General Mixed-Mode Single-Output DDCC-based Universal Biquad Filter

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***Abstract*—This paper presents a general mixed-mode (including voltage, current, transadmittance, and transimpedance modes) universal filter using only three single-output differential difference current conveyors (DDCCs), two grounded capacitors, three grounded resistors, and one floating resistor. The proposed circuit can realize all four modes five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) from the same topology. The proposed circuit uses only single-output DDCCs with simpler implementation configuration than the multiple-output current-conveyors. This represents the attractive feature from chip area and power consumption point of view. Moreover, the proposed circuit has no need of component matching constraints for all five universal filtering responses in voltage and transadmittance modes. Furthermore, the proposed filter offers the following features: (i) using two grounded capacitors, (ii) no component-value constraints except the current/transimpedance allpass response, (iii) no need of extra inverting or non-inverting amplifiers, (iv) no need of extra current replicas degrading the final output impedance, and (v) low active and passive sensitivity performance. H-Spice simulation results confirm the theory.**

Keywords*—Active filters, differential difference current conveyors (DDCCs), general mixed-mode, universal biquad filter.

I. INTRODUCTION

The applications and advantages in the designing general mixed-mode universal biquad filters have received considerable attentions in recent years. This is because general mixed-mode operations (including voltage-mode (VM), current-mode (CM), transadmittance-mode (TAM), and transimpedance-mode (TIM), i.e. four modes) such as TAM and TIM can play a very important role for transferring from VM to CM and vice versa, respectively. Therefore, the general mixed-mode universal biquad filters with input currents or/and voltages and output currents or/and voltages, are worthy of research and presented for the use of any filtering requirement, which is compatible with modern microelectronic systems applications, such as controls and voice and data communications, where consideration of size and weight make the use of inductors prohibitive.

In the past several decades, many single-mode, dual-mode, or mixed-mode filters using different active elements have been presented [1-51]. The filters consist of more modes and filtering functions, meaning more applications for which they can be used. However, only several circuits [1-4, 6-8, 10, 12, 15, 17, 22, 24, 25, 27, 31-34, 36, 38-40] can realize all five universal filtering functions (lowpass, highpass, bandpass, notch, and allpass) in VM, CM, TIM, and TAM. Such filters are referred to in this paper as general mixed-mode universal filter. The general mixed-mode universal filter structures employ at least four active elements in [1-4, 12, 15, 17, 25, 27, 31, 32, 36, 39, 40] and need some matching conditions for realizing some VM or TAM filtering functions [1-4, 12, 15, 17, 25, 27, 36, 39, 40]. For example, in 2012, Lee proposed a multiple-mode (i.e. general mixed-mode) universal filter [25] using five operational transconductance amplifiers (OTAs) as active elements and two grounded capacitors (for second-order). The filter [25] can offer all five universal filtering functions in all the four possible modes. However, it needs component matching conditions for realizing VM and TAM allpass responses. In 2013, it has shown that the mixed-mode universal biquad filter [27] needs to use four multiple-output current controlled current conveyors (MOCCCIIs) and two grounded capacitors. However, it needs component matching conditions for realizing VM notch, allpass responses and TAM lowpass, notch, allpass responses. In 2016, two digitally programmable mixed-mode universal biquad filters were proposed in [31, 32], which can achieve many main advantages. However, the filter in [31] uses two multi-output second-generation current conveyors (MOCCIIs), six digitally programmable second-generation current conveyors (DPCCIIs) (i.e. eight active elements), four grounded resistors and two grounded capacitors. In [32], the filter uses followers with a minimal realization. However, the filter in [32] still needs to use seven current/voltage followers (i.e. seven active elements), three switches, three floating resistors, one grounded resistor, and two grounded capacitors. In 2018, Zanjani *et al.* proposed a mixed-mode Gm-C biquad filter [39] with independently electronic tunability. However, the filter needs to employ 19 inverters as operational transconductance amplifiers and two grounded capacitors. In 2018, Tsukutani *et al.* proposed a novel general mixed-mode universal biquad filter [40]. However, the biquad filter [40] needs to use five DVCCs, five grounded resistors, and two grounded capacitors. Few general mixed-mode universal biquad filter structures employ three active elements of simple implementation configuration [6-8, 10, 22, 24]. For example, in [24], the reported general mixed-mode biquad uses three differential difference current conveyors (DDCCs), two floating resistors, two grounded resistors, and two grounded capacitors. However, it needs component matching conditions for realizing VM, CM, TAM, and TIM allpass responses. In 2017, the reported general mixed-mode biquad filter [35] uses only

