Current-Mode Biquad Filters Employing Single FDCCII

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Abstract. *In this study, to realize current-mode multifunction filters, three new circuit configurations are presented. The circuits include fully differential current conveyor (FDCCII) and four passive components. First proposed circuit is a universal filter with single-input and three-outputs, which can simultaneously realize current mode low-pass, band-pass and high-pass filter responses employing all grounded passive components. The last two proposed are universal filters with three-inputs single-output, which can realize current mode low-pass, band-pass, high-pass, band-stop and all-pass filter responses employing single FDCCII. Furthermore, each of the proposed circuits still enjoys realization using a minimum number of active and passive components. First and last of the proposed circuits have no requirement with the component choice conditions to realize specific filtering functions. No parameter matching condition is required. Active and passive sensitivities of filters are investigated and calculated 5 percentage hangings. Simulation results are found in close agreement with the theoretical results.*

Keywords

FDCCII, current-mode filter, analog MOS integrated circuit, analog signal processing.

1. Introduction

Current-mode circuits are receiving considerable attention owing to their larger dynamic range, higher bandwidth, greater linearity, simpler circuitry, lower power consumption and require less chip area then voltage-mode counterparts [1]-[4]. Current-mode circuits and related active components such as current conveyor (CC) [5], four terminal floating nullor (FTFN) [6], operational transconductance amplifier (OTA) [7], current differencing buffered amplifier (CDBA) [8] and current feedback operational amplifier (CFOA) [9] emerged as an important class of circuits with properties that enable them to rival their voltage-mode counterparts in wide range applications. One of most popular analog filters is a universal biquad filter, since they can provide multiple functions. Simultaneous realization of filter functions can be found extensively used in applications such as phase-locked loop FM stereo demodulation, and touch-tone telephone tone decoding. Nowadays, universal current modes filter to work in well-being of popularity as a voltage-mode. Several single-input three-outputs (SITO) current mode filter have been proposed in the literature [10]-[18]. However these circuits contain too many active components and/or passive components. For example, J. W. Horng et al. [10] proposed current-mode (CM) biquad filter using three multiple outputs second-generation current conveyors (MOCCIIs), four resistors and two grounded capacitors. A. U. Keskin et al. [11] proposed current-mode (CM) biquad filter using three DOCCIIs and four passive elements. A. M. Soliman [12] designed a new configuration low-pass, band-pass and high-pass filter using four ICCIIs and five passive elements. The work by E. Yuce et al. [13] reported universal CM filter circuit employing one CFOA and five passive elements. M. Sagbas et al. [14] proposed CM biquad filter using three MO-CCIIs and five passive components. J.-W. Horng [15] proposed two CM biquad filters. The first proposed filter employs single Current follower, three capacitors and four resistors while the second proposed filter uses one current follower, one voltage follower, four capacitors and five resistors. Moreover, these filters require matching conditions.

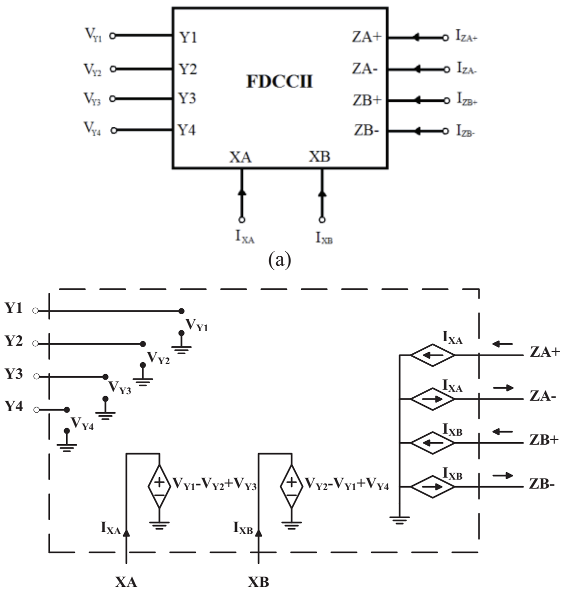
Furthermore, several circuits realizing multi-inputs single-output (MISO) current transfer functions have been presented in the literature [19]-[31]. Tangsrirat and Surakampontorn [20] proposed biquad filter configuration that can realize all second-order functions, namely low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP), but requires three CDBAs, two virtually grounded resistors and two grounded capacitors. Jiang and He [21] reported universal active CM filters using one MOCCII, one CCII-, two grounded resistors and two grounded capacitors. Feki and Masmoudi [22] proposed CM biquad filter using two CCIIs, one CCIII, two grounded resistors and two grounded capacitors. Pandey et al. [23] described universal biquad filter that can realize all second-order functions but uses two MOCCCIIs, one grounded resistor and two grounded capacitors. Tangsrirat and Surakampontorn [24] proposed CM universal filter using five CCCIIs and two grounded capacitors. Besides it needs a minus input current signal to realize AP filter. The configuration [25] implements all second- order functions and employs single CFOA, three grounded resistors, one grounded capacitor and one floating capacitor. In addition it needs a minus input current signal to realize LP filter. Sharma and Senani [26] proposed CM biquads filter using single CFOA, four passive components, one or few of floating components, and it needs a minus input current signal to realize the filter. Tanjaroen et al. [27] proposed CM multifunction filter using three CDTAs and two grounded capacitors. The work by Özcan et al. [28] reported biquad filter employing single CCII+, one floating resistor, one grounded resistor and one floating capacitor, one grounded capacitor. However it realizes only LP, BP and HP filter besides it needs a minus input current signal to realize standard filter (LP, BP, and HP).

