Current-Mode Resistorless SIMO Universal Filter and Four-Phase Quadrature Oscillator

Jie Jin

Abstract—In this paper, a new CMOS current-mode single input and multi-outputs (SIMO) universal filter and quadrature oscillator with a similar circuit are proposed. The circuits only consist of three Current differencing transconductance amplifiers (CDTA) and two grounded capacitors, which are resistorless, and they are suitable for monolithic integration. The universal filter uses minimum CDTAs and passive elements to realize SIMO type low-pass (LP), high-pass (HP), band-pass (BP) band-stop (BS) and all-pass (AP) filter functions simultaneously without any component matching conditions. The angular frequency ($\omega 0$) and the quality factor (Q) of the proposed filter can be electronically controlled and tuned orthogonal. By some modifications of the filter, a new current-mode four-phase quadrature oscillator (QO) can be obtained easily. The condition of oscillation (CO) and frequency of oscillation (FO) of the QO can be controlled electronically and independently through the bias current of the CDTAs, and it is suitable for variable frequency oscillator. Moreover, all the passive and active sensitivities of the circuits are low. SPICE simulation results are included to confirm the theory.

Keywords—Universal Filter, Quadrature Oscillator, Current mode, Current differencing transconductance amplifiers.

I. INTRODUCTION

DURING the past few years, in active filters and oscillators design, the current-mode approach [1] has become more popular due to its advantages of providing larger dynamic range, wider bandwidth, lower power consumption and simpler filtering configurations over the voltage-mode counterparts, especially for the high-frequency operation. Many current-mode active elements have been reported, such as operational transconductance amplifier (OTA) [2], [3], current conveyor [4], [5], current operational amplifier [6], [7], current differencing buffered amplifier (CDBA) [8], [9] and current differencing transconductance amplifiers (CDTA).

After D. Biolek proposed the current differencing transconductance amplifier [10], [11], great interests have been devoted to analyze and develop this new block [12]. The CDTA is a synthesis of the well-know advantages of the CDBA [13] and OTA. It is a really current-mode element whose inputs and outputs are all current form. Several realizations of current-mode filters and oscillators using CDTA have been reported in the literature [11], [12], [14]-[18], [19]-[26].

The filters in [12], [16]-[18] are not SIMO type filters; they cannot provide universal filter functions simultaneously. The SIMO type filters are also reported in [11], [14], [15]. However, the work in [11] can only provide LP, BP and HP filter functions, and the band-stop (BS) and all-pass (AP) responses

cannot be realized from this configuration; although, the work in [14], [15] only use one or two CDTA, they cannot realize high-impedance outputs, they need component matching at the outputs. Moreover, four passive components are used in [15], and two of them are floating, which is not suitable for monolithic integration. The QOs reported in [19]-[26] cannot provide completely independently controlling of the CO and FO, and the works in [19], [20], [24] have floating passive components. Moreover, the works in [19]-[22], [24] cannot provide four-phase quadrature outputs.

This paper presents a new CMOS SIMO universal filter and QO based on CDTA. The two circuits are all resistorless, and only consist of three CDTAs and two grounded capacitors, respectively. The universal filter uses minimum CDTAs and passive elements to realize SIMO type low-pass (LP), high-pass (HP), band-pass (BP) band-stop (BS) and all-pass (AP) filter functions simultaneously without any component matching conditions. The angular frequency (ω_0) and the quality factor (Q) of the proposed filter can be electronically controlled and tuned orthogonal. By some modification of the filter, a new current-mode four-phase quadrature oscillator (QO) can be obtained easily. The condition of oscillation (CO) and frequency of oscillation (FO) of the QO can be controlled electronically and independently through the bias current of the CDTAs, and it is suitable for variable frequency oscillator. Moreover, all the passive and active sensitivities of the circuits are low.