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three current controlled current conveyor transconductance amplifiers (CCCCTAs) and two grounded capacitors. However, the circuit in [35] can not realize notch and allpass responses in TIM. Moreover, the CCCCTA is a complex active element.

The applications and advantages in the designing current-conveyor-based active circuits have received considerable attentions [1, 2, 6-11, 13, 14, 18, 20-24, 26, 27, 30, 31, 33-35, 37, 38, 40-50]. Especially, the differential difference current conveyor (DDCC) [49, 50] has the ability to perform the operations of the intrinsic voltage addition and subtraction [47, 48]. Therefore, it is very important for the design of general mixed-mode universal biquad filters [33]. Moreover, the DDCC has simplest implementation configuration in all of the other complex current conveyors, such as, fully differential current conveyor (FDCCII), current controlled current conveyor transconductance amplifiers (CCCCTA), differential difference current conveyor transconductance amplifier (DDCCTA), differential voltage current conveyor transconductance amplifier (DVCCTA), digitally programmable second-generation current conveyors (DPCCIIs), and dual X current conveyor differential input transconductance amplifier (DXCCDITA). The use of a FDCCII can be divided into two separate DDCCs. A CCCCTA can be produced by cascading a CCCII with an OTA. Similarly, a DDCCTA (or DVCCTA) also can be produced by cascading a DDCC (or DVCC) with an OTA. Therefore, each of them can be regarded as two basic active elements. In [13], Lee and Chang proposed a single FDCCII-based mixed-mode biquad filter [13]. The circuit [13] uses only a single FDCCII, three floating/grounded resistors, and two grounded capacitors. In 2017, the reported mixed-mode biquad filter [37] employs only a DXCCDITA and four passive components. Although single active element based mixed-mode biquad filters have been proposed in [13, 37], both circuits [13, 37] are not general mixed-mode universal filters. Moreover, both used active elements (i.e. FDCCII and DXCCDITA) are complex active elements. There are three general mixed-mode universal biquad filters using two active elements [33, 34, 38]. In 2016, Lee proposed two general mixed-mode universal biquad filters [33, 34]. The filter in [33] uses one FDCCII, one DDCC, six grounded/floating resistors, and two grounded capacitors. The circuit has versatile input/output functions [33] which can offer all five universal filtering responses in single-input multiple-output (SIMO) and multiple-input single output (MISO) types, respectively. The circuit in [34] uses two plus-type FDCCIIs, five grounded/floating resistors, and two grounded capacitors. The circuit [34] has no need of any matching conditions which includes no need of component and input matching conditions. Similarly, in 2018, the reported mixed-mode biquad filter [38] also uses two FDCCIIs, four floating/grounded resistors and two grounded capacitors. Although the filters in [33, 34, 38] use only two active elements and can achieve many important advantages, it was shown that the use of the complex active elements and many resistors was unavoidable. In 2013 the reported mixed-mode [28] biquad filter employs only two voltage differencing transconductance amplifiers (VDTAs) and two grounded capacitors. The circuit can realize all five universal filtering functions in VM and TAM, but it [28] has not been operated in CM and TIM.

