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Mixed-Mode Biquadratic Filter Using Only Two DVCC and Grounded Passive Components

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***Abstract*— This paper presents a new mixed-mode (including voltage, current, transadmittance, and transimpedance modes) biquad filter using only two differential voltage current conveyors (DVCCs), two grounded capacitors and three grounded resistors, which are the least number of active components and the minimum number of grounded passive components necessary for realizing current-mode (with high output impedance) and transimpedance modes all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass), in addition to high input impedance voltage-mode and fully cascadable transadmittance-mode highpass and bandpass filtering responses without changing the filter topology. This represents the attractive feature from chip area and power consumption point of view. Moreover, the proposed biquadratic filter still enjoys many advantages like having no need of components matching conditions, in addition to using only grounded passive components, no need of extra inverting or non-inverting amplifiers for special input signals, and low active and passive sensitivities. H-Spice simulation results confirm the theory.**

***Keywords*—Active filters, differential voltage current conveyors (DVCCs), mixed-mode, biquadratic filter.**

I. Introduction

Over the last decade, many voltage and/or current-mode current-conveyor-based biquadratic filters have been reported. In some applications, however, we may intend to connect the voltage-mode (VM) circuits with the current-mode (VM) circuits. Thus, the transimpedance-mode (TIM, i.e. input as current and output as voltage) and transadmittance-mode (TAM, i.e. input as voltage and output as current) may play a very important role in the special filtering applications where we need to connect a CM circuit with a VM circuit and vice versa. Therefore, the mixed-mode (including VM, CM, TAM, and TIM) circuits are worthy of researches 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 mixed-mode filters using different active elements have been proposed [1-36]. The applications and advantages in the designing mixed-filters using current conveyors have received considerable attentions [1, 2, 6-11, 13, 14, 18, 20-24, 26, 27, 30-33, 35, 36]. Many mixed-mode current-conveyor-based biquadratic filters with different attractive advantages have been proposed [1, 2, 6-11, 13, 14, 18, 20-24, 26, 27, 30-33, 35, 36]. However, each of the mixed-mode structures in [1-4, 12, 14-17, 25, 27, 31, 33, 34] employs more than three active elements. For example, in [1], a second-generation current-conveyor (CCII)-based mixed-mode universal biquadratic filter is proposed. The biquadratic filter can realize all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) in VM, CM, TAM, and TIM. However, it needs to use seven CCIIs, eight grounded/floating resistors, and two grounded capacitors. In [2], a mixed-mode CCII-based universal biquadratic filter is proposed. However, it needs to use five CCIIs, seven grounded/floating resistors resistors, and two grounded capacitors. In [7, 8, 10, 11, 18, 21-24], the mixed-mode biquadratic filter structures use three current conveyors, in addition to two/three capacitors and three/four/five resistors. For example, in [7], the mixed-mode biquad filter uses only three CCIIs but it needs to use two switches and two/three grounded capacitors in addition to four grounded/floating resistors. In [10], the mixed-mode biquad filter also employs three CCIIs but it needs five grounded/floating resistors, and two floating capacitors. If the active filter employs grounded capacitors and grounded resistors, it is attractive for monolithic IC implementation and suitable for the variations of filter parameters. In [24], the SIMO mixed-mode universal biquad filter with one input and eight outputs uses only three differential difference current conveyors (DDCCs), four resistors, and two ground capacitors, but it also needs to use floating resistors in filter structure. Although the mixed-mode universal/multifunction biquadratic filters [8, 11, 22, 23] uses only grounded passive elements, they still need to use three current conveyors.