II. CIRCUIT SYMBOL OF CDTA AND ITS REALIZATION CIRCUIT

Fig. 1 (a) denotes the symbol of CDTA, Fig. 1 (b) is the equivalent circuit of the CDTA. The terminal relation of the CDTA can be characterized by the following set of equations [18]:

$$
\begin{aligned}
v_p &= v_n = 0 \\
i_z &= i_p - i_n \\
i_x+ &= g_m v_z = g_m Z_z i_z \\
i_x- &= -g_m v_z = -g_m Z_z i_z
\end{aligned}
\tag{1}
$$

where p and n are input terminals, z and x are output terminals, g_m is the transconductance gain, and Zz is an external impedance connected at the terminal z. From (1), the current i_z follows the difference of the currents through the terminals p and n (i_p-i_n), and flows from the terminal z into an impedance Zz. The voltage drop at the terminal z is transferred to a current at the terminal x (i_x) by a transconductance gain (g_m), which is

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generally electronically controllable by an external bias current Ib.
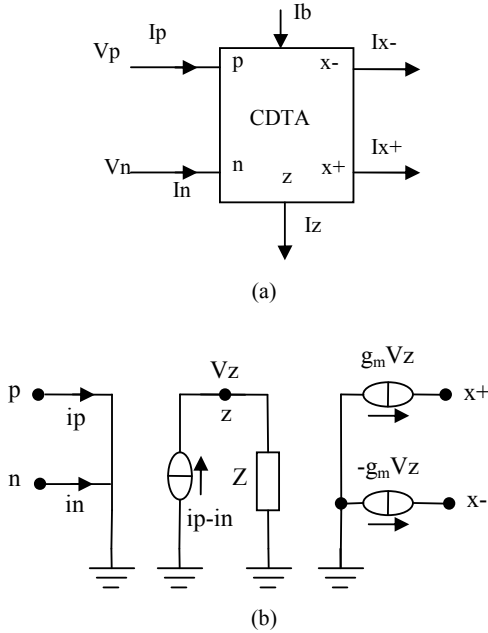

(a)

(b)
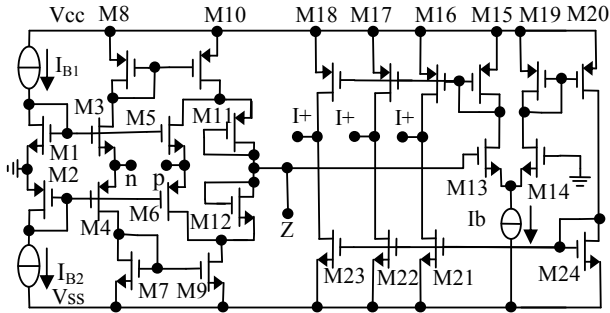
Fig. 1 CDTA (a) Symbol (b) Equivalent circuit

Fig. 2 CMOS-based CDTA in this work [19]

The possible CMOS realization of the CDTA used in this work is shown in Fig. 2 [19]. The circuit consists of a current differencing circuit M1-M12, and a transconductance amplifier M13-M24. The current differencing circuit part (M1-M12) realize the function of "Iz=Ip-In"; and the transconductance amplifier (M13-M24) realize the function of "Ix=g_m*(Ip-In) =g_mVz", and the transconductance gain (g_m) of the transconductance amplifier can be set by Ib.

The CDTA used in this work is shown in Fig. 2. Assuming transistors M13 and M14 are operated in the saturation region, the transconductance gain (g_m) can be expressed as:

$$g_m = \sqrt{\mu C_{OX}(W/L)|I_b|} \qquad (2)$$

where u is carrier mobility, C_{ox} is the gate oxide capacitance per unit area.

From (2), we can know that the transconductance gain can be electronically controlled by adjusting the bias current I_b

III. PROPOSED CURRENT MODE FILTER AND QUADRATURE OSCILLATOR

A. The CDTA-Based Current-Mode SIMO Universal Filter

The proposed circuit is shown in Fig. 3. This circuit contains three CDTAs and two grounded capacitors. I_{in} denotes input signal, and I_{o1}, I_{o2}, I_{o3}, I_{o4} present the four outputs respectively.
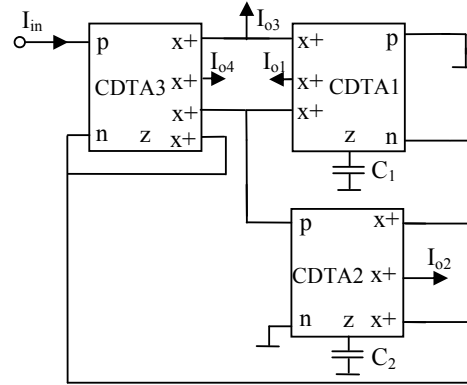