In the literature, there are current-mode biquad filter realized with FDCCII [29]-[33]. Kaçar et al. [29] proposed two multifunction filters. However first proposed filter employs single FDCCII, one floating capacitor, one grounded capacitor and one floating resistor, one grounded resistor. Second proposed filter employs single FDCCII, two grounded resistors and two grounded capacitors. However second proposed filter which has two-inputs two-outputs realizes standard filters. Chang et al. [30] proposed filter employs single FDCCII, two grounded capacitors and two grounded resistors. However multiple input terminals were used, so as to realize standard filters and output terminals of FDCCII are multiplexed. Gür [31] proposed current-mode biquad filter with FDCCII. However the proposed filter includes two FDCCIIs, two grounded capacitors and three grounded resistors. Kacar and Yesil [32] proposed voltage mode filters that are both SITO filters and TISO filters. Finally, Kacar and Kuntman [33] reported biquad filter employing single FDCCII two capacitors and two resistors. However each filter realizes only two outputs.

In this paper, current-mode biquad filters have been presented. All of the circuits contain single FDCCII and four passive elements. First proposed circuit is a universal filter with single-input and three-outputs, which can simultaneously realize current mode low-pass, band-pass and high-pass filter responses employing all grounded passive components. The last two proposed are universal filters with three-inputs single-output, which can realize current mode low-pass, band-pass, high-pass, band-stop and all-pass filter responses employing single FDCCII. Furthermore, each of the proposed circuits still enjoys realization using a minimum number of active and passive components. First and last of the proposed circuits have no requirement with the component choice conditions to realize specific filtering functions. No parameter matching condition is required. Active and passive sensitivities of filters are investigated and calculated 5 percentage hangings. The performances of the proposed FDCCII and current-mode biquad filters are illustrated by LTSPICE simulations and they show good agreement as mentioned.

2. Circuit Description

The block diagram of the FDCCII and its behavioral model which are shown in Fig. 1a and Fig. 1b, respectively, are defined by the following terminal equations [34]:



(a)

(b)

Fig. 1. a) Block diagram and b) equivalent circuit of FDCCII.

$$\begin{bmatrix} V_{XA} \\ V_{XB} \\ I_{ZA+} \\ I_{ZA-} \\ I_{ZB+} \\ I_{ZB-} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} V_{Y1} \\ V_{Y2} \\ V_{Y3} \\ V_{Y4} \\ I_{XA} \\ I_{XB} \end{bmatrix}. \tag{1}$$

It is shown that for an ideal FDCCII all the four Y terminals exhibit an infinite input resistance. The two ports X exhibit zero input resistance and the four ports Z exhibit an infinite output resistance. The first type proposed current mode single-input four-outputs (SIFO) biquad filter is shown in Fig. 2. The proposed circuit which is composed of a FDCCII uses two capacitors and two resistors.

Note that the filter structure of Fig. 2 is a core structure where filter functions are available via currents flowing over grounded passive elements. It is possible to obtain BP1 and HP filter functions from a separate high impedance output by modifying the CMOS structure using Z-Copy techniques for ZA-, ZB and ZB- terminals [1], [2], [35]. Fortunately, due to the behavior of the active elements, cascading of two filters of this type can be achieved simply by connecting lower terminal of the related passive element directly to the input of the next filter stage instead of the ground. Due to internal grounded XA and XB terminals, used as input, the filters can be cascaded without any problem. In this case, no additional terminal is needed.

Fig. 2 Current transfer functions of the proposed circuit are given in (2). Routine analysis of this circuit yields the following current-mode filter transfer functions:

$$\frac{I_{LP}}{I_{IN}} = \frac{G_1 G_2}{s^2 C_1 C_2 + s C_1 G_2 + G_1 G_2}, \tag{2a}$$

$$\frac{I_{BP1}}{I_{IN}}=\frac{C_1G_2s}{s^2C_1C_2+sC_1G_2+G_1G_2}, \tag{2b}$$

$$\frac{I_{BP2}}{I_{IN}}=\frac{C_1G_2s}{s^2C_1C_2+sC_1G_2+G_1G_2}, \tag{2c}$$

$$\frac{I_{HP}}{I_{IN}}=\frac{C_1C_2s^2}{s^2C_1C_2+sC_1G_2+G_1G_2}. \tag{2d}$$

From (2), the expressions for the resonance angular frequency ω_{01} and the quality factor Q_1 of the poles of the proposed circuit are given by

$$\omega_{01}=\sqrt{\frac{G_1G_2}{C_1C_2}}, \tag{3a}$$

$$Q_1=\sqrt{\frac{G_1C_2}{G_2C_1}}. \tag{3b}$$

The second type of proposed current-mode MISO biquad filters are shown in Fig. 3. Each of the proposed circuit, which is composed of a FDCCII, uses all grounded two capacitors and two resistors. In addition to, proposed circuits have high output impedance so these circuits enable easy cascadability.

Note that the circuits of Fig. 3 exhibit multiple-input and single-output configuration. As a result, similar to many other multiple-input filter structures available in the literature, multiple-output current followers/inverters are required to derive the input signals properly [36]-[37].

The first circuit can be realized multi-inputs single-output current-mode biquad filter is shown in Fig. 3a. By routine circuit analysis based on (1), the current transfer function of the proposed FDCCII based filter can be given by

$$I_{out}=\frac{I_3s^2C_1C_2+s\left(I_4C_1G_2-(I_1+I_2)C_2G_2\right)+2I_4G_1G_2}{s^2C_1C_2+sC_1G_2+2G_1G_2}. \tag{4}$$

Depending on the current status of I_1, I_2, I_3 and I_4 in the numerator of (4), one of the following five filter functions is realized:

(i) LP: $I_2=I_3=0$, $I_1=I_4=I_{IN}$;

(ii) BP: $I_2=I_3=I_4=0$, $I_1=I_{IN}$ or $I_1=I_3=I_4=0$, $I_2=I_{IN}$;

(iii) HP: $I_1=I_2=I_4=0$, $I_3=I_{IN}$;

(iv) BS: $I_2=0$, $I_1=I_3=I_4=I_{IN}$ and $C_1=C_2$ or $I_1=0$, $I_2=I_3=I_4=I_{IN}$ and $C_1=C_2$;

(v) AP: $I_1=I_2=I_3=I_4=I_{IN}$ and $C_1=C_2$.