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Only two mixed-mode (including VM, CM, TIM, and TAM) universal (not only multifunction) biquadratic filters which use only two current conveyors have been presented [35, 36]. In 2016, the very recently reported mixed-mode universal biquadratic filters using only two current conveyors and several passive elements can realize all five universal filtering functions in all four possible modes [35, 36]. The mixed-mode circuit, reported in [36], with no need of matching conditions, uses two fully differential current conveyor (FDCCII) as active elements. Another mixed-mode circuit, reported in [35], with versatile input/output functions and independent tunability, uses one FDCCII and one DDCC as active elements. However, the FDCCII has more complex implementation configuration than the DVCC. In 2013, a new current-mode and transresistance-mode (i.e. transimpedance-mode) universal biquad filter was proposed [26]. Although the biquad filter [26] uses only two multiple-output CCIIs (MOCCIIs) in addition to two grounded capacitors and three grounded resistors, it can not be operated in VM and TAM. In 2013, the reported mixed-mode [28] biquad using only two voltage differencing transconductance amplifiers (VDTAs) and two grounded capacitors can realize all five universal filtering functions, but the biquad in [28] has not included CM and TIM. In 2014, the recently reported mixed-mode [29] biquads using three operational transconductance amplifiers (OTAs) and two grounded capacitors can realize all five universal filtering functions, but the biquad filter in [29] needs to use three active elements. Moreover, the biquad filter [29] only can be operated in TAM. In 2015, the new mixed-mode (including VM, CM, TAM, and TIM) biquadratic filter using only two second-generation current conveyors as active elements has been presented [32]. Although the biquad [32] is not universal filter for all four possible modes, it uses only two current conveyors with simple implementation configuration. This represents the attractive feature from chip area and power consumption point of view. However, the circuit in [32] needs to use floating resistors in filter structure.

Therefore, this leads to prospective research work: investigating and developing a mixed-mode (including VM, CM, TAM, and TIM) biquadratic filter structure using two current conveyors (with simple implementation configuration) and only grounded passive components.

In this paper, the proposed circuit using only two DVCC, two grounded capacitors, and three grounded resistors (all passive components grounded), which can be operated in all four possible modes (i.e. VM, CM, TAM, and TIM) and can realize CM and TIM all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) in addition to VM and TAM highpass, bandpass filtering responses without changing the filter topology. The DVCC has simpler implementation configuration than some complex current conveyors, such as, FDCCII, differential difference current conveyor transconductance amplifier (DDCCTA), differential voltage current conveyor transconductance amplifier (DVCCTA), current controlled current conveyor transconductance amplifiers (CCCCTA), etc. For example, the use of a FDCCII can be divided into two separate DDCCs. Similarly, a DDCCTA (DVCCTA, CCCCTA) also can be produced by cascading a DDCC (DVCC, CCCII) with an OTA. Moreover, the proposed circuit still achieves many important advantages which are (i) using only two grounded capacitors at the Z terminals of the DVCCs (attractive for monolithic IC implementation and absorbing shunt parasitic capacitance), (ii) using two grounded resistors at the X terminals of the DVCCs (suitable for the variations of filter parameters and having no capacitors bringing extra poles degrading high-frequency performance), (iii) high output impedance for CM and TAM, (iv) high input impedance for VM and TAM, (v) no need of component matching conditions, (vi) no need of inverting-type input signals or double-type input signals for the use of special input signals, and (vii) low active and passive sensitivities.

II. PROPOSED CIRCUIT

Figure 1 shows the proposed mixed-mode biquadratic filter structure using only two DVCCs, two grounded capacitors (attractive for integrated circuit implementation) and three grounded resistors (suitable for the adjustment of filter parameters) where I_{in1}, I_{in2}, I_{in3} are the filter input currents and V_{in1}, V_{in2} are the filter input voltages whose setting determine the filter functions as shown later, I_{out} and V_{out} are the filter current output and voltage output, respectively. Using standard notation, the port relations of a DVCC can be characterized by $I_{Y1} = I_{Y2} = 0$, $V_X = V_{Y1} - V_{Y2}$ and $I_{Z\pm} = \pm I_X$.

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The multiple current outputs of DVCC(1) can be simply reconstructed using current mirrors. Moreover, all voltage inputs have very high input impedance and the current output has very high output impedance. We notice that two grounded capacitors connected to the *Z* terminals of two DVCCs are attractive for absorbing shunt parasitic capacitance. Moreover, two grounded resistors connected to the *X* terminals of two DVCCs are suitable for absorbing series parasitic resistances (R_x) of two DVCCs as a part of the main resistance. Because the *X* terminal of DVCCs has a series parasitic resistance (R_x), when the *X* terminal of DVCCs is connected to a capacitor, it leads to an improper transfer functions which do not exhibit good performance at high frequency [18]. Therefore, the proposed biquadratic filter has the advantage: no capacitors bringing extra poles degrading high-frequency performance.

