Minimum Configuration Insensitive Multifunctional Current-Mode Biquad Using Current Conveyors and All-Grounded Passive Components

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Abstract. *This paper proposes a new current conveyor-based high-output impedance single-input three-output current mode filter with minimum configuration. It contains two dual output second generation current conveyors, one third generation dual output current conveyor, and four grounded resistors and capacitors. The circuit simultaneously provides low-pass, band-pass, and high-pass filtering outputs, without any passive component matching conditions and restrictions on input signals. Additionally, the proposed circuit offers following advantages: Minimum active and passive element count, high output and low input impedances, suitable for cascading identical current-mode sections, all passive elements are grounded (no virtual grounding), low natural frequency and Q-factor sensitivities. The influences of non-ideal current conveyors on the proposed circuit are researched in the last.*

Keywords

Current conveyor, current-mode circuit, filter, parasitic impedance.

1. Introduction

Second generation current conveyor (CCII) element which has a single current output terminal is one of the versatile active building blocks to construct continuous-time universal and multipurpose filters, and many of these filters have already been reported in literature [1-3]. CCII can not provide feedforward and feedback currents at the same time, and CCII-based filters become rather complex. Modified current conveyors, such as MOCCII (current conveyor with multi-output terminals) [4-5] and DOCCII (second generation current conveyors with dual output terminals) [6-8] are employed to produce filters. Although the MOCCII-based filters have simple structure, their current tracking errors will increase proportionally with the number of current output terminals. On the other hand, DOCCII has two current output terminals (one positive, another negative), its current tracking errors are relatively small, and it has a balanced output structure.

Many different current mode filter topologies can be realized by employing second generation current conveyors with dual output terminals [6–16]. Structurally, DOCCII based filters and their variants can be divided into three classes: (i) multi-input and multi-output (MIMO) filters [6]; (ii) multi-input and single-output filters [7-9]; (iii) single-input and three-output (SITO) filters [10-16]. The SITO filters can realize second order low-pass (LP), band-pass (BP), high-pass (HP) filters simultaneously without any passive component matching conditions and restrictions on input signals. These filters also allow the realizations of notch and all-pass (AP) filter responses without having to change the filter configurations.

Soliman proposes current mode filter circuit with high-output impedance using three DOCCII and five grounded RC elements [10], the filter's natural frequency and quality factor can be adjusted independently. However, the circuit only produces two-outputs (low-pass and band-pass). In another study, Soliman gives several dual and three outputs CM filter configurations with high impedance outputs [11].

Abuelma'atti et al. propose SITO current mode filter circuit with high-output impedance using three DOCCIIs, one OTA (operational transconductance amplifier) and five grounded RC elements [12]. Gunes et al. describe a SITO current mode filter circuit employing three DOCCIIs and four grounded RC components [13]. However, the band-pass and high-pass outputs of this circuit do not provide high-output impedances. Toker et al. present a SITO current mode filter circuit with high-output impedance using three DOCCIIs, five grounded RC elements [14]. Toker et al. proposed another SITO filter circuit for low frequency operation in [15]. The circuit includes four DOCCIIs and eight passive elements. Cicekoglu introduces five SITO current mode filter circuits, each of them containing four DOCCII and seven RC components with high-output impedances [16]. Keskin and Cam propose a new SITO current mode filter circuit with high-output impedance using three DOCCIIs and four passive elements [17]. Although it is a minimum configuration structure, there is one virtually grounded resistor in addition to three grounded passive components in their circuit. The CM DOCCII-based filter introduced by Ikeda and Tomita [18] has three active and four passive elements, but does not provide simultaneous outputs. While the works in [19], [20] describe minimum configuration circuits with high impedance outputs, both of them contain floating capacitors.

Tangsrirat et al. propose a two-input three-output current-mode filter, which employs three dual-output current-controlled current conveyors (DOCCCIIs) and two grounded capacitors [21]. In another study, Tangsrirat demonstrates a CM filter with two inputs and two outputs employing four DOCCCIIs and two grounded capacitors [22]. However, neither of these circuits belongs to SITO topology.

Singh et al. show how a four current conveyor based voltage mode biquad filter with five resistors and two grounded capacitors provides also current mode capability [23].