From (4), the resonance angular frequency ω_{02} and the quality factor Q_2 are given by

$$\omega_{02}=\sqrt{\frac{2G_1G_2}{C_1C_2}}, \tag{5a}$$

$$Q_2=\sqrt{\frac{2G_1C_2}{G_2C_1}}. \tag{5b}$$

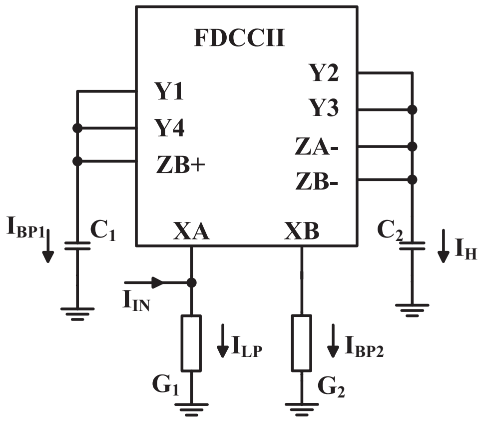
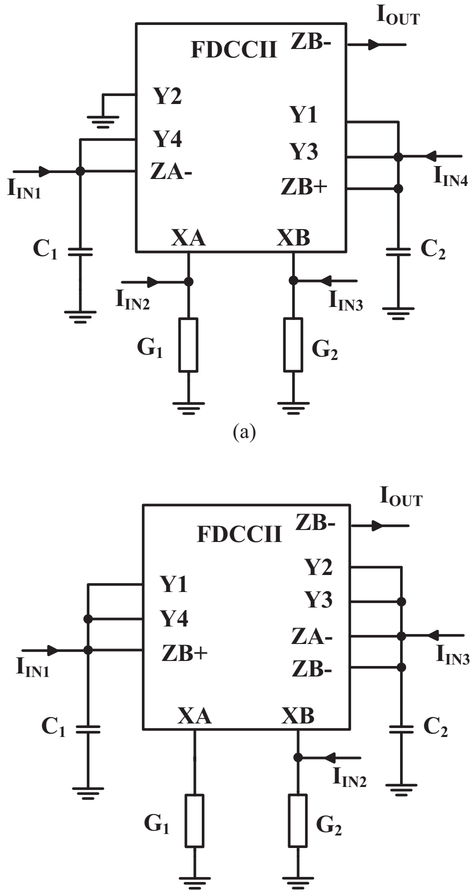


Fig. 2. Proposed SIFO biquad filter employing FDCCII.



(a)

(b)

Fig. 3. Proposed MISO biquad filters employing FDCCII.

	Fig. 2
LP	$\frac{I_{LP}}{I_{IN}}=\frac{sC_1G_1\alpha_{\text{an}}\left(-\beta_2+\beta_3\right)+G_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_3\left(\beta_1-\beta_4\right)+\beta_2\beta_4\right)}{s^2C_1C_2+sC_1G_1\alpha_{\text{an}}\left(-\beta_2+\beta_3\right)+sC_1G_2\alpha_{\text{bn}}\beta_2+sC_2G_2\alpha_{\text{bp}}\left(\beta_1-\beta_4\right)+G_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_3\left(\beta_1-\beta_4\right)+\beta_2\beta_4\right)}$
BP$_1$	$\frac{I_{BP1}}{I_{IN}}=\frac{sC_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\beta_2}{s^2C_1C_2+sC_1G_1\alpha_{\text{an}}\left(-\beta_2+\beta_3\right)+sC_1G_2\alpha_{\text{bn}}\beta_2+sC_2G_2\alpha_{\text{bp}}\left(\beta_1-\beta_4\right)+G_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_3\left(\beta_1-\beta_4\right)+\beta_2\beta_4\right)}$
BP$_2$	$\frac{I_{BP2}}{I_{IN}}=\frac{sC_1G_2\alpha_{\text{an}}\beta_2}{s^2C_1C_2+sC_1G_1\alpha_{\text{an}}\left(-\beta_2+\beta_3\right)+sC_1G_2\alpha_{\text{bn}}\beta_2+sC_2G_2\alpha_{\text{bp}}\left(\beta_1-\beta_4\right)+G_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_3\left(\beta_1-\beta_4\right)+\beta_2\beta_4\right)}$
HP	$\frac{I_{HP}}{I_{IN}}=\frac{s^2C_1C_2\alpha_{\text{an}}+sC_2G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_1-\beta_4\right)}{s^2C_1C_2+sC_1G_1\alpha_{\text{an}}\left(-\beta_2+\beta_3\right)+sC_1G_2\alpha_{\text{bn}}\beta_2+sC_2G_2\alpha_{\text{bp}}\left(\beta_1-\beta_4\right)+G_1G_2\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_3\left(\beta_1-\beta_4\right)+\beta_2\beta_4\right)}$

Tab. 1. Non-ideal cases for the proposed SIFO circuit.