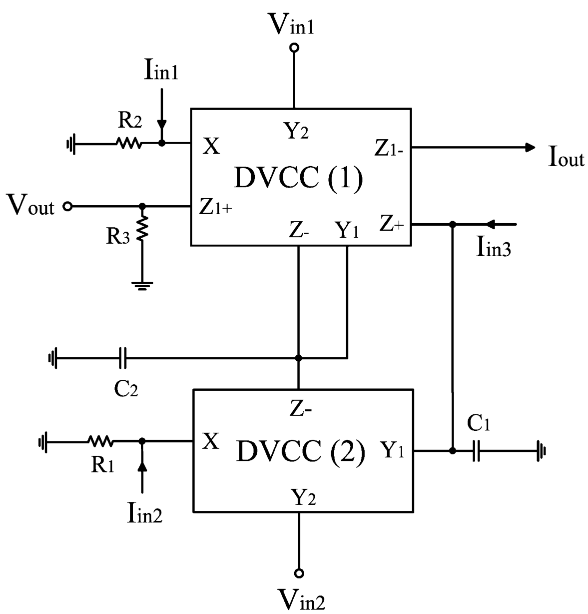

Figure 1. Proposed mixed-mode biquadratic filter structure.

Routine circuit analysis for Figure 1 yields the following transfer functions:

$$V_{out} = \frac{G_2 N_1(s) - N_2(s)}{G_3 D(s)} \tag{1}$$

and

$$I_{out} = \frac{-G_2 N_1(s) + N_2(s)}{D(s)} \tag{2}$$

in which

$$N_1(s) = -s^2 C_1 C_2 V_{in1} + sC_1 G_1 V_{in2} \tag{3}$$

$$N_2(s) = s^2 C_1 C_2 I_{in1} - sC_1 G_2 I_{in2} + G_1 G_2 I_{in3} \tag{4}$$

$$D(s) = s^2 C_1 C_2 + sC_1 G_2 + G_1 G_2 \tag{5}$$

From Eqs. (1) - (5), the mixed-mode biquad filter transfer functions are obtained according to input voltage or current conditions as follows.

Part I: If $V_{in1} = V_{in2} = 0$, the following CM all five universal filtering responses can be obtained from I_{out} as below.

(i) Non-inverting highpass: $I_{in1} = I_{in}$, and all the other input currents are zero.
(ii) Non-inverting lowpass: $I_{in3} = I_{in}$, and all the other input currents are zero.
(iii) Inverting bandpass: $I_{in2} = I_{in}$, and all the other input currents are zero.
(iv) Non-inverting notch: $I_{in1} = I_{in3} = I_{in}$, and the other input current is zero.
(v) Non-inverting all-pass: $I_{in1} = I_{in2} = I_{in3} = I_{in}$.

Part II: If $V_{in1} = V_{in2} = 0$, the following TIM all five universal filtering responses can be obtained from V_{out} as below.

(i) Inverting highpass: $I_{in1} = I_{in}$, and all the other input currents are zero.
(ii) Inverting lowpass: $I_{in3} = I_{in}$, and all the other input currents are zero.
(iii) Non-inverting bandpass: $I_{in2} = I_{in}$, and all the other input currents are zero.
(iv) Inverting notch: $I_{in1} = I_{in3} = I_{in}$, and the other input current is zero.
(v) Inverting all-pass: $I_{in1} = I_{in2} = I_{in3} = I_{in}$.

Part III: If $I_{in1} = I_{in2} = I_{in3} = 0$, the following VM inverting highpass and non-inverting bandpass filtering responses can be obtained from V_{out} as below.

(i) Inverting highpass: $V_{in1} = V_{in}$, and the other input voltage is zero.
(ii) Non-inverting bandpass: $V_{in2} = V_{in}$, and the other input voltage is zero.

Part IV: If $I_{in1} = I_{in2} = I_{in3} = 0$, the following TAM non-inverting highpass and inverting bandpass filtering responses can be obtained from I_{out} as below.

(i) Non-inverting highpass: $V_{in1} = V_{in}$, and the other input voltage is zero.
(ii) Inverting bandpass: $V_{in2} = V_{in}$, and the other input voltage is zero.