In this paper, the proposed circuit uses only three single-output DDCC, two grounded capacitors, three grounded resistors, and one floating resistor, which can realize general mixed-mode (including VM, CM, TIM, and TAM) all five universal filtering responses (lowpass (LP), highpass (HP), bandpass (BP), notch (NH), and allpass (AP)) from the same topology. Over the last decade, the general mixed-mode universal filters have been presented in the literature [1-4, 6-8, 10, 12, 15, 17, 22, 24, 25, 27, 31-34, 36, 38-40]. With respect to the references [1-3, 31, 32, 40], the proposed biquad filter employs fewer active and passive elements. With respect to the references [4, 12, 15, 17, 25, 27, 36, 39], the proposed biquad filter employs fewer active elements. With respect to the references [7, 10], the proposed biquad filter uses active elements of same number but the proposed circuit has the following advantages: less component matching conditions, the use of only two grounded capacitors and no switches. With respect to the references [6, 8, 22, 24], the proposed biquad filter uses the same active elements (DDCCs) in same number but the proposed circuit has the following advantages: no need of component matching constraints for VM and TAM all five universal filtering responses and the use of only single-output DDCCs. Filters using only single-output DDCCs have the advantages: (i) no need of extra current replicas degrading the final output impedance, and (ii) simpler implementation configuration than multiple-output DDCCs. This represents the attractive feature from chip area and power consumption point of view. With respect to the references [33, 34, 38], the proposed biquad filter uses the DDCCs with far simpler implementation configuration than FDCCIIs.

II. PROPOSED CIRCUIT

Fig. 1 shows the proposed general mixed-mode biquad filter structure using only three single-output DDCCs, two grounded capacitors, three grounded resistors, and one floating resistor, where V_{in1}, V_{in2}, V_{in3} are the filter input voltages and I_{in1}, I_{in2}, I_{in3} are the filter input currents whose setting determine the filter functions as shown later, V_{out1} V_{out2}, V_{out3}, V_{out4}, and I_{out} are the filter voltage outputs and current output, respectively. Using standard notation, the port relations of a DDCC can be characterized by $I_{Y1} = I_{Y2} = I_{Y3} = 0$, $V_X = V_{Y1} - V_{Y2} + V_{Y3}$, $I_{Z+} = +I_X$ and $I_{Z-} = -I_X$. The current output has very high output impedance.

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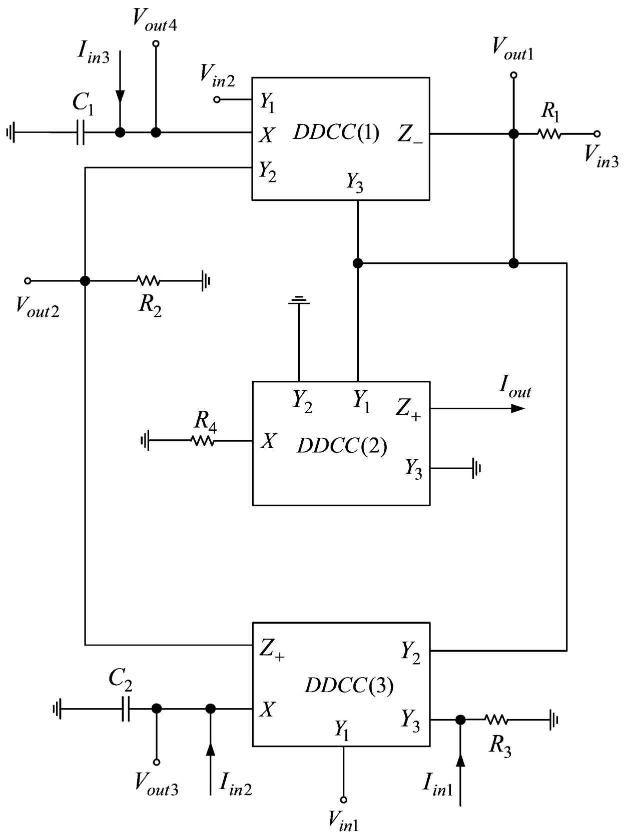

Fig. 1. Proposed general mixed-mode biquad filter structure.

Part I: VM and TAM universal biquad filters with three inputs and one output

If $I_{in1} = I_{in2} = I_{in3} = 0$, and V_{in1} , V_{in2} , V_{in3} are given by the input signals, circuit analysis for Fig. 1 yields the following VM and TAM universal transfer functions:

$$V_{out1} = \frac{s^2C_1C_2V_{in1} - sC_1G_2V_{in2} + G_1G_2V_{in3}}{s^2C_1C_2 + sC_1G_2 + G_1G_2}$$

VM universal transfer function (1)

$$I_{out} = \frac{s^2C_1C_2G_4V_{in1} - sC_1G_2G_4V_{in2} + G_1G_2G_4V_{in3}}{s^2C_1C_2 + sC_1G_2 + G_1G_2}$$

TAM universal transfer function (2)

Specializations of the numerator in (1) and (2) result in the following VM and TAM five universal filtering responses from voltage-output and current-output as below.