So far (to the best knowledge of authors), there exists no study on DOCCII-based CM SITO filters offering minimum filter configurations accompanied with all-grounded passive component structure with high impedance outputs.

On the other hand, third generation current conveyor (CCIII) is proposed by Fabre [24], and a CMOS implementation of this circuit is presented in [25]. DOCCIII (third generation current conveyor with two current outputs) can easily be constructed in a CMOS technology. Numerous applications of CCIII element have already been presented in literature [26-30].

In this paper, a new current mode SITO type minimum configuration filter is proposed. This circuit consists of one third generation current conveyor and two second generation current conveyors in addition to four grounded passive elements.

2. The Proposed Circuit

The symbolic notations of DOCCII and DOCCIII four terminal active elements are shown in Fig. 1.a, b. DOCCII is characterized by

$$V_x = V_y, I_y = 0, I_{z+} = I_x, I_{z-} = -I_x. \quad (1)$$

On the other hand, third generation current conveyor with dual outputs, DOCCIII is described by

$$V_x = V_y, I_y = -I_x, I_{z+} = I_x, I_{z-} = -I_x. \quad (2)$$

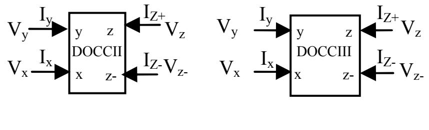

Fig.1. Circuit symbols of DOCCII and DOCCIII.

The proposed circuit is shown in Fig. 2. The circuit contains two DOCCIIs, one DOCCIII, two grounded resistors and grounded capacitors, and it can realize low-pass, band-pass and high-pass filters simultaneously, at high impedance outputs. From Fig. 2, the input terminal of circuit is terminal Y of DOCCIII, so according to (2) (namely: $V_x = V_y$, $I_y = -I_x$), it is clear that the circuit has low input impedance. It is convenient for the circuit to be cascaded for its high output impedance and low input impedance.

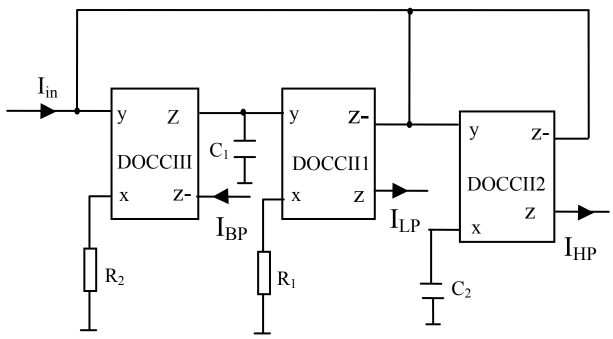

Fig. 2. Proposed SITO current mode filtering circuit.

The filter provides the following transfer functions simultaneously:

$$\frac{I_{LP}}{I_{in}} = \frac{1}{s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1}, \quad (3)$$

$$\frac{I_{BP}}{I_{in}} = \frac{s R_1 C_1}{s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1}, \quad (4)$$

$$\frac{I_{HP}}{I_{in}} = \frac{s^2 R_2 R_1 C_1 C_2}{s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1}. \quad (5)$$

The band-stop (BS) filtering output can be obtained by connecting low-pass and high-pass outputs ($I_{LP}+I_{HP}$), and all-pass (AP) filtering output can be obtained by connecting low-pass, band-pass and high-pass outputs ($I_{LP}-I_{BP}+I_{HP}$) together as depicted in (6), (7). Therefore, the proposed circuit can be easily transformed into a universal filter.

$$\frac{I_{BS}}{I_{in}} = \frac{I_{LP} + I_{HP}}{I_{in}} = \frac{s^2 R_2 R_1 C_1 C_2 + 1}{s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1}, \quad (6)$$

$$\frac{I_{AP}}{I_{in}} = \frac{I_{LP} + I_{HP} - I_{BP}}{I_{in}} = \frac{s^2 R_2 R_1 C_1 C_2 - s R_1 C_1 + 1}{s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1}. \quad (7)$$

The natural angular frequency and quality factor are given in (8a, 8b), respectively.

$$\omega_0 = \sqrt{\frac{1}{R_1 R_2 C_1 C_2}}, \quad (8a)$$

$$Q = \sqrt{\frac{R_2 C_2}{R_1 C_1}}. \quad (8b)$$

Ideal passive ω_0 and Q sensitivities are both 1/2 in magnitude.