The second circuit realizing multi-inputs single-output current-mode biquad filter is shown in Fig. 3b. Circuit analysis yields the following for the output current can be expressed as

$$I_{out}=\frac{\mathrm{I}_2s^2C_1C_2-\mathrm{I}_3sC_1G_2+\mathrm{I}_1G_1G_2}{s^2C_1C_2+sC_1G_2+G_1G_2}\,. \tag{6}$$

Depending on the current status of I$_1$, I$_2$, and I$_3$ in the numerator of equation (6), one of the following five filter functions is realized:

(i) LP: $\mathrm{I}_2=\mathrm{I}_3=0$, $\mathrm{I}_1=\mathrm{I}_{\mathrm{IN}}$;

(ii) BP: $\mathrm{I}_1=\mathrm{I}_2=0$, $\mathrm{I}_3=\mathrm{I}_{\mathrm{IN}}$;

(iii) HP: $\mathrm{I}_1=\mathrm{I}_3=0$, $\mathrm{I}_2=\mathrm{I}_{\mathrm{IN}}$;

(iv) BS: $\mathrm{I}_3=0$, $\mathrm{I}_1=\mathrm{I}_2=\mathrm{I}_{\mathrm{IN}}$;

(v) AP: $\mathrm{I}_1=\mathrm{I}_2=\mathrm{I}_3=\mathrm{I}_{\mathrm{IN}}$;

The resonance angular frequency ω_{03} and the quality factor Q_3 for above configuration are given by

$$\omega_{03}=\sqrt{\frac{G_1G_2}{C_1C_2}}\,, \tag{7a}$$

$$Q_3=\sqrt{\frac{G_1C_2}{G_2C_1}}\,. \tag{7b}$$

3. Non-ideal Analyses

The effects of FDCCII non idealities on the filter performances have been now considered in this section. By taking into consideration the non-ideal FDCCII, the relationship of the terminal voltages and currents given with (1) can be rewritten as:

$$\begin{bmatrix} V_{XA} \\ V_{XB} \\ I_{ZA+} \\ I_{ZA-} \\ I_{ZB+} \\ I_{ZB-} \end{bmatrix}=\begin{bmatrix} \beta_1 & -\beta_2 & \beta_3 & 0 & 0 & 0 \\ -\beta_1 & \beta_2 & 0 & \beta_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha_{ap} & 0 \\ 0 & 0 & 0 & 0 & -\alpha_{an} & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_{bp} \\ 0 & 0 & 0 & 0 & 0 & -\alpha_{bn} \end{bmatrix}\begin{bmatrix} V_{Y1} \\ V_{Y2} \\ V_{Y3} \\ V_{Y4} \\ I_{XA} \\ I_{XB} \end{bmatrix} \tag{8}$$

where α and β are current and voltage gains, respectively, and $\alpha = 1 - t_i$, $\beta = 1 - t_v$. Here, t_i is the current tracking error and t_v is the voltage tracking error, absolute values of all terms being much less than unit value. Taking into account non-idealities of FDCCII, the equations (2) of the filter in Fig. 2 are converted and given in Tab. 1.

The natural frequency $\omega`_{01}$ and the quality factor $Q`_1$ of the filter in Fig. 2 are given by

$$\omega_{01}^{'}=\frac{\sqrt{\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_1\beta_3+(\beta_2-\beta_3)\beta_4\right)G_1G_2}}{\sqrt{C_1C_2}}\,, \tag{9a}$$

$$Q_1^{'}=\frac{\sqrt{\alpha_{\text{an}}\alpha_{\text{bp}}\left(\beta_1\beta_3+(\beta_2-\beta_3)\beta_4\right)C_1C_2G_1G_2}}{\alpha_{\text{bp}}(\beta_1-\beta_4)C_2G_2+C_1\left(\alpha_{\text{an}}(\beta_3-\beta_2)G_1+\alpha_{\text{bn}}\beta_2G_2\right)}\,. \tag{9b}$$

Using (9a) and (9b), the active and passive sensitivities of $\omega`_{01}$ and $Q`_1$ are given by (10) and Tab. 2,

$$\begin{aligned} &S_{G_1}^{\omega_{01}^{'}}=S_{G_2}^{\omega_{01}^{'}}=-S_{C_1}^{\omega_{01}^{'}}=-S_{C_2}^{\omega_{01}^{'}}=S_{\alpha_{an}}^{\omega_{01}^{'}}=S_{\alpha_{bp}}^{\omega_{01}^{'}}=\frac{1}{2} \\ &S_{\alpha_{ap}}^{\omega_{01}^{'}}=S_{\alpha_{bn}}^{\omega_{01}^{'}}=0 \end{aligned} \tag{10}$$

According to Tab. 2, sensitivities related to components depend on current gain (α) and voltage gain (β). These terms are calculated with error ±5 % and minimum, maximum and mean values are found. It is clearly observed from (10) and Tab. 2 that active and passive sensitivities of $\omega`_{01}$ and $Q`_1$ are within acceptable limits. Taking into account non-idealities of FDCCII, the equations (4) and (6) of the filters in Fig. 3 are converted and given in Tab. 3.

The natural frequency $\omega`_{02}$ and the quality factor $Q`_2$ of the filter in Fig. 3a are given by

$$\omega_{02}^{'}=\frac{\sqrt{\alpha_{\text{an}}\alpha_{\text{bp}}\beta_4\left(\beta_1+\beta_3\right)G_1G_2}}{\sqrt{C_1C_2}}\,, \tag{11a}$$

$$Q_2^{'}=\frac{\sqrt{\alpha_{\text{an}}\beta_4\left(\beta_1+\beta_3\right)C_2G_1}}{\beta_1\sqrt{\alpha_{\text{bp}}C_1G_2}}\,. \tag{11b}$$

	$\omega_{01}^{'}$				$Q_1^{'}$				$Q_1^{'}$				$Q_1^{'}$		
	min	max	**mean**		min	max	**mean**		min	max	**Mean**		min	max	**mean**
β_1	0.40	0.56	**0.5**	G_1	0.38	0.63	**0.5**	α_{ap}	0	0	**0**	β_1	-0.82	-0.27	**-0.5**
β_2	0.45	0.56	**0.5**	G_2	-0.63	-0.38	**-0.5**	α_{an}	0.38	0.63	**0.5**	β_2	0.36	0.68	**0.5**
β_3	-0.06	0.05	**0**	C_1	-0.63	-0.395	**-0.5**	α_{bp}	0.395	0.63	**0.5**	β_3	-1.31	-0.77	**-1**
β_4	-0.06	0.05	**0**	C_2	0.395	0.63	**0.5**	α_{bn}	-1.27	-0.81	**-1**	β_4	0.71	1.45	**1.05**

Tab. 2. Sensitivities of active and passive component within ±%5 error for Fig. 2.