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Note that there are no critical component-matching conditions or cancellation constraints in the design. Moreover, the structure does not need inverting-type input current signals or double-type amplifier and also does not need to change the network topology. Inspection of Eq. (5) shows that, in all cases the parameters ω_0, ω_0/Q, and Q are given by

$$\omega_0 = \sqrt{\frac{G_1G_2}{C_1C_2}} \tag{6}$$

$$\frac{\omega_0}{Q} = \frac{G_2}{C_2} \tag{7}$$

$$Q = \sqrt{\frac{C_2G_1}{C_1G_2}} \tag{8}$$

From Eqs. (6) and (7), the parameters ω_0 and ω_0/Q are orthogonally adjustable through the resistor R_2 and then the resistor R_1 in that order. From Eqs. (6) and (8), the parameters ω_0 and Q are interactive. However, non-interactive filter parameter control can be obtained as follows: for the fix-valued capacitors, ω_0 can be tuned arbitrarily without disturbing Q by simultaneously changing G_1 and G_2 and keeping the ratio G_1/G_2 constant. The parameter Q also can be adjusted without disturbing ω_0 by simultaneously changing G_2 and G_1 and keeping the product G_1G_2 constant.

III. Nonideal Analysis

Taking the tracking errors of the DVCC into account, the relationship of the terminal voltages and currents can be written as: $I_Y = 0$, $V_X = \beta_1(s)V_{Y1} - \beta_2(s)V_{Y2}$, $I_{Z\pm} = \pm\alpha(s)I_X$, where α(s) and β_1(s), β_2(s) represent the frequency transfer functions of the internal current and voltage followers of the DVCC. They can be approximated by the first order lowpass functions [37, 38]. For frequencies much less than the corner frequencies of the DVCC, the α(s), β_1(s), and β_2(s) are real quantities of magnitudes slightly less than one [37, 38]. Assuming the circuit works at frequencies much less than the corner frequencies of α(s), β_1(s), and β_2(s) namely, $\alpha(s) = \alpha = 1-\varepsilon_i$ ($\varepsilon_i << 1$) denotes the current tracking error of the DVCC and $\beta_1(s) = \beta_1 = 1-\varepsilon_{v1}$ ($\varepsilon_{v1} << 1$), $\beta_2(s) = \beta_2 = 1-\varepsilon_{v2}$ ($\varepsilon_{v2} << 1$) denote the voltage tracking error of the DVCC. Taking into account the non-idealities of the DVCC(1) and DVCC(2), we obtain the non-idealities as below:

$$I_Y = 0, V_X = \beta_{(1)1}V_{Y1} - \beta_{(1)2}V_{Y2}, I_{Z+} = \alpha_{(1)0}I_X,$$
$$I_{Z1+} = \alpha_{(1)1}I_X, I_{Z-} = -\alpha_{(1)2}I_X, I_{Z1-} = -\alpha_{(1)3}I_X \quad \text{for DVCC(1)} \tag{9}$$

$$I_Y = 0, V_X = \beta_{(2)1}V_{Y1} - \beta_{(2)2}V_{Y2}, I_{Z-} = -\alpha_{(2)0}I_X \quad \text{for DVCC(2)} \tag{10}$$

The non-ideal denominator of the mixed-mode transfer functions becomes:

$$D(s) = s^2C_1C_2 + sC_1G_2\alpha_{(1)2}\beta_{(1)1} + G_1G_2\alpha_{(2)0}\alpha_{(1)0}\beta_{(1)1}\beta_{(2)1} \tag{11}$$

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

$$\omega_0 = \sqrt{\frac{\alpha_{(2)0}\alpha_{(1)0}\beta_{(2)1}\beta_{(1)1}G_1G_2}{C_1C_2}} \tag{12}$$

$$Q = \frac{1}{\alpha_{(1)2}}\sqrt{\frac{\alpha_{(1)0}\alpha_{(2)0}\beta_{(2)1}G_1C_2}{\beta_{(1)1}G_2C_1}} \tag{13}$$

The active and passive sensitivities of ω_0 and Q are:

$$-S^{\omega_0}_{C_1,C_2} = S^{\omega_0}_{G_1,G_2} = S^{\omega_0}_{\alpha_{(2)0},\alpha_{(1)0},\beta_{(2)1},\beta_{(1)1}} = \frac{1}{2}$$

$$S^{Q}_{C_2,G_1} = -S^{Q}_{C_1,G_2} = S^{Q}_{\alpha_{(1)0},\alpha_{(2)0},\beta_{(2)1}} = -S^{Q}_{\beta_{(1)1}} = \frac{1}{2}$$

$$S^{Q}_{\alpha_{(1)2}} = -1, \quad S^{\omega_0}_{\alpha_{(1)1},\alpha_{(1)2},\alpha_{(1)3},\beta_{(1)2},\beta_{(2)2}} = 0$$

$$S^{Q}_{\alpha_{(1)1},\alpha_{(1)3},\beta_{(1)2},\beta_{(2)2}} = 0 \tag{14}$$

From Eq. (14), the proposed mixed-mode biquad filter has low active and passive sensitivities (not larger than unity in absolute value).