Taking the non-idealities of the DOCCII and DOCCIII into account, their terminal relationships can be rewritten respectively as follows:

$$V_x = \beta V_y, I_y = 0, I_{z+} = \alpha I_x, I_{z-} = -\alpha I_x, \quad (9)$$

$$V_x = \beta V_y, I_y = \gamma I_x, I_{z+} = \alpha I_x, I_{z-} = -\alpha I_x \quad (10)$$

where α and γ are current gains and β is voltage gain, and $\alpha = 1-\varepsilon_{iz}$, $\gamma = 1-\varepsilon_{ix}$, $\beta = 1-\varepsilon_v$. Here, ε_{iz}, ε_{ix}, ε_v are current- and voltage-tracking errors of the DOCCII and DOCCIII.

Considering these non-idealities of the DOCCII and DOCCIII, current transfer functions in Fig. 2 become:

$$\frac{I_{LP}}{I_{in}} = \frac{1}{D(s)}, \frac{I_{BP}}{I_{in}} = \frac{sR_1C_1/(\alpha_1\beta_1)}{D(s)}$$
$$\frac{I_{HP}}{I_{in}} = \frac{s^2R_1R_2C_1C_2\alpha_1\beta_1/(\alpha\alpha_1\beta\beta_1)}{D(s)} \quad (11)$$

where

$$D(s) = s^2R_1R_2C_1C_2\alpha_2\beta_2/(\alpha\alpha_1\beta\beta_1) + sR_1C_1\gamma/(\alpha\alpha_1\beta_1)+1 \quad (12)$$

In (11), (12); α, β and γ are parameters of DOCCIII, and α_i, β_i are parameters of DOCCIIi (i=1,2).

The natural angular frequency and quality factor are

$$\omega_0 = \sqrt{\frac{\alpha\alpha_1\beta\beta_1}{R_1R_2C_1C_2\alpha_2\beta_2}}, Q = \frac{1}{\gamma}\sqrt{\frac{R_2C_2\alpha\alpha_1\alpha_2\beta\beta_1\beta_2}{R_1C_1\beta}}. \quad (13)$$

Active sensitivities of the natural angular frequency and the quality factor of the filter shown in Fig. 2 are

$$S^{\omega_0}_{\alpha,\alpha_1,\beta,\beta_1} = -S^{\omega_0}_{\alpha_2,\beta_2} = \frac{1}{2}, S^{\omega_0}_{\gamma} = 0 \quad (14)$$

$$S^{Q}_{\alpha,\alpha_1,\alpha_2,\beta,\beta_1,\beta_2} = -S^{Q}_{\beta} = \frac{1}{2}, S^{Q}_{\gamma} = -1 . \quad (15)$$

It is clearly observed that active sensitivities of ω_0 and Q do not exceed unity.

3. Results of Circuit Simulations

In order to confirm the practical validity of the proposed SITO filter circuit, it is simulated in SPICE using 0.5μm CMOS process parameters for transistors shown in Tab. 1. The CMOS DOCCII [31] given in Fig. 3, and CMOS DOCCIII [25] of Fig. 4 are used in circuit simulations. Tab. 2 lists the transistor dimensions used in two circuits.

Fig. 5 displays the results of circuit simulations for the proposed multifunction filter. Fig. 6 denotes the simulations results of phase and gain for all-pass filtering output.

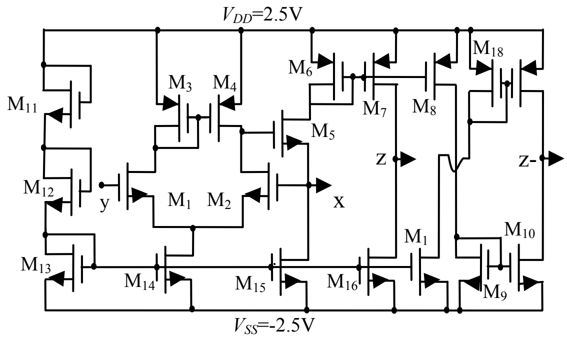

Fig. 3. CMOS DOCCII circuit.