Fig. 3 The proposed current-mode SIMO universal filter

Using (1), analyzing Fig. 3 yields following current transfer functions as (3)-(7).

$$T_{LP}(s) = \frac{I_{o1}}{I_{in}} = -\frac{\dfrac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}} \qquad (3)$$

$$T_{BP}(s) = \frac{I_{o2}}{I_{in}} = \frac{s\dfrac{g_{m2}}{C_2}}{s^2 + s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}} \qquad (4)$$

$$T_{HP}(s) = \frac{I_{o3}}{I_{in}} = \frac{s^2}{s^2 + s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}} \qquad (5)$$

$$T_{BS}(s) = \frac{I_{o4}}{I_{in}} = \frac{s^2 + \dfrac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}} \qquad (6)$$

$$T_{AP}(s) = \frac{I_{o4} - I_{o2}}{I_{in}} = \frac{s^2 - s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\dfrac{g_{m2}}{C_2} + \dfrac{g_{m1}g_{m2}}{C_1C_2}} \qquad (7)$$

It is clear from (3)-(7) that I_{o1} is the low-pass output, I_{o2} is the band-pass output, I_{o3} is the high-pass output, I_{o4} is the notch output and (I_{o4}- I_{o2}) is the all-pass output. From the above

calculations, the angular frequency and quality factor of this filter can get in (8)-(9).

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \qquad (8)$$

$$Q = \sqrt{\frac{g_{m1}C_2}{g_{m2}C_1}} \qquad (9)$$

From (8)-(9), it is clear that the SIMO filter has orthogonal tuning capability for the characteristic parameters ω_0 and Q.

B. The CDTA-Based Quadrature Oscillator

By setting $I_{in}=0$, connecting the terminals p and z of the CDTA3 to the terminals x and z of the CDTA$_2$ respectively, and disconnecting the terminal x of the CDTA3 to the terminal x of the CDTA1 in Fig. 3, the proposed CDTA-based current-mode four-phase quadrature oscillator can be obtained as shown in Fig. 4.
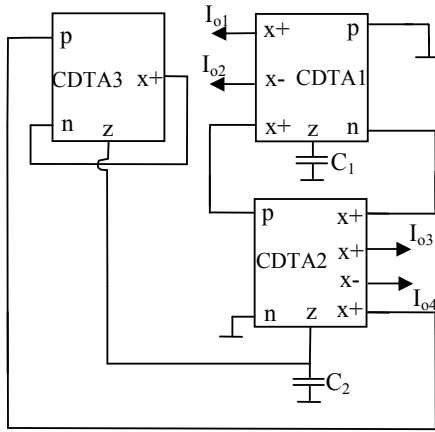

Fig. 4 The proposed current-mode quadrature oscillator

A routine circuit analysis of the configuration using (1), the characteristic equation of the oscillator is:

$$s^2C_1C + s\left(g_{m3} - g_{m2}\right)C_1 + g_{m1}g_{m2} = 0 \qquad (10)$$

From (10), the condition of oscillation (CO) and frequency of oscillation (FO) can be expressed as:

$$g_{m3} \leq g_{m2} \qquad (11)$$

$$\omega_{osc} = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \qquad (12)$$

From Fig. 4, the current transfer function between Io1 and Io2 is:

$$\frac{I_{o1}(s)}{I_{o2}(s)} = -\frac{g_{m1}}{sC_2} = \frac{I_{o1}(j\omega)}{I_{o2}(j\omega)} = \frac{g_{m1}}{\omega C_2}e^{j90^o} \qquad (13)$$

Therefore, the phase difference between Io1 and Io2 is 90°, and the two currents are quadrature. From (11) and (12), it can be seen that the CO can be adjusted independently from the FO by g_{m3}, while the FO can be adjusted independently by g_{m1}, and it is suitable for variable frequency oscillator. The CO and FO are controlled independently and electronically, which is a big advantage of the proposed QO.

