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An Approach to CFOA-based Second-Order Universal Filters

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***Abstract*—In this work, two universal current-mode (CM) filters are proposed. These filters are single-input three-output filter and three-input single-output filter. The proposed single-input CM filter simultaneously provides low-pass filter (LPF), high-pass filter (HPF), and band-pass filter (BPF) responses without requiring passive component matching. The LPF and BPF provide gains. Additionally, a notch filter (NF) response can be obtained by subtracting the output current of the LPF from the output current of the HPF, while an all-pass filter (APF) response can be achieved by subtracting the output current of the BPF from the output current of the NF. The proposed three-input CM filter generates LPF, HPF, BPF, NF, and APF responses at its output when the inputs are appropriately selected. The BPF response of the three-input CM filter has a gain. However, HPF, NF, and APF responses require a passive component matching condition. Both proposed circuits contain two grounded capacitors, which makes them suitable for integrated circuit technology and exhibit low active and passive sensitivities. The performance of the proposed filters is verified through SPICE simulations using 0.18 µm Taiwan Semiconductor Manufacturing Company (TSMC) complementary metal-oxide-semiconductor (CMOS) technology parameters. Additionally, experimental validation is performed using AD844s to demonstrate their practical performance.**

***Index Terms*—CFOA; Universal filter; Second-order; Current-mode.**

I. INTRODUCTION

In the literature, current-feedback operational amplifiers (CFOAs) [1]–[11] have been found to have wide applications. Many current-mode (CM) analogue filter circuits have been designed using CFOA(s) [2]–[11]. The CFOA-based second-order CM filters in [2]–[11] have some disadvantages, as discussed below.

– Contain more than two CFOAs [2], [6], [9]–[11];
– Include more than three resistors [2], [3], [9]–[11];
– Comprise floating capacitor(s) [2], [4], [5], [7], which are not preferred in integrated circuit (IC) technology;
– Have complex responses [3]–[5];
– Not universal [3], [7], [8];
– Include inverting CFOA [9];
– Use the switch [10].

CFOAs can be implemented with commercially available active components, such as AD844s [12]. Second-generation current conveyor (CCII) and second-generation current controlled current conveyor (CCCII)-based CM universal filters have been developed in [13]–[25]. Single Z terminal CCII can be divided into two categories, plus-type one (CCII+) and minus-type one (CCII-). CCII+ can be easily realised with one AD844, while the CCII- can be easily implemented with two AD844s. Furthermore, CCCII-based circuits can be designed with CCIIs and extra resistors. The number of the AD844s required to implement the filters in [13]–[16], [18]–[25] is more than two. Filters in [13], [19], [20], [22]–[25] contain floating capacitor(s). The filters in [14], [16], [21], [25] include more than two capacitors.

A capacitor connected in series to the X terminal of the CFOA/CCII/CCCII limits the upper frequency responses [16]. However, as the authors stated in [26]–[28], CM circuits offer several potential advantages over their voltage mode counterparts, such as a wider bandwidth, higher dynamic range, and better linearity.

This work proposes two novel CM universal filters: a single-input three-output filter and a three-input single-output filter. The single-input CM filter is capable of simultaneously providing low-pass filter (LPF), high-pass filter (HPF), and band-pass filter (BPF) responses without the need for passive component matching, with both LPF and BPF offering tunable gain. A notch filter (NF) current can be obtained by subtracting the output current of the LPF from the output current of the HPF. Similarly, an all-pass filter (APF) current can be achieved by subtracting the output current of the BPF from the output current of the NF. The three-input CM filter generates LPF, HPF, BPF, NF, and APF responses at its output when the inputs are properly selected. Additionally, the BPF response exhibits gain. However, to obtain HPF, NF, and APF responses from this configuration, passive component matching is required. Both proposed circuits incorporate two grounded capacitors, making them well-suited for IC technology, while exhibiting low sensitivity.