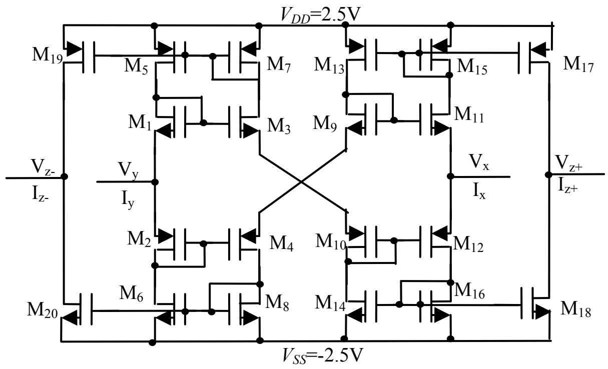

Fig. 4. CMOS DOCCIII circuit.

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.MODEL seanmos NMOS(LEVEL=3 PHI=0.700000
+TOX=9.6000E-09 XJ=0.200000U TPG=1 VTO=0.6684
+DELTA=1.0700E+00 LD=4.2030E-08 KP=1.7748E-04
UO=493.4 +THETA=1.8120E-01 RSH=1.6680E+01
GAMMA=0.5382 +NSUB=1.1290E+17 NFS=7.1500E+11
VMAX=2.7900E+05 +ETA=1.8690E-02 KAPPA=1.6100E-01
CGDO=4.0920E-10 +CGSO=4.0920E-10 CGBO=3.7765E-10
CJ=5.9000E-04 +MJ=0.76700 CJSW=2.0000E-11
MJSW=0.71000 PB=0.990000)
.MODEL seapmos PMOS(LEVEL=3 PHI=0.700000
+TOX=9.6000E-09 XJ=0.200000U TPG=-1 VTO=-0.9352
+DELTA=1.2380E-02 LD=5.2440E-08 KP=4.4927E-05
UO=124.9 +THETA=5.7490E-02 RSH=1.1660E+00
GAMMA=0.4551 +NSUB=8.0710E+16 NFS=5.9080E+11
VMAX=2.2960E+05 +ETA=2.1930E-02 KAPPA=9.3660E+00
CGDO=2.1260E-10 +CGSO=2.1260E-10 CGBO=3.6890E-10
CJ=9.3400E-04 +MJ=0.48300 CJSW=2.5100E-10
MJSW=0.21200 PB=0.930000)
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Tab. 1. 0.5μm CMOS process parameters for transistors.

DOCCII	M_1~ M_4	M_5~ M_{10}	M_{11} M_{12}	M_{13}	M_{14}	M_{15}~ M_{17}	M_{18} M_{19}
W/L(um)	8/2	10/2	4/2	12/2	19/2	8/2	4/2
DOCCIII	$M_1 M_3 M_6 M_8 M_9 M_{11}$ $M_{14} M_{16} M_{18} M_{20}$				$M_2 M_4 M_5 M_{10} M_{12}$ $M_{13} M_{15} M_{17} M_{19}$		
W/L(um)	4/2				16/2		

Tab. 2. Transistor dimensions in the DOCCII and DOCCIII circuits.

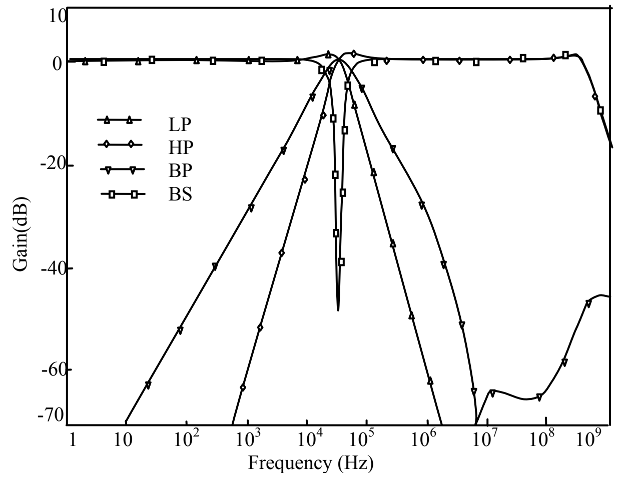

Fig. 5. Results of circuit simulations for basic filter responses of the proposed DOCCII-based SITO biquad.