IV. NON-IDEAL ANALYSIS

Taking the non-idealities of the CDTA into account, the port relations of the non-ideal CDTA can be rewritten as:

$$\begin{aligned} v_p &= v_n = 0 \\ i_z &= \alpha_p i_p - \alpha_n i_n \\ i_x+ &= \beta g_m v_z \end{aligned} \qquad (14)$$

where $\alpha_p =1-\epsilon_p$ denotes the current tracking error from terminal p to z, and $\alpha_n =1-\epsilon_n$ denotes the current tracking error from terminal n to z, and β is transconductance inaccuracy factor from the z to x terminals of the CDTA, respectively. α_{pi}, α_{ni} and β_i are the parameters α_p, α_n and β of the i-th CDTA, respectively.

Using (14), the denominator polynomials of the current transfer functions of the SIMO universal filter can be described by:

$$D(s) = s^2 + s\frac{\alpha_{n3}\alpha_{p2}\beta_2 g_{m2}}{C_2} + \frac{\alpha_{n1}\alpha_{p2}\beta_1\beta_2 g_{m1}g_{m2}}{C_1C_2} \qquad (15)$$

In this case, the modified parameters ω_0 and Q are given by:

$$\omega_0' = \sqrt{\frac{\alpha_{n1}\alpha_{p2}\beta_1\beta_2 g_{m1}g_{m2}}{C_1C_2}} \qquad (16)$$

$$Q' = \frac{1}{\alpha_{n3}}\sqrt{\frac{\alpha_{n1}\beta_1 g_{m1}C_2}{\alpha_{p2}\beta_2 g_{m2}C_1}} \qquad (17)$$

The active and passive sensitivities of the SIMO universal filter are:

$$S^{\omega_0'}_{\alpha_{n1},\alpha_{p2},\beta_1,\beta_2,g_{m1},g_{m2}} = \frac{1}{2}, S^{\omega_0'}_{C_1,C_2} = -\frac{1}{2}$$

$$S^{Q'}_{\alpha_{n1},\beta_1,g_{m1},C_2} = \frac{1}{2}, S^{Q'}_{\alpha_{p2},\beta_2,g_{m2},C_1} = -\frac{1}{2} \qquad (18)$$

$$S^{Q'}_{\alpha_{n3}} = -1$$

And the characteristic equation of the QO can be rewritten as:

$$\begin{aligned} s^2C_1C + s\left(\alpha_{n3}\beta_3 g_{m3} - \alpha_{p3}\beta_2 g_{m2}\right)C_1 \\ + \alpha_{n1}\alpha_{p2}\beta_1\beta_2 g_{m1}g_{m2} = 0 \end{aligned} \qquad (19)$$

Considering the non-ideal effects, the CO and FO of the QO is revised as:

$$\alpha_{n3}\beta_3 g_{m3} \leq \alpha_{p3}\beta_2 g_{m2} \tag{20}$$

$$\omega_{osc} = \sqrt{\frac{\alpha_{n1}\alpha_{p2}\beta_1\beta_2 g_{m1} g_{m2}}{C_1 C_2}} \tag{21}$$

The active and passive sensitivities for the QO can be written as:

$$S^{\omega_{osc}}_{\alpha_{n1},\alpha_{p2},\beta_1,\beta_2,g_{m1},g_{m2}} = \frac{1}{2}$$
$$S^{\omega_{osc}}_{C_1,C_2} = -\frac{1}{2} \tag{22}$$

From the above calculations, it can be seen that all the active and passive sensitivities of the SIMO universal filter and the QO are constant and less than or equal to unity.

V. SIMULATION RESULTS

The characteristics of the proposed circuit of Figs. 3 and 4 have been verified using PSPICE. The CMOS CDTA used in the simulations is given in Fig. 2. [19].

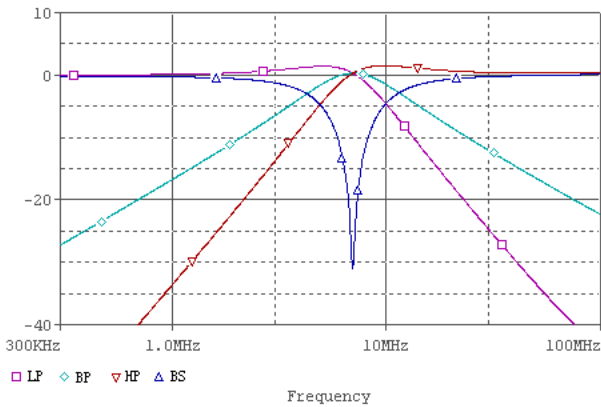The simulation results of the SIMO universal filter are presented in Figs. 5–8.