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The paper is organised as follows. Section II presents the proposed CM filters, including its mathematical formulations, sensitivity analysis, and nonideal conditions. Section III explores the impact of parasitic impedances. Section IV provides simulation results for the CM filters using the SPICE programme with 0.18 µm Taiwan Semiconductor Manufacturing Company (TSMC) complementary metal-oxide-semiconductor (CMOS) technology parameters [29]. Section V presents experimental results that validate the mathematical predictions of the first proposed CM filter. Finally, Section VI concludes the paper with a summary of the findings.

II. PROPOSED FILTERS

CFOA is ideally defined as $I_Y = 0$, $I_Z = I_X$, $V_X = V_Y$, and $V_W = V_Z$. The matrix equation of the CFOA given below is illustrated as an active block structure in Fig. 1

$$\begin{bmatrix} I_Y \\ I_Z \\ V_X \\ V_W \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \eta \end{bmatrix} \begin{bmatrix} I_X \\ V_Y \\ V_Z \end{bmatrix}. \quad (1)$$

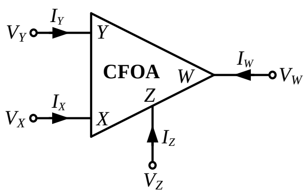

Fig. 1. Active block structure of the CFOA.

The parameters α, β, and η in (1) are nonideal gains. In the ideal case, all these gains are equal to one. The second-order CM universal filter proposed in Fig. 2 provides the following LPF, HPF, and BPF transfer functions (TFs) for the ideal case, respectively:

$$\frac{I_{LPF}}{I_{in}} = -\frac{R_1}{R_3}\frac{1}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}, \quad (2)$$

$$\frac{I_{HPF}}{I_{in}} = \frac{s^2C_1C_2R_1R_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}, \quad (3)$$

$$\frac{I_{BPF}}{I_{in}} = \frac{R_1}{R_2}\frac{sC_2R_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}. \quad (4)$$

For the CM filter in Fig. 2, to obtain high output impedance LPF and HPF currents, extra two current followers (CFs) are needed. Also, a CF can be easily obtained from the CFOA by grounding the Y terminal of the CFOA. In the circuit shown in Fig. 2, the following equations are used to obtain the NF response with $R_1 = R_3$ and the APF response with $R_1 = R_2 = R_3$, respectively:

$$I_{NF} = I_{HPF} - I_{LPF}, \quad (5)$$

$$I_{APF} = I_{HPF} - I_{LPF} - I_{BPF}. \quad (6)$$

Here, CFs should be employed to realise the functions described in (5) and (6). As can be understood from the equations above, the LPF and BPF responses have gains of R_1/R_3 and R_1/R_2, respectively. By accounting for the nonideal gains, the LPF, HPF, and BPF TFs are, respectively, derived as follows:

$$\frac{I_{LPF}}{I_{in}} = -\frac{R_1}{R_3}\frac{\alpha_2\beta_1\eta_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}, \quad (7)$$

$$\frac{I_{HPF}}{I_{in}} = \frac{s^2C_1C_2R_1R_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}, \quad (8)$$

$$\frac{I_{BPF}}{I_{in}} = \frac{R_1}{R_2}\frac{sC_2R_2\alpha_1\beta_1}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}. \quad (9)$$

The resonance frequency (f_0) and quality factor (Q) can be derived from (7)–(9) as follows:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\alpha_2\beta_1\eta_2}{C_1C_2R_1R_2}}, \quad (10)$$

$$Q = \sqrt{\frac{\alpha_2\beta_1\eta_2C_2R_2}{C_1R_1}}. \quad (11)$$

With the help of the above equations, Q of the LPF, BPF, and HPF currents can be changed without disturbing f_0 by adjusting R_2/R_1, while keeping $R_1 \times R_2$ constant. In addition to this, the active and passive sensitivities for f_0 and Q are assessed as:

$$S_{\alpha_2}^{f_0} = S_{\beta_1}^{f_0} = S_{\eta_2}^{f_0} = -S_{C_1}^{f_0} = -S_{C_2}^{f_0} = -S_{R_1}^{f_0} = -S_{R_2}^{f_0} = \frac{1}{2}, \quad (12)$$

$$S_{\alpha_2}^{Q} = S_{\beta_1}^{Q} = S_{\eta_2}^{Q} = S_{C_2}^{Q} = S_{R_2}^{Q} = -S_{C_1}^{Q} = -S_{R_1}^{Q} = \frac{1}{2}. \quad (13)$$

It is evident from the preceding analysis that all sensitivities have a magnitude of one-half.