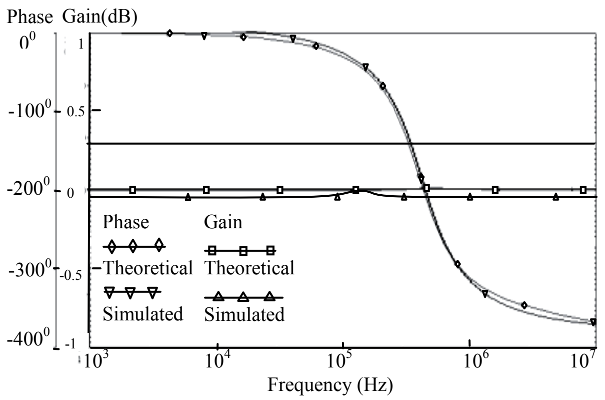

Fig. 6. Frequency responses characteristic of the AP filter.

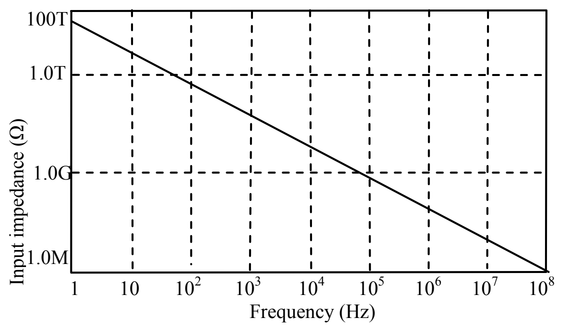

Fig. 7. Input impedance of the filter.

The input and output impedance of CFBCCII can be seen in Fig. 7 and Fig. 8. Here, component values are selected as R_1= R_2= 5 kΩ, and C_1= C_2= 1 nF, which yield f_0 = 34 kHz and Q = 1. Fig. 9 shows the simulated band-pass responses with Q-tuning (i.e. Q = 1, 4, 6). In this case, R_1= 5 kΩ, 1.25 kΩ, 0.84 kΩ and R_2= 5 kΩ, 20 kΩ, 30 kΩ and C_1= C_2= 1 nF respectively while keeping ω_0 invariant. Supply voltages are ±2.5 V. It is noted that the results of circuit simulations are in agreement with theory. For the band-pass filter, the simulated curve departs from ideal beginning at about 10 MHz, due to the parasitic impedances of DOCCII and DOCCIII. This behavior is further analyzed in the following section.

Note that, since the aim of this study is to design a minimum configuration CM-SITO filter, independent control of frequency or quality factor is not expected.

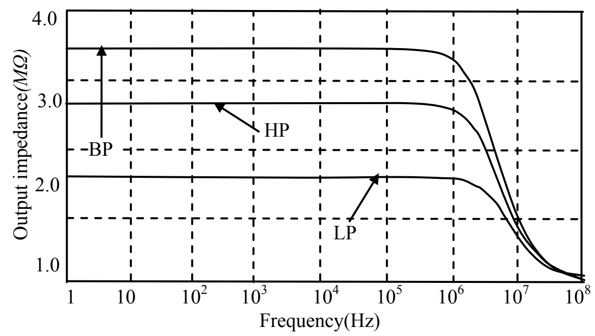

Fig. 8. Output impedance of the filter.

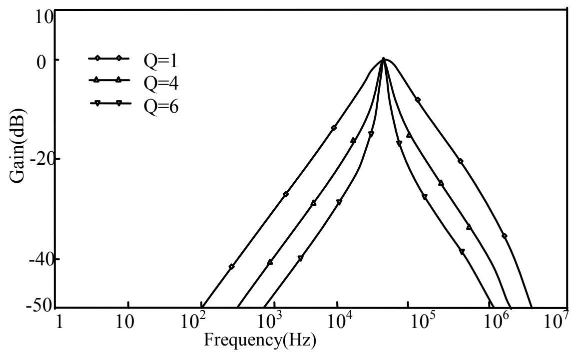

Fig. 9. Simulation results of frequency response of BP filter with different Q (keeping ω_0 invariant).