IV. H-Spice Simulations

A CMOS implementation of the DVCC± is shown in Fig. 2 [39] with the NMOS and PMOS transistor aspect ratios, W/L=5µm/1µm and 10µm/1µm, respectively. The multiple current outputs of DVCC± are easily obtained by applying current replicas.

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To verify the theoretical analysis of the proposed biquadratic filter, the H-SPICE simulations, using the TSMC 0.25μm process with the parameters of level 49 for the proposed mixed-mode circuit of Fig. 1, were performed with the component values: (i) $C_1 = C_2 = 4$pF and $R_1 = R_2 = R_3 = 10$kΩ, for the CM and TIM five universal filtering responses, leading to a center frequency of $f_0 = 3.9789$MHz and quality factor of $Q = 1$, (ii) $C_1 = C_2 = 4$pF and $R_1 = R_2 = R_3 = 12$kΩ, for the VM and TAM filtering responses, leading to a center frequency of $f_0 = 3.3157$MHz and quality factor of $Q = 1$. Their supply voltages are $V_{DD} = -V_{SS} = 1.25$V, $V_b = 0.49$V, and $V_{b1} = -0.41$V. Fig. 3 presents the simulated CM and normalized TIM (with the normalized transimpedances magnitude = 20 log $|V_{out}$ / 10000 $I_{in}|$ dB due to R_3 =10 kΩ) lowpass and highpass amplitude-frequency responses of the proposed mixed-mode biquadratic filter. Fig. 4 presents the simulated CM and normalized TIM (with the normalized transimpedances magnitude) bandpass and notch amplitude-frequency responses of the proposed mixed-mode biquadratic filter. Fig. 5 presents the simulated CM and normalized TIM (with the normalized transimpedances magnitude) allpass phase and amplitude-frequency responses of the proposed mixed-mode biquadratic filter. Fig. 6 presents the simulated VM and normalized TAM (with the normalized transadmittance magnitude = 20 log $|12000 I_{out} / V_{in}|$ dB due to R_3 =12 kΩ) bandpass and highpass amplitude-frequency responses of the proposed mixed-mode biquadratic filter. As can be seen, there is a close agreement between theory and simulation.

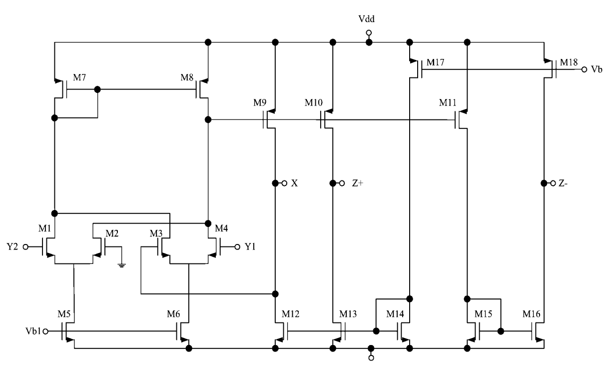

Figure 2. CMOS implementation of the DVCC.

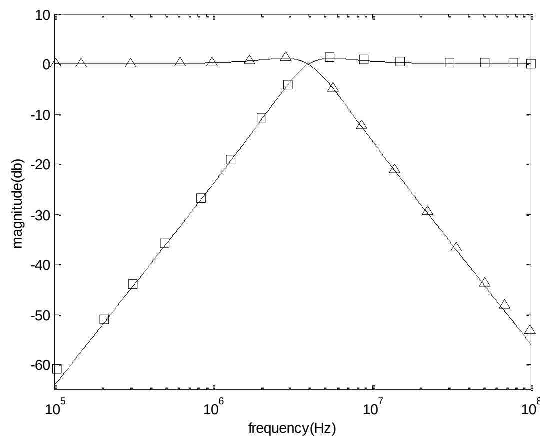

Figure 3. CM and normalized TIM amplitude-frequency responses with highpass and lowpass signals of the proposed biquadratic filter (□, simulated highpass; Δ, simulated lowpass; and ____,theoretical curve).