Fig.3a	$I_{out} = \dfrac{I_3 s^2 C_1 C_2 \alpha_{bn} - (I_1\beta_4 + I_2\alpha_{an}\beta_4) s C_2 G_2 \alpha_{bn} + I_4 \beta_1 s C_1 G_2 \alpha_{bn} + I_4 G_1 G_2 \alpha_{an}\alpha_{bn}\beta_4(\beta_1+\beta_3)}{s^2 C_1 C_2 + s C_1 G_2 \alpha_{bp}\beta_1 + G_1 G_2 \alpha_{an}\alpha_{bp}\beta_4(\beta_1+\beta_3)}$
Fig.3b	$I_{out} = \dfrac{I_2 s^2 C_1 C_2 \alpha_{bn} + s(I_1 C_2 G_2 \alpha_{bn}(\beta_1-\beta_4) + I_2 C_1 G_1 \alpha_{an}\alpha_{bn}(\beta_3-\beta_2) + I_3 C_1 G_2 \alpha_{bn}\beta_2) + I_1 G_1 G_2 \alpha_{an}\alpha_{bn}(\beta_1\beta_3 + (\beta_2-\beta_3)\beta_4)}{s^2 C_1 C_2 + s(C_1 G_2 \alpha_{bn}\beta_2 + C_1 G_1 \alpha_{an}(\beta_3-\beta_2) + C_2 G_2 \alpha_{bp}(\beta_1-\beta_4)) + G_1 G_2 \alpha_{an}\alpha_{bp}(\beta_1\beta_3 + (\beta_2-\beta_3)\beta_4)}$

Tab. 3. Non-ideal cases for the proposed MISO circuits.

Similarly, using (11a) and (11b), the resonance angular frequency $\omega`_{02}$ and the quality factor $Q`_2$ are determined by denominators of current transfer functions of MISO filter in Fig. 3a. Sensitivities of active and passive components of $\omega`_{02}$ and $Q`_2$ are given by (12) and Tab. 4,

$$S_{G_1}^{\omega_{02}^{'}} = S_{G_2}^{\omega_{02}^{'}} = -S_{C_1}^{\omega_{02}^{'}} = -S_{C_2}^{\omega_{02}^{'}} = S_{\alpha_{an}}^{\omega_{02}^{'}} = S_{\alpha_{bp}}^{\omega_{02}^{'}} = \frac{1}{2}$$
$$S_{\alpha_{ap}}^{\omega_{02}^{'}} = S_{\alpha_{bn}}^{\omega_{02}^{'}} = 0 \tag{12a}$$

$$S_{G_1}^{Q_2^{'}} = -S_{G_2}^{Q_2^{'}} = -S_{C_1}^{Q_2^{'}} = S_{C_2}^{Q_2^{'}} = S_{\alpha_{an}}^{Q_2^{'}} = -S_{\alpha_{bn}}^{Q_2^{'}} = \frac{1}{2}$$
$$S_{\alpha_{ap}}^{Q_2^{'}} = S_{\alpha_{bn}}^{Q_2^{'}} = S_{\beta_2}^{Q_2^{'}} = 0 \tag{12b}$$

Sensitivities of the proposed circuit in Fig. 3b are the same as the first proposed circuit in Fig. 2 due to the same denominators term. It is shown that active and passive sensitivities are within acceptable limits for all proposed configurations.

Using (9) and (11), natural frequencies and quality factors of the proposed filters are calculated with ±5 % error and minimum, maximum and mean values are found. In Tab. 5, it can be seen that the means of natural frequency and quality factor cannot change for the filter in Fig. 2 while these parameters change for the filter in Fig. 3b.

4. Simulation Results

To verify the validity of theoretical analysis, we simulated the circuits proposed in Fig. 2 and Fig. 3a using the LTSPICE circuit simulation program. We simulated the FDCCII using the schematic implementation taken in [38]. ZA- and ZB- terminals of the FDCCII were added and edited again according to original paper [38]. The supply voltages and biasing currents are given by V_{DD} =-V_{SS} = 1.3 V and $I_B = I_{SB}$ = 125 µA, respectively. The dimensions of the MOS transistor for the FDCCII implementation are given in Tab. 6. The MOS transistors are simulated using TSMC CMOS 0.35 µm process model parameters. Simulation results show that this choice yields parasitic impedances of R_{PZA+} = 9.5 GΩ, C_{PZA+} = 91 fF, R_{PXA} = 60 mΩ and L_{PXA} = 61 nH, parasitic parallel resistance and capacitance at ZA terminal and parasitic series resistance and inductance at XA terminal, respectively. The voltage clipping limits at terminal XA for the FDCCII are obtained as V_{XAmax} = 350 mV and V_{XAmin} = -310 mV. The lower and upper boundaries of the current I_{ZA+} for the FDCCII are determined as: I_{ZA+max} = 1.5 mA and I_{ZA+min} = 2 mA for the positive Z terminal. The f_{3dB} frequencies for the FDCCII are found as 280 MHz for V_{XA}/V_{Y1} and 220 MHz for I_{ZA+}/I_{XA}.