(i) Highpass: $V_{in1} = V_{in}$, and $V_{in2} = V_{in3} = 0$ (grounded).
(ii) Lowpass: $V_{in3} = V_{in}$, and $V_{in1} = V_{in2} = 0$ (grounded).
(iii) Bandpass: $V_{in2} = V_{in}$, and $V_{in1} = V_{in3} = 0$ (grounded).
(iv) Notch: $V_{in1} = V_{in3} = V_{in}$, and $V_{in2} = 0$ (grounded).
(v) Allpass: $V_{in1} = V_{in2} = V_{in3} = V_{in}$

Note that it is no need to impose component choice for realizing any filtering responses. Moreover, no inverting or non-inverting amplifiers (for special input signals) are needed in the realizations.

Part II: VM universal biquad filter with one input and four outputs

If $I_{in1} = I_{in2} = I_{in3} = 0$, and $V_{in2} = 0$, $V_{in1} = V_{in3}$ is given by the single input signal, circuit analysis yields the following VM filtering responses:

$$\frac{V_{out1}}{V_{in}} = \frac{s^2C_1C_2 + G_1G_2}{s^2C_1C_2 + sC_1G_2 + G_1G_2} \quad \text{VM notch} \quad (3)$$

$$\frac{V_{out2}}{V_{in}} = \frac{s^2C_1C_2}{s^2C_1C_2 + sC_1G_2 + G_1G_2} \quad \text{VM highpass} \quad (4)$$

$$\frac{V_{out3}}{V_{in}} = \frac{sC_1G_2}{s^2C_1C_2 + sC_1G_2 + G_1G_2} \quad \text{VM bandpass} \quad (5)$$

$$\frac{V_{out4}}{V_{in}} = \frac{G_1G_2}{s^2C_1C_2 + sC_1G_2 + G_1G_2} \quad \text{VM lowpass} \quad (6)$$

Examining (3) and (5) show that the voltage difference between V_{out1} and V_{out3} yields an allpass filtering response.

$$\frac{V_{out1} - V_{out3}}{V_{in}} = \frac{s^2C_1C_2 - sC_1G_2 + G_1G_2}{s^2C_1C_2 + sC_1G_2 + G_1G_2} \quad \text{VM allpass} \quad (7)$$

Note that it is no need to impose component choice for realizing any filtering responses. Moreover, no inverting or non-inverting amplifiers (for special input signals) are needed in the realizations.

Part III: CM and TIM universal biquad filters with three inputs and one output

If $V_{in1} = V_{in2} = V_{in3} = 0$, and I_{in1} , I_{in2} , I_{in3} are given by the input signals, circuit analysis for Fig. 1 yields the following CM and TIM universal transfer functions:

$$I_{out} = \frac{s^2C_1C_2G_4I_{in1} - sC_1G_3G_4I_{in2} + G_2G_3G_4I_{in3}}{s^2C_1C_2G_3 + sC_1G_2G_3 + G_1G_2G_3}$$

CM universal transfer function (8)

$$V_{out1} = \frac{s^2C_1C_2I_{in1} - sC_1G_3I_{in2} + G_2G_3I_{in3}}{s^2C_1C_2G_3 + sC_1G_2G_3 + G_1G_2G_3}$$

TIM universal transfer function (9)

Specializations of the numerator in (8) and (9) result in the following CM and TIM five universal filtering responses from current-output and voltage-output as below.