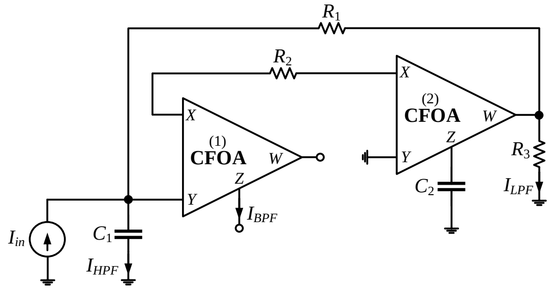

Fig. 2. The first proposed second-order CM universal filter with one input and three outputs.

The second-order CM universal filter proposed in Fig. 3 provides the following output current for the ideal case

$$I_{out} = -\frac{s^2C_1C_2R_1R_2I_{in3} + sC_2R_2I_{in3} - sC_2R_1I_{in1} - I_{in2} + I_{in3}}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}. \quad (14)$$

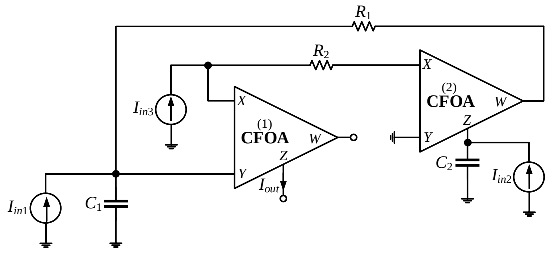

Fig. 3. The second proposed second-order CM universal filter with three inputs and one output.

The responses of LPF, HPF, BPF, APF, and NF are determined based on the selection of the inputs in (14) and a passive element matching condition for some responses. These responses are given in Table I. Also, the filter illustrated in Fig. 3 has a high output impedance; thus, it can easily cascade with other ones.

From Table I, it is evident that the BPF response of the circuit in Fig. 3 exhibits a gain.

TABLE I. THE FILTER RESPONSES PROVIDED BY THE CIRCUIT IN FIG. 3 FOR THE IDEAL CASE.

Input Selections	Filter Type	Transfer Function (ideal)
$I_{in2} = I_{in}$ $I_{in1} = I_{in3} = 0$	LPF	$\frac{I_{out}}{I_{in}} = \frac{1}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}$
$I_{in1} = I_{in2} = I_{in3} = I_{in}$ $R_1 = R_2$	HPF	$\frac{I_{out}}{I_{in}} = -\frac{s^2C_1C_2R_1R_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}$
$I_{in1} = I_{in}$ $I_{in2} = I_{in3} = 0$	BPF	$\frac{I_{out}}{I_{in}} = \frac{R_1}{R_2}\frac{sC_2R_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}$
$I_{in1} = I_{in3} = I_{in}$ $I_{in2} = 0$ $R_1 = 2R_2$	APF	$\frac{I_{out}}{I_{in}} = -\frac{s^2C_1C_2R_1R_2 - sC_2R_2 + 1}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}$
$I_{in1} = I_{in3} = I_{in}$ $I_{in2} = 0$ $R_1 = R_2$	NF	$\frac{I_{out}}{I_{in}} = -\frac{s^2C_1C_2R_1R_2 + 1}{s^2C_1C_2R_1R_2 + sC_2R_2 + 1}$

TABLE II. THE FILTER RESPONSES PROVIDED BY THE CIRCUIT IN FIG. 3 FOR THE NONIDEAL CASE.