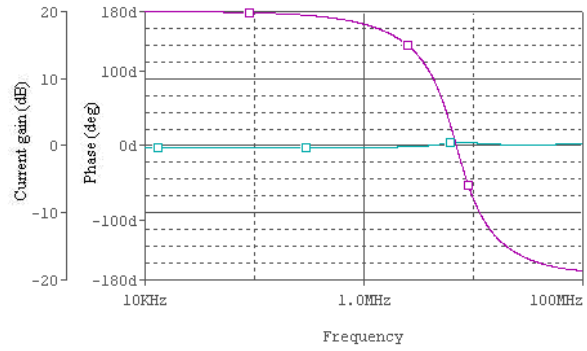Fig. 5 Frequency responses for LP, BP, HP and BS characteristic

Fig. 6 Frequency responses for the AP characteristic

Fig. 5 presents the LP, BP, HP and BS simulation results of the SIMO universal current-mode filter; Fig. 6 shows the gain and phase responses of the AP simulation results of the filter with $C_1=10pF$, $C_2=10pF$, $I_{B1}=I_{B2}=100\mu A$, $I_b=350\mu A$ for all the three CDTAs. From (2), (8) and (9), we can get $f_o=\omega_o/2\pi \approx 8.42MHz$, while $Q=1$.
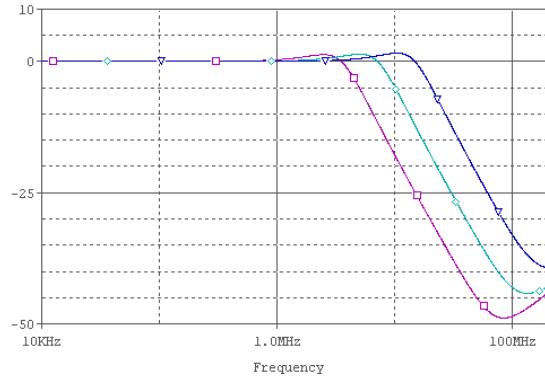
Fig. 7 Frequency responses for the LP with f0 –tuning

Fig. 7 shows the simulated low-pass responses with f_o ($f_o=\omega_o/2\pi$) tuning (i.e. f_o =4.8MHz, 8.4MHz, 16.8MHz), while keeping $Q=1$. In this case, the capacitances are $C_1=20pF$, $C_2=20pF$ for $f_o=4.8MHz$; $C_1=10pF$, $C_2=10pF$ for $f_o= 8.4MHz$; $C_1=5pF$, $C_2=5pF$ for $f_o= 16.8MHz$.
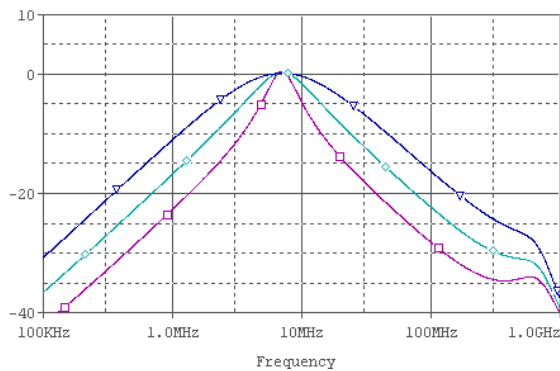
Fig. 8 Frequency responses for the BP with Q –tuning

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Fig. 8 shows the simulated band-pass responses with Q -tuning (i.e. Q=0.5, 1, 2), while keeping f_o = 8.4 MHz. In this case, the capacitances are C_1=20pF, C_2=5pF for Q=0.5; C_1=10pF, C_2=10pF for Q=1; C_1=5pF, C_2=20pF for Q=2.