(i) Highpass: $I_{in1} = I_{in}$, and $I_{in2} = I_{in3} = 0$.
(ii) Lowpass: $I_{in3} = I_{in}$, and $I_{in1} = I_{in2} = 0$.
(iii) Bandpass: $I_{in2} = I_{in}$, and $I_{in1} = I_{in3} = 0$.
(iv) Notch: $I_{in1} = I_{in3} = I_{in}$, and $I_{in2} = 0$.
(v) Allpass: $I_{in1} = I_{in2} = I_{in3} = I_{in}$, and $G_1 = G_2 = G_3$

In (iv), a low-pass notch and a high-pass notch can be obtained by tuning the grounded conductances G_1 or G_3. Note that it is no need to impose component choice except CM/TIM allpass response. Moreover, no inverting amplifiers (for special input signals) are needed in the realizations.

Inspection of (1) to (9) show that, in all cases the parameters ω_0, ω_0/Q, and Q are given by

$$\omega_0 = \sqrt{\frac{G_1G_2}{C_1C_2}} \quad (10)$$

$$\frac{\omega_0}{Q} = \frac{G_2}{C_2} \quad (11)$$

$$Q = \sqrt{\frac{C_2 G_1}{C_1 G_2}} \tag{12}$$

From (10) and (11), the parameters ω_0 and ω_0/Q can be orthogonally adjustable by tuning the grounded resistor R_2 for ω_0/Q first and then resistor R_1 for ω_0 without disturbing parameter ω_0/Q. However, (10) and (12) show that the parameters ω_0 and Q are interactive. The technique to obtain the non-interactive filter parameter control can be suggested as follows [44]. For the fix-valued capacitors, the ω_0 can be adjusted arbitrarily without disturbing Q by simultaneously changing resistor R_1 and grounded resistor R_2 and keeping the G_1/G_2 constant. On the other hand, the parameter Q can be tuned arbitrarily without disturbing ω_0 by simultaneously increasing $1/R_1$ and grounded R_2 and keeping the product G_1G_2 constant.

III. NONIDEAL ANALYSIS

Taking the tracking errors of the single-output DDCC into account, the relationship of the terminal voltages and currents can be written as: $I_{Y1} = I_{Y2} = I_{Y3} = 0$, $V_X = \beta_1(s)V_{Y1} - \beta_2(s)V_{Y2} + \beta_3(s)V_{Y3}$, $I_{Z\pm} = \pm\alpha(s)I_X$, where $\alpha(s)$ and $\beta(s)$ represent the frequency transfers of the internal current and voltage followers of the DDCC. They can be approximated by the first order lowpass functions [33, 42, 45-50]. For frequencies much less than the corner frequencies of the DDCC, all $\alpha(s)$ and $\beta(s)$ are real quantities of magnitudes slightly less than one [33, 42, 45-50]. Assuming the circuit works at frequencies much less than the corner frequencies of $\alpha(s)$ and $\beta(s)$, namely, $\alpha(s) = \alpha = 1-\varepsilon_i$ and ε_i ($\varepsilon_i << 1$) denotes the current tracking error of the DDCC and $\beta(s) = \beta = 1-\varepsilon_v$ and ε_v ($\varepsilon_v << 1$) denotes the voltage tracking error of the DDCC. Taking into account the non-idealities of the DDCC(1), DDCC(2) and DDCC(3), we obtain the non-idealities as below:

$$I_{Y1} = I_{Y2} = I_{Y3} = 0 \quad , \quad V_X = \beta_{11}V_{Y1} - \beta_{12}V_{Y2} + \beta_{13}V_{Y3} \quad , \quad I_{Z-} = -\alpha_1 I_X \quad \text{for DDCC(1)} \tag{13}$$

$$I_{Y1} = I_{Y2} = I_{Y3} = 0 \quad , \quad V_X = \beta_{21}V_{Y1} - \beta_{22}V_{Y2} + \beta_{23}V_{Y3} \quad , \quad I_{Z+} = \alpha_2 I_X \quad \text{for DDCC(2)} \tag{14}$$

$$I_{Y1} = I_{Y2} = I_{Y3} = 0 \quad , \quad V_X = \beta_{31}V_{Y1} - \beta_{32}V_{Y2} + \beta_{33}V_{Y3} \quad , \quad I_{Z+} = \alpha_3 I_X \quad \text{for DDCC(3)} \tag{15}$$