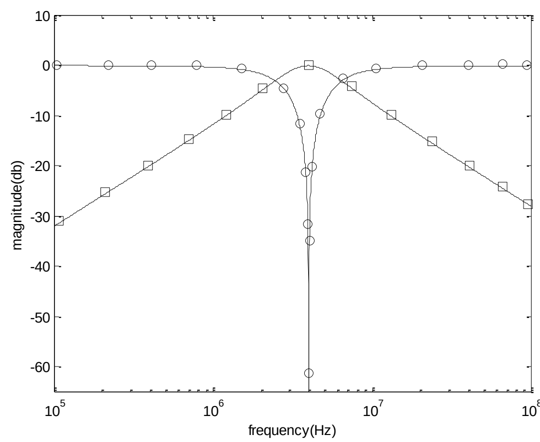

Figure 4. CM and normalized TIM amplitude-frequency responses with notch and bandpass signals of the proposed biquadratic filter (○, simulated notch; □, simulated bandpass; and ____, theoretical curve).

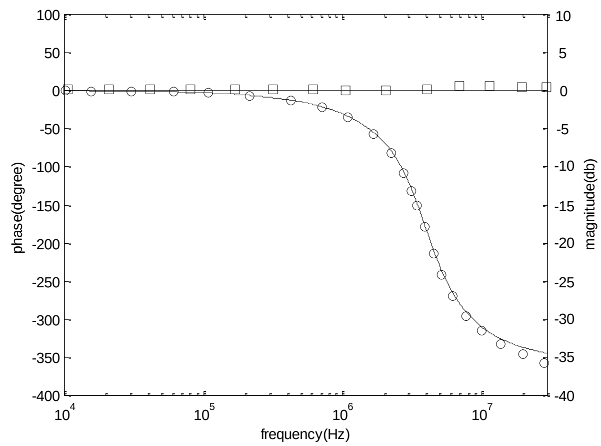

Figure 5. Phase-frequency and amplitude-frequency responses with CM and normalized TIM allpass signals of the proposed biquadratic filter (○, simulated phase; □, simulated amplitude; and ——, theoretical curve).

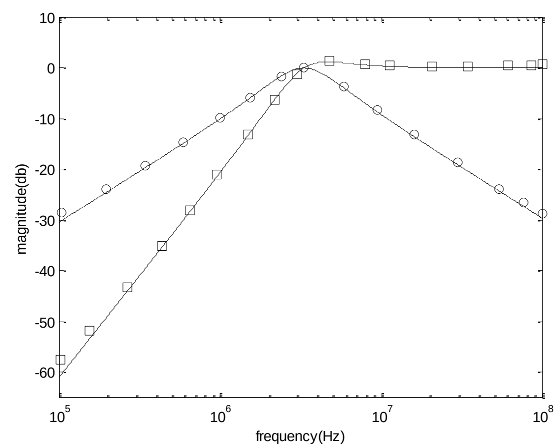

Figure 6. VM and normalized TAM amplitude-frequency responses with highpass and bandpass signals of the proposed biquadratic filter (□, simulated highpass; ○, simulated bandpass; and ____, theoretical curve).

V. CONCLUSIONS

Only using two DVCCs (with simple implementation configuration), three grounded resistors, and two grounded capacitors (all passive components grounded), to design a mixed-mode biquadratic filter is presented in this paper, which can be operated in all four possible modes (i.e. VM, CM, TAM, and TIM) and can realize CM and TIM all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) in addition to VM and TAM highpass, bandpass filtering responses without changing the filter topology.

Moreover, the proposed mixed-mode circuit still enjoys many main advantages: no component-value constraints, no inverting or non-inverting amplifiers for special input signals, no capacitors bringing extra poles degrading high-frequency performance, high input impedance VM, fully cascadable TAM, high output impedance CM, and low active and passive sensitivities. H-Spice simulations with TSMC 0.25μm process confirm the theoretical predictions.

Acknowledgements

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