The simulation results of the four-phase QO are presented in Figs. 9–12. Fig. 9 shows the output waveforms of Io1 and Io3; Fig. 10 shows the output waveforms of Io2 and Io4; Fig. 11 shows all the output waveforms of I_{o1}, I_{o2}, I_{o3} and I_{o4}; the frequency spectrums of the QO are shown in Fig. 12. The simulated frequency of the oscillation is found to be 2.1 MHz, the amplitude of the output currents is about 200uA., and the total harmonic distortion (THD) of the output waveforms I_{o1}, I_{o2}, I_{o3} and I_{o4} are 0.9% to 1.2%.
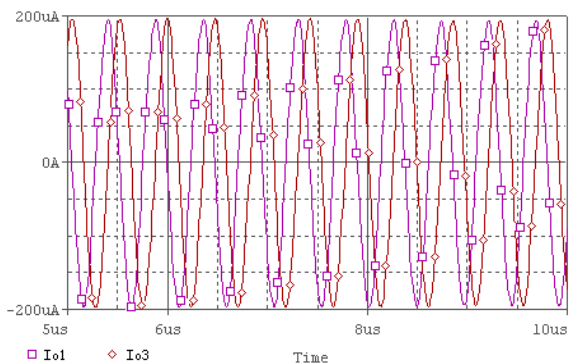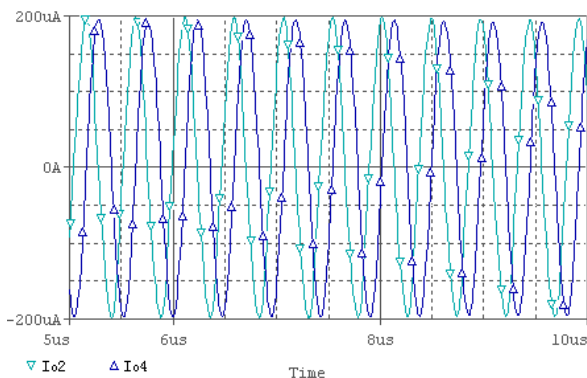

Fig. 9 The Simulated Io1 and Io3 of the oscillator
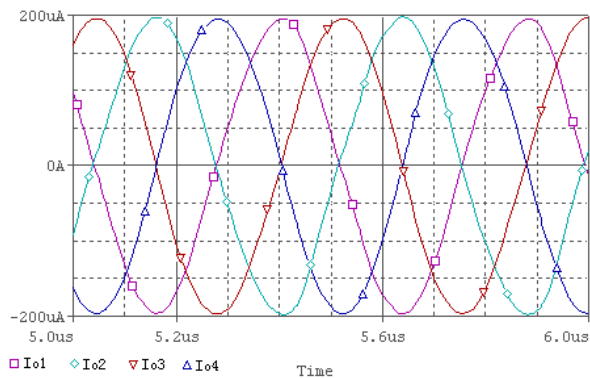

Fig. 10 The Simulated Io2 and Io4 of the oscillator

Fig. 11 The Simulated Io1, Io2, Io3 and Io4 of the oscillator
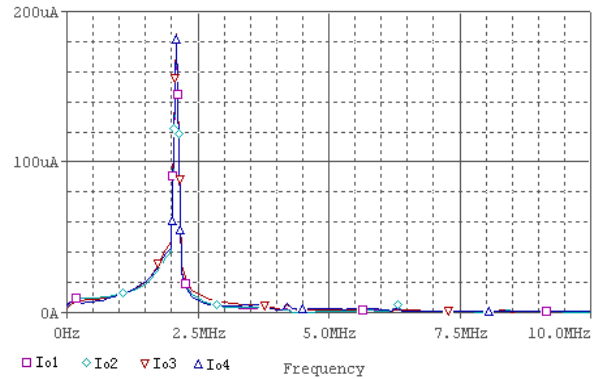

Fig. 12 The simulated frequency spectrums of the oscillator

VI. CONCLUSIONS

This paper presents new CDTA based SIMO universal filter and QO in a similar circuit. The two circuits have following advantages: (a) the circuits only consist of active blocks and grounded capacitors, and it is easy for monolithic integration; (b) The SIMO universal filter uses minimum CDTAs and passive elements to realize LP, HP, BP, BS and AP filter functions simultaneously without any component matching conditions; (c) the angular frequency (ω_o) and the quality factor (Q) of the proposed filter can be electronically controlled and tuned orthogonal; (d) by some modifications of the filter, a new current-mode four-phase quadrature oscillator (QO) can be obtained easily, and the CO and FO of the QO can be controlled electronically and independently through the bias current of the CDTAs, and it is suitable for variable frequency oscillator. (e) all the passive and active sensitivities of the circuits are low.

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