The denominator of the non-ideal general mixed-mode universal biquad transfer function becomes

$$D(s) = s^2 + s\frac{G_2\beta_{13}}{C_2\alpha_3\beta_{32}\beta_{12}} + \frac{G_1G_2}{C_1C_2\alpha_1\alpha_3\beta_{12}\beta_{32}} \tag{16}$$

The ω_0 and Q of the non-ideal mixed-mode biquad are:

$$\omega_0 = \sqrt{\frac{G_1G_2}{C_1C_2\alpha_1\alpha_3\beta_{12}\beta_{32}}} \tag{17}$$

$$Q = \frac{1}{\beta_{13}}\sqrt{\frac{\alpha_3\beta_{12}\beta_{32}G_1C_2}{\alpha_1G_2C_1}} \tag{18}$$

The active and passive sensitivities of ω_0 and Q are:

$$S^{\omega_0}_{G_1,G_2} = -S^{\omega_0}_{C_1,C_2} = -S^{\omega_0}_{\alpha_1,\alpha_3,\beta_{12},\beta_{32}} = 0.5 \tag{19}$$

$$S^{Q}_{C_2,G_1} = -S^{Q}_{C_1,G_2} = S^{Q}_{\alpha_3,\beta_{12},\beta_{32}} = -S^{Q}_{\alpha_1} = 0.5 \tag{20}$$

$$S^{Q}_{\beta_{13}} = -1 \tag{21}$$

$$S^{\omega_0}_{G_3,G_4,\alpha_2,\beta_{11},\beta_{13},\beta_{21},\beta_{22},\beta_{23},\beta_{31},\beta_{33}} = 0 \tag{22}$$

$$S^{Q}_{G_3,G_4,\alpha_2,\beta_{11},\beta_{21},\beta_{22},\beta_{23},\beta_{31},\beta_{33}} = 0 \tag{23}$$

From (19) to (23), the proposed general mixed-mode universal biquad filter has low active and passive sensitivities (not larger than unity in absolute value).

IV. H-SPICE SIMULATIONS

The CMOS implementations of the single-output plus-type DDCC are shown in Fig. 2 [42, 49]. Note that, the DDCC has simpler implementation configuration than the FDCCII, VDTA, DDCCTA, DVCCTA, CCCCTA, DPCCII, and DXCCDITA. Moreover, the single-output DDCC has no need of applying the realization of current replicas. Therefore, the proposed circuit has the advantage: no need of extra current replicas degrading the final output impedance. To verify the theoretical analysis of the proposed general mixed-mode universal biquad filter, the H-SPICE simulations with the NMOS transistor aspect ratios (W/L=5μm/1μm) and PMOS transistor aspect ratios (W/L=10μm/1μm) of Fig. 2, using the TSMC 0.25μm process for the proposed circuit of Fig. 1, were performed with the component values: $C_1 = C_2 = 4$pF and $R_1 = R_2 = R_3 = R_4 = 10$kΩ, for the general mixed-mode universal filtering responses, leading to a center frequency of $f_0 = 3.9789$MHz and quality factor of $Q = 1$. Their supply voltages are $V_{DD} = -V_{SS} = 1.25$V, $V_{b1} = -0.4$V, and $V_b = 0.41$V. Fig. 3 presents the simulated bandpass, lowpass, highpass, notch, and allpass amplitude-frequency responses of the proposed general mixed-mode biquad filter (operated in TAM with the normalized transadmittance magnitude = 20 log $|10000 I_{out} / V_{in}|$ dB due to $R = 10$ kΩ). Fig. 4 presents the simulated allpass phase-frequency responses of the proposed general mixed-mode biquad filter (operated in TAM). Although not included in this paper, it can be shown that the other modes simulated results (with the normalized magnitude) are very similar to the above simulated results. As can be seen, there is a close agreement between theory and simulation.