	$\omega_{02}^{'}$				$Q_2^{'}$		
	min	max	**Mean**		min	max	**mean**
β_1	0.24	0.26	**0.25**	β_1	-0.76	-0.74	**-0.75**
β_2	0	0	**0**	β_2	0	0	**0**
β_3	0.24	0.26	**0.25**	β_3	0.24	0.26	**0.25**
β_4	0.5	0.5	**0.5**	β_4	0.5	0.5	**0.5**

Tab. 4. Sensitivities of active and passive components within ±5 % error for Fig. 3a.

	min	max	mean
$\omega_{01}^{'}$	0.8975 ω_{01}	1,1025 ω_{01}	0,9994 ω_{01}
$Q_1^{'}$	0.803 Q_1	1.3383 Q_1	1.0038 Q_1
$\omega_{02}^{'}$	1.2763 ω_{02}	1.5592 ω_{02}	1.4143 ω_{02}
$Q_2^{'}$	1.2487 Q_2	1.6037 Q_2	1.4157 Q_2

Tab. 5. The changing of natural frequencies and quality factors within ±5 % error.

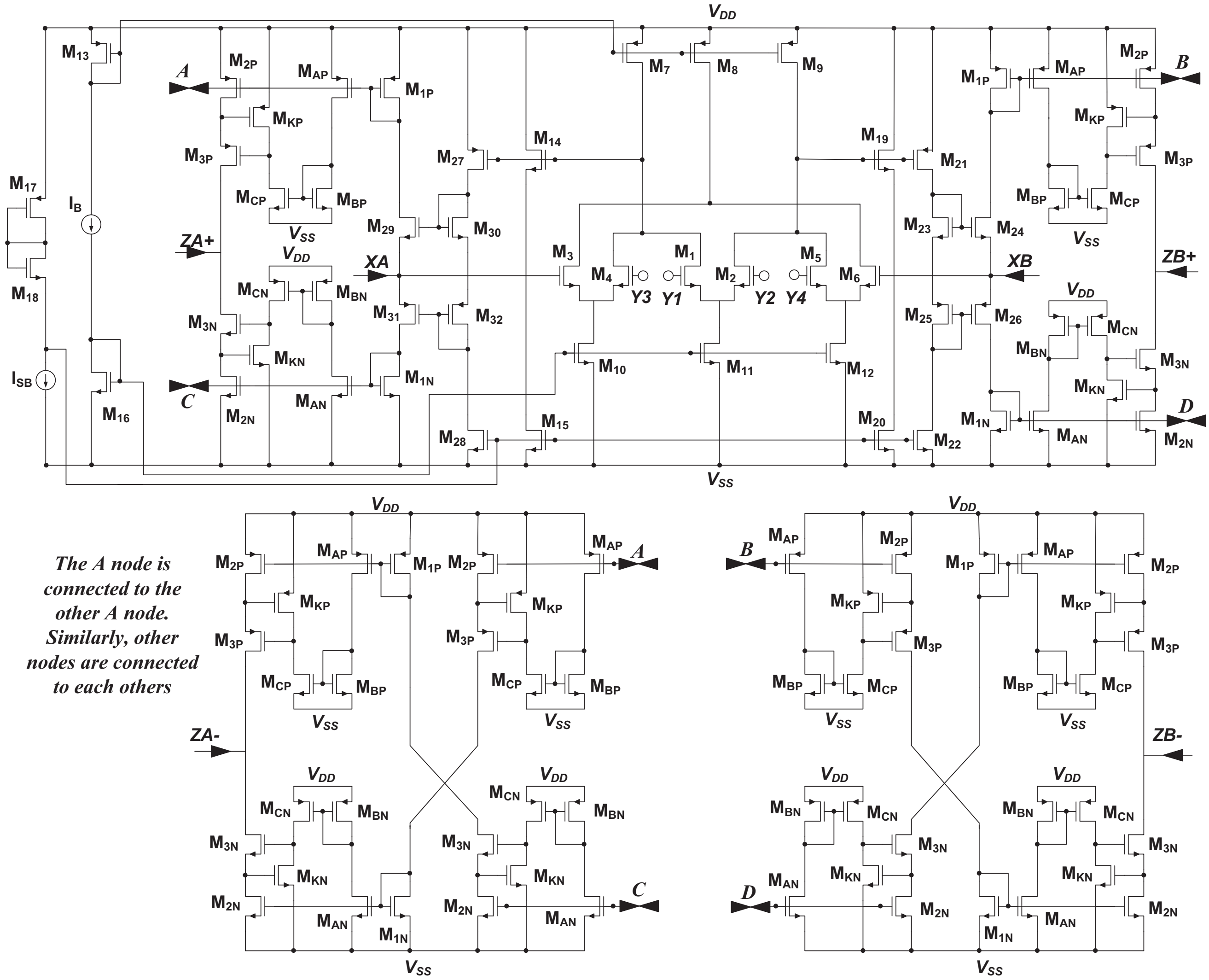


Fig. 4. CMOS FDCCII implementation.

Transistors	W(μm)	L(μm)
M_1-M_6	8.75	0.7
M_7-M_9, M_{13}, M_{17}, M_{21}, M_{27}, M_{1P}-M_{3P}	70	0.7
M_{10}-M_{12}, M_{16}, M_{18}, M_{1N}-M_{3N}	17.5	0.7
M_{14}, M_{15}, M_{19}, M_{20}	0.7	0.7
M_{22}, M_{28}, M_{AN}, M_{BN}, M_{CN}, M_{KN}	3.5	0.7
M_{23}-M_{24}, M_{29}-M_{30}	35	0.7
M_{25}-M_{26}, M_{31}-M_{32}	105	0.7
M_{AP}, M_{BP}, M_{CP}, M_{KP}	7	0.7

Tab. 6. Transistors aspect ratios for the FDCCII.

For this simulation the passive component values of Fig. 2 were chosen as, $R_1 = R_2 = 1$ kΩ and $C_1 = C_2 = 100$ pF, leading to a center frequency of $f_0 = 1.59$ MHz and quality factor of $Q = 1$. Fig. 5 shows the simulated results of low-pass, band-pass and high-pass gain-frequency responses. It is noted that the results of circuit simulations agree quite well with theory.

