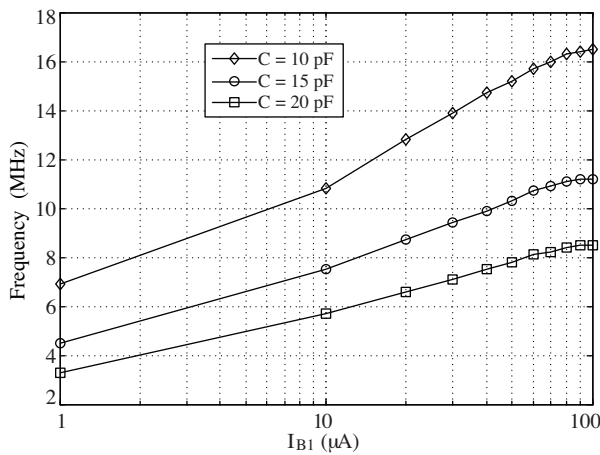**Figure 6.** The simulation results of the output spectrum.

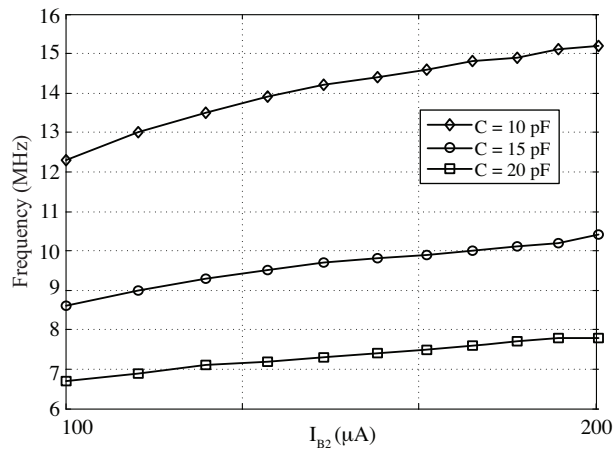**Figure 7.** Oscillation frequencies against bias current I_{B1}.

Figure 8. Oscillation frequencies against bias current I_{B2}.

4. Conclusion

Two current-mode quadrature oscillators based on a CCCDTA have been presented. The proposed circuits consist of 2 CCCDTAs and grounded capacitors. Noninteractive dual-current control of both the CO and FO is achieved. Due to high-output impedances, they enable easy cascading in a current-mode configuration. As a mentioned advantage, the proposed circuits are convenient to fabricate in ICs. The PSpice simulation results agree well with the theoretical anticipation.

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