4. Parasitic Impedance Influence of DOCCII and DOCCIII

The non-ideal CCII [32] and CCIII models are shown in Fig. 10. The real CCII and CCIII has parasitic resistors and capacitors at terminal z to the ground, and a serial resistor at the input terminal x. In the CCII, parasitic resistors and capacitors exist at terminal y to the ground [32]. A series parasitic resistor exists at the terminal y of the CCIII. Here, $\alpha(s)$ and $\beta(s)$ are used to represent the frequency domain transfer functions of the internal current and voltage followers of the CCII and CCIII, respectively, and they are considered as having unity values here.

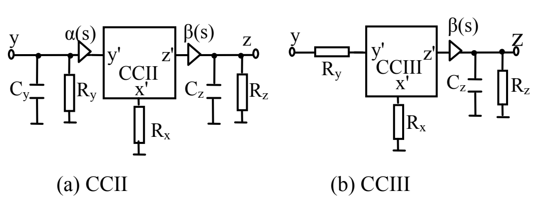

Fig. 10. Non-ideal CCII and CCIII with their parasitic resistors and capacitors.

In a non-ideal DOCCII and DOCCIII, parasitic resistors and capacitors at the z+, z- terminals are assumed to have the same values, all being equal to R_z and C_z respectively.

In order to study the influence of parasitic elements in DOCCII and DOCCIII, the proposed filter shown in Fig. 2 can be transformed to Fig. 11.

We define R_{z1}, R_{z2}, C_{z1}, C_{z2} as the parasitic resistors and capacitors of the z terminals of DOCCII1 and DOCCII2 in Fig. 11, and R_{z0}, C_{z0} at the z terminal of DOCCIII. R_{x1}, R_{x2} are the serial parasitic resistances at the x terminals of DOCCII1 and DOCCII2, R_{x0} is the parasitic resistance for DOCCIII, while R_{y1}, R_{y2}, C_{y1}, C_{y2} are the parasitic resistors and capacitors at the y terminals of DOCCII1 and DOCCII2. R_{y0} is the serial parasitic resistance of DOCCIII which is equal to R_{x0} approximately.

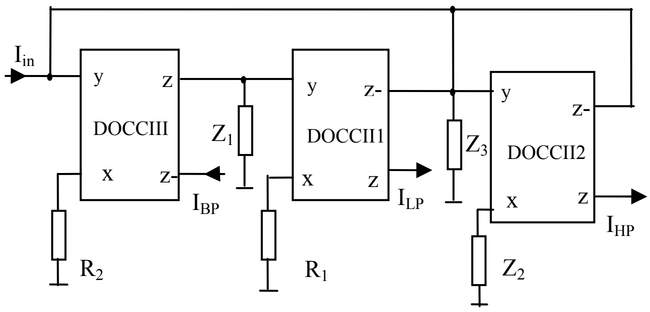

Fig. 11. The proposed filter including the parasitic elements of the DOCCII and DOCCIII.

Assuming that $C_1 >> (C_{y1}+C_{z0})$, it can be shown that

$$Z_1 = C_1 // R_{z0} // (C_{z0} // C_{y1}) \approx \frac{R_{z0}}{1+sC_1R_{z0}}, \quad (16)$$

$$Z_2 = R_{x2} + \frac{1}{sC_2} = \frac{1+sC_2R_{x2}}{sC_2}, \quad (17)$$

$$Z_3 = (R_{z1} // R_{z2}) // (C_{z1} // C_{y2} // C_{z2}) \approx \frac{R_{z2}/2}{sC_{yz}R_{z2}/2+1} \quad (18)$$

where $C_{yz}=C_{z1}+C_{y2}+C_{z2}$. From Fig. 11 one can obtain the following transfer functions:

$$\frac{I_{LP}}{I_{in}} = \frac{Z_1Z_2Z_3}{Z_1Z_2Z_3+R_1R_2Z_2+R_1R_2Z_3+R_1Z_2Z_3} = \frac{1}{D(s)}, \quad (19)$$

$$\frac{I_{BP}}{I_{in}} = \frac{R_1Z_2Z_3}{Z_1Z_2Z_3+R_1R_2Z_2+R_1R_2Z_3+R_1Z_2Z_3} = \frac{R_1Z_2Z_3}{D(s)}, \quad (20)$$

$$\frac{I_{HP}}{I_{in}} = \frac{R_1R_2Z_3}{Z_1Z_2Z_3+R_1R_2Z_2+R_1R_2Z_3+R_1Z_2Z_3} = \frac{R_1R_2Z_3}{D(s)} \quad (21)$$

where

$$D(s) = s^2(R_1R_2C_1(C_{yz} + \frac{C_2}{1+sC_2R_{x2}}) + s(C_1R_1 + \frac{2R_1R_2C_1}{R_{z2}} + \frac{R_1R_2C_2}{R_{z0}(1+sC_2R_{x2})}) + (1+\frac{R_1}{R_{z0}}) \quad (22)$$