Input Selections	Filter Type	Transfer Function (nonideal)
$I_{in2} = I_{in}$ $I_{in1} = I_{in3} = 0$	LPF	$\frac{I_{out}}{I_{in}} = \frac{\alpha_1\beta_1\eta_2}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}$
$I_{in1} = I_{in2} = I_{in3} = I_{in}$ $R_1 = R_2$	HPF	$\frac{I_{out}}{I_{in}} = -\frac{s^2C_1C_2R_1R_2\alpha_1}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}$
$I_{in1} = I_{in}$ $I_{in2} = I_{in3} = 0$	BPF	$\frac{I_{out}}{I_{in}} = \frac{R_1}{R_2}\frac{sC_2R_2\alpha_1\beta_1}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}$
$I_{in1} = I_{in3} = I_{in}$ $I_{in2} = 0$ $R_1 = 2R_2$	APF	$\frac{I_{out}}{I_{in}} = -\frac{\alpha_1\left(s^2C_1C_2R_1R_2 + sC_2R_2\left(1-2\beta_1\right) + \alpha_2\beta_1\eta_2\right)}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}$
$I_{in1} = I_{in3} = I_{in}$ $I_{in2} = 0$ $R_1 = R_2$	NF	$\frac{I_{out}}{I_{in}} = -\frac{\alpha_1\left(s^2C_1C_2R_1R_2 + sC_2R_2\left(1-\beta_1\right) + \alpha_2\beta_1\eta_2\right)}{s^2C_1C_2R_1R_2 + sC_2R_2 + \alpha_2\beta_1\eta_2}$

However, the HPF, APF, and NF responses obtained from the circuit in Fig. 3 require a passive element matching condition. The second-order CM universal filter proposed in Fig. 3 yields the following output current for the nonideal case

$$I_{out} = -\frac{\alpha_1\left(s^2aI_{in3} + sbI_{in3} - sd\beta_1I_{in1} - \beta_1\eta_2I_{in2} + eI_{in3}\right)}{s^2a + sb + e}. \quad (15)$$

Here, a, b, d, and e are defined as:

$$a = C_1C_2R_1R_2, \quad (16)$$

$$b = C_2R_2, \quad (17)$$

$$d = C_2R_1, \quad (18)$$

$$e = \alpha_2\beta_1\eta_2. \quad (19)$$

The filter responses of the circuit in Fig. 3 for the nonideal case are shown in Table II. The f_0 and Q of the filters in Table II are the same as those given in (10) and (11), respectively. Therefore, the active and passive sensitivities of f_0 and Q are identical to those of the circuit in Fig. 2.

III. Parasitic Impedance Effects

As an example, in this section, parasitic impedance effects on the performance of the filter in Fig. 2 are given. Figure 4 illustrates the parasitic impedances of CFOA. These parasitic impedances are expressed by

$$\begin{bmatrix} I_Y \\ I_Z \\ V_X \\ V_W \end{bmatrix} = \begin{bmatrix} 0 & sC_Y & 0 & 0 \\ 1 & 0 & sC_Z + 1/R_Z & 0 \\ R_X & 1 & 0 & 0 \\ 0 & 0 & 1 & R_W \end{bmatrix} \begin{bmatrix} I_X \\ V_Y \\ V_Z \\ I_W \end{bmatrix}. \quad (20)$$

If R_3 in Fig. 2 is removed and only the parasitic impedances are considered, the proposed second-order CM universal filter depicted in Fig. 2 yields the following BPF transfer function

$$\frac{I_{BPF}}{I_{in}} = \frac{R_1 + R_{W2}}{R_2 + R_{X1} + R_{X2}} \frac{s\left(C_2 + C_{Z2}\right) + \frac{1}{R_{Z2}}}{f + g + 1}. \quad (21)$$