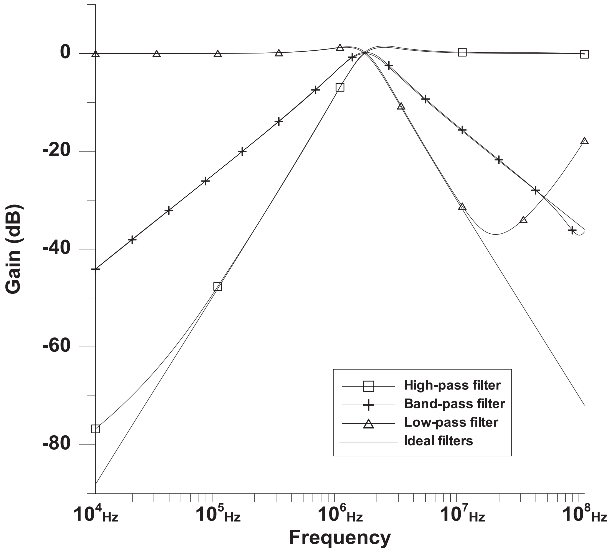


Fig. 5. Results of circuit simulations for basic filter responses of the proposed FDCCII-based CM SIFO biquad for $f_0 = 1.59$ MHz and $Q = 1$.

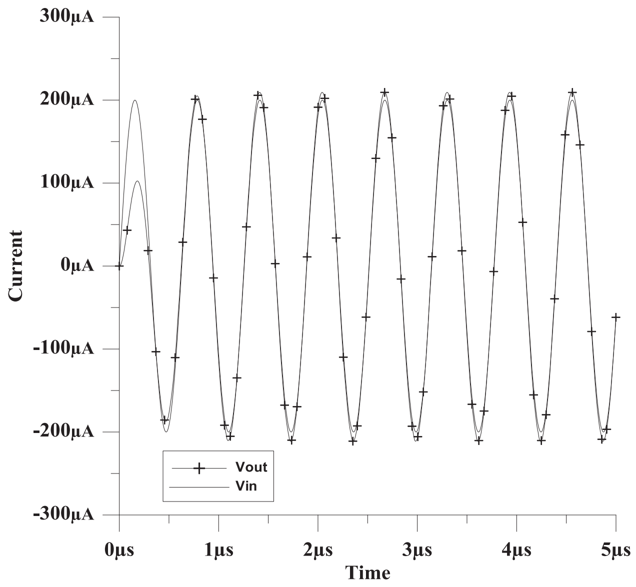


Fig. 6. Time domain response of band-pass filter configuration.

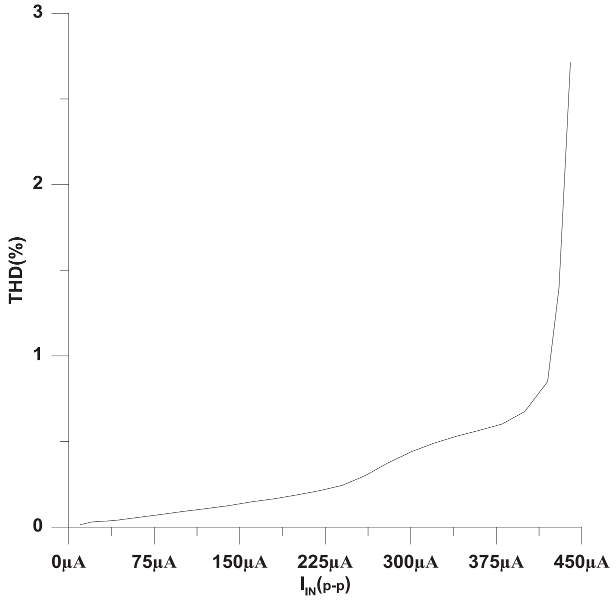


Fig. 7. Dependence of the output harmonic distortion of the band-pass filter on the input signal amplitude.

Time domain analysis result is given in Fig. 6 for 200 µA sine wave at 1.59 MHz input for band-pass filter. The large signal behavior of the circuit was tested by investigating the dependence of the output harmonic distortion of the band-pass response on the input signal amplitude. Fig. 7 shows that the harmonic distortion increases rapidly. Below 440 µA (p-p), the total harmonic distortion (THD) is in acceptable limits of the order of 3 %.

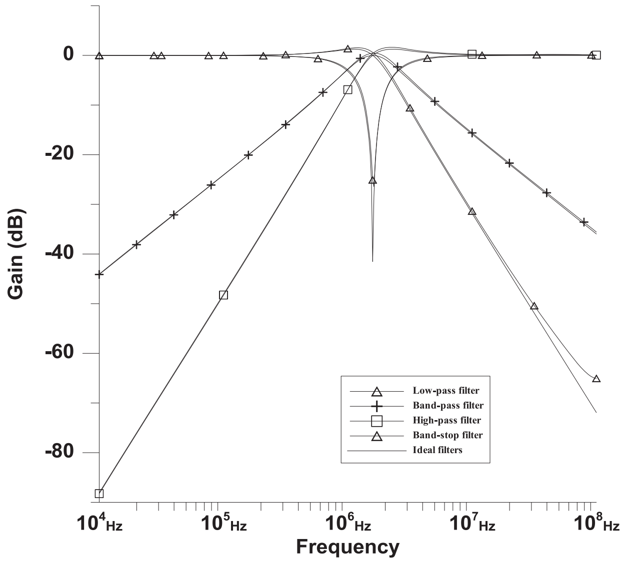


Fig. 8. The simulated results of the gain–frequency responses of Fig. 3a.