For the value of C_{yz} is smaller than 10 pF and that of R_{z0}, R_{z2} is larger than 1 MΩ, so C_1, C_2, R_1, R_2 are chosen under the following relations: $C_{yz} << \min(C_1, C_2)$, $\min(R_{z0}, R_{z0}) >> \max(R_1, R_2)$. Therefore ,

$$\omega_0' = \sqrt{\frac{1+R_1/R_{z0}}{R_1R_2C_1C_2(1/(1+sC_2R_{x2})+C_{zy}/C_2)}} \approx \omega_0\sqrt{1+sC_2R_{x2}} \quad (23)$$

$$Q' = \frac{\sqrt{(1+R_1/R_{z0})R_1R_2C_1(C_{yz}+1/(1+sC_2R_{x2}))}}{C_1R_1+2R_1R_2C_1/R_{z2}+R_1R_2C_2/(R_{z0}(1+sC_2R_{x2}))} \approx Q\sqrt{\frac{1}{1+sC_2R_{x2}}} \quad (24)$$

From (23) and (24), it is clear that when considering influence of parasitic elements, the natural angular frequency is larger than the one in ideal condition, namely $\omega_0' > \omega_0$, and the quality factor is lower than that of the ideal one ($Q' < Q$). If $\omega C_2R_{x2} << 1$, the influence of non-ideal characteristics of DOCCII can be ignored. Note that the value of R_x is low, as given below [32].

$$R_x = (g_{m1}+g_{m2})(g_{d2}+g_{d4})/g_{m1}g_{m2}g_{m5} \approx 40\Omega \quad (25)$$

The influence of parasitic elements on the proposed filter is simulated by PSPICE. It can be seen in Fig. 12 that in the proposed filter, the parasitic elements have some influences on the ω_0 and Q of the proposed filter. In this case, $C_1 = C_2 = 0.25$ nF, 1 nF, 5 nF, 10 nF and $R_1 = R_2 = 20$ kΩ, 5 kΩ, 1 kΩ, 0.5 kΩ, respectively. Supply voltages are ±2.5 V. When $\omega C_2R_{x2} << 1$ (e.g. $C_2 = 0.25$ nF as shown in Fig. 11), the DOCCII can be seen as the ideal one. Therefore, the simulation results are in good agreement with the theoretical analysis.

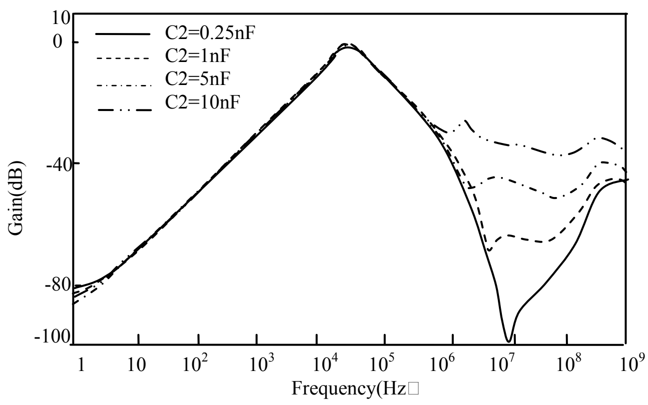

Fig. 12. Simulation results of the influence of parasitic elements on the proposed filter.

5. Conclusions

In this work, a new current mode SITO biquad is presented. This filter employs minimum number of active and passive elements. The proposed current mode filter can be easily cascaded, since it realizes three simultaneous filter functions at high impedance outputs, while its input impedance is low. In this filter, AP and notch responses can also be obtained by interconnecting the corresponding outputs. Moreover, all passive components are grounded, and its frequency and Q-factor sensitivities are low.

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