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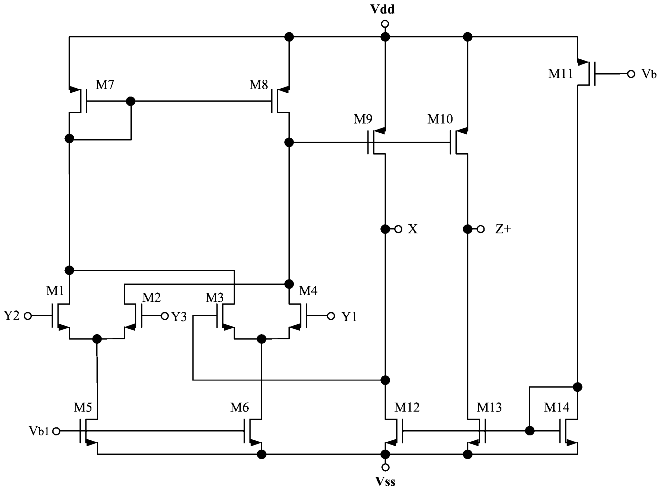

Fig. 2. The CMOS implementation of the single-output plus-type DDCC.

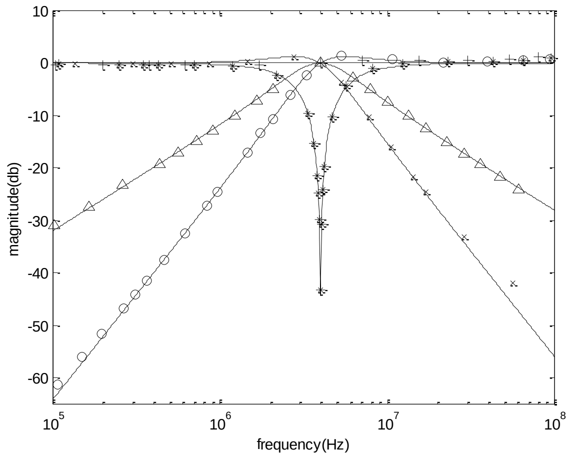

Fig. 3. Amplitude-frequency responses of the proposed general mixed-mode universal biquad filter with normalized TAM signals (△, simulated BP; ×, simulated LP; ○, simulated HP; *, simulated NH; +, simulated AP; and ____, theoretical curve).

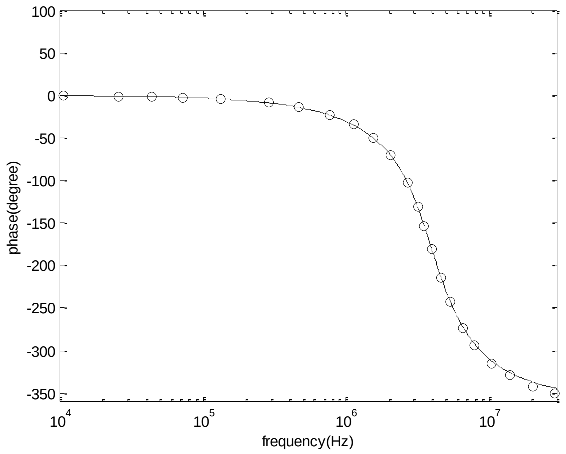

Fig. 4. Allpass phase-frequency responses of the proposed general mixed-mode universal biquad filter with TAM operation (○, simulated phase; and ____,theoretical curve).

V. CONCLUSIONS

Only using three single-output DDCCs, two grounded capacitors, three grounded resistors, and one floating resistor, to design a general mixed-mode universal biquad filter is presented in this paper. Filters using active elements with simple implementation configuration, such as single-output DDCCs, have the advantages of the lowest cost, power dissipation, chip area, and noise. Filters using single-output active elements, such as single-output DDCCs, have the advantage: no need of extra current replicas degrading the final output impedance. The proposed circuit can be operated in general mixed-mode (i.e. VM, CM, TAM, and TIM) and can realize all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) in the general mixed-mode applications without changing the filter topology. Moreover, the proposed circuit has no need of component matching constraints for VM and TAM all five universal filtering responses. Furthermore, the proposed general mixed-mode circuit still enjoys many main advantages: using two grounded capacitors attractive for integration, no inverting or non-inverting amplifiers for special input signals, no component-value constraints except the CM/TIM allpass responses, high output impedance, and low active and passive sensitivities. H-Spice simulations with TSMC 0.25μm process confirm the theoretical predictions.

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