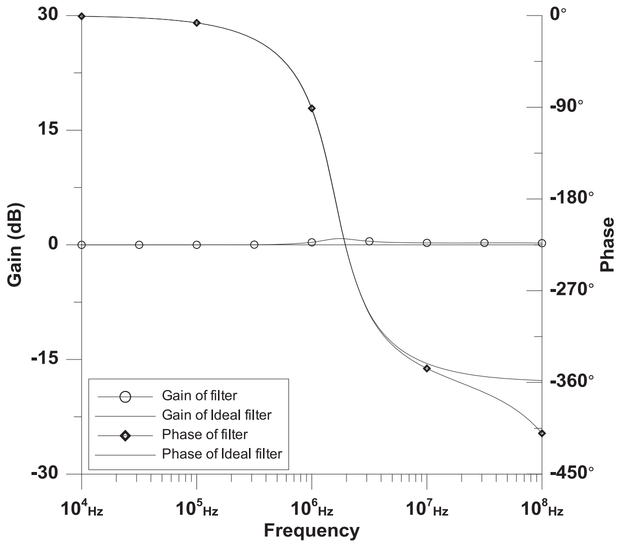


Fig. 9. All-pass gain and phase-frequency responses of Fig. 3a.

For this purpose, passive components were chosen as $C_1 = C_2 = 100$ pF and $R_1 = 2$ kΩ, $R_2 = 1$ kΩ which results in a center frequency of 1.59 MHz and quality factor of $Q = 1$. The simulated frequency responses for the low-pass, band-pass, high-pass and band-stop configurations are shown in Fig. 8. Gain and phase frequency responses of the all-pass filter are given in Fig. 9. The simulation results show that filter characteristics are in good agreement with the predicted theory. The THD result for the BP filter in Fig. 3a is given in Fig. 10, which clearly shows that for an input signal lower than 340 µA peak to peak, the THD remains in acceptable limits thus confirming the practical utility of the proposed circuit.

Time domain analysis result is given in Fig. 11 for peak-to-peak 300 µA, 1.59 MHz sine wave input for band-pass filter configuration for the circuit in Fig. 3a. We chose the quality factor $Q = 1$ to demonstrate that the circuit is even more suitable for realization of filters with Q values than standard Butterworth approximation.

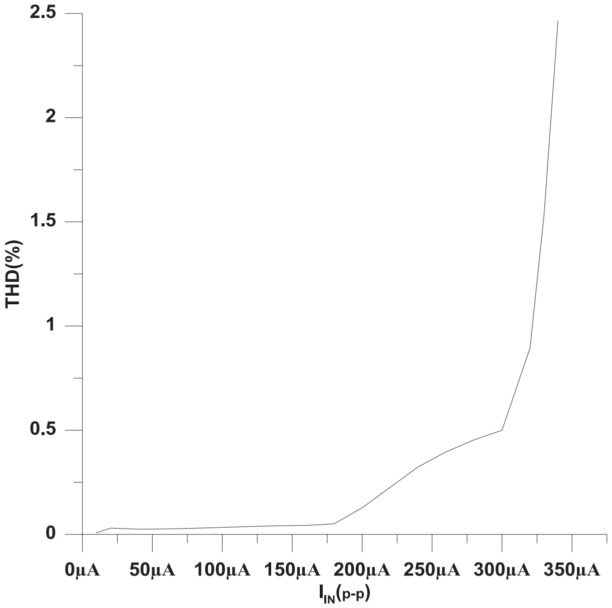


Fig. 10. Dependence of output current harmonic distortion on input current amplitude of the proposed band-pass filter.

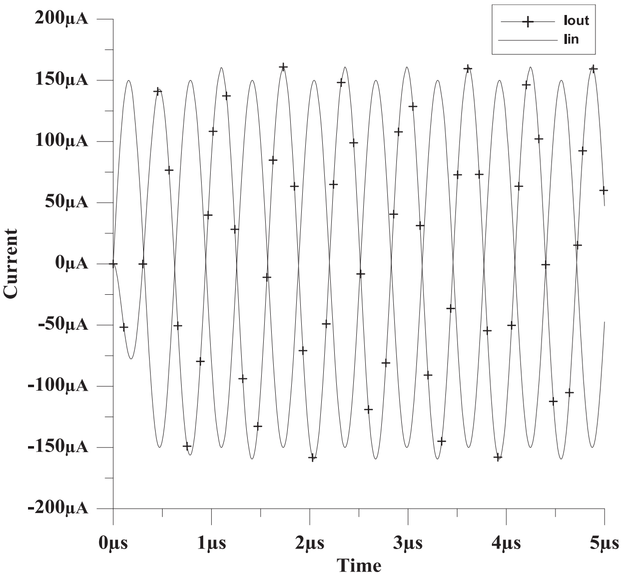


Fig. 11. Time domain response of circuit in Fig. 3a for 300 µA peak to peak 1.59 MHz sine wave input for band-pass filter configuration.

5. Conclusion

In this paper we proposed new single-input four-outputs (SIFO) current-mode multifunction filters using single FDCCII, two capacitors and two resistors. The circuit has the following advantages:

(i) It can simultaneously realize low-pass, band-pass and high-pass filter functions without changing the circuit topology and elements.

(ii) It uses minimum number of active and passive elements.

(iii) It has grounded resistors and grounded capacitors which can be easily fabricated for VLSI.

(iv) It does not require any parameter matching condition.

(v) It has low active and passive sensitivities.

Another type of proposed circuits are two new multi-inputs single-output (MISO) biquad filter circuits. The salient features of the proposed circuits can now be summarized as follows:

(i) They use only a single active component and minimum passive components (two resistors and two capacitors).

(ii) They employ all grounded passive components and are convenient for IC integration.

(iii) They provide current output explicitly from a high impedance output node so they enable easy cascadability.

(iv) They realize the five standard filtering functions.

(v) They don't use inverting input current terminal for realizing the five standard filters.

LTSPICE simulation results have been presented which confirm the workability of these circuits. The proposed CM biquad filters with these properties will be useful in many areas for example analog communication systems and in analog signal processing.

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