Here, the terms f and g are, respectively, defined as:

$$f = s\left(C_1 + C_{Y1}\right)h(R_1 + R_{W2})(R_2 + R_{X1} + R_{X2}), \quad (22)$$

$$g = \left(s\left(C_2 + C_{Z2}\right) + \frac{1}{R_{Z2}}\right)R_2, \quad (23)$$

where h is found as

$$h = s\left(C_2 + C_{Z2}\right) + \frac{1}{R_{Z2}}. \tag{24}$$

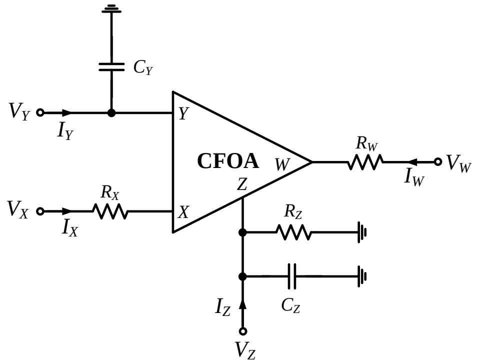

Fig. 4. CFOA with its parasitic impedances.

From (21)–(23), it is evident that to minimise the effects of the parasitic impedances, the following conditions must be met: $R_1 \gg R_{W2}$, $R_2 \gg R_{X1} + R_{X2}$, $R_{Z2} \rightarrow \infty$, $C_{Y1} \rightarrow 0$, and $C_{Z2} \rightarrow 0$. Further, the following constraint occurs [16]

$$\omega\left(C_2 + C_{Z2}\right) >> \frac{1}{R_{Z2}}. \tag{25}$$

From (25), the following frequency range is obtained [30]

$$f \geq \frac{10}{2\pi} \frac{1}{\left(C_2 + C_{Z2}\right) R_{Z2}}. \tag{26}$$

IV. SIMULATIONS

Figure 5 illustrates the internal structure based on CFOA, obtained by modifying the self-biased CMOS CCII circuit reported in [31] using cascode current mirrors to enhance the Z-terminal output resistance. This structure is used in all simulations using 0.18 µm CMOS technology parameters, with supply voltages set to ±1.4 V. The dimensions of the NMOS and PMOS transistors are listed in Table III. Notably, the structure features self-biasing; that is, it does not require any externally generated bias voltages, as the MOS transistors are internally self-biased. The parasitic impedances and nonideal DC gains of the structure, extracted using SPICE simulations, are also provided in Table IV. Furthermore, Fig. 6 presents a graphical representation of β, η, and α.

Simulations of the CM filter demonstrated in Fig. 2 are performed using the passive components set to $C_1 = C_2 = 25$ pF and $R_1 = R_2 = R_3 = 1$ kΩ. Under these conditions, the ideal resonance frequency is approximately $f_0 \cong 6.366$ MHz with a quality factor $Q = 1$. Figure 7 illustrates the AC simulation results for the LPF, HPF, and BPF, while Fig. 8 shows the AC temperature simulation results for the same filters. Figure 9 shows the AC results for LPF, HPF, and BPF under varying DC supply voltages. Figure 10 displays the results of the AC Monte Carlo (MC) simulation, which accounts for a 10 % uniform variation in the values of resistors and capacitors across 100 samples. For the simulation in the time domain, a 50 µA peak-to-peak sinusoidal current is applied to the input of the circuit in Fig. 2. The test frequencies are 2 MHz, 15 MHz, and f_0 for the LPF, HPF, and BPF, respectively. The total harmonic distortion (THD) values obtained for these filters are 0.447 %, 0.059 %, and 0.129 %, respectively. The results of these simulations are given in Figs. 11–13.

Several simulations are performed for the circuit shown in Fig. 3. In these simulations, the resistors are selected as 1 kΩ and the capacitors as 25 pF for the LPF, HPF, BPF, and NF responses. Consequently, the f_0 of this circuit remains the same as that of the circuit in Fig. 2. For the APF in Fig. 3, R_1 is selected as 2 kΩ to ensure proper matching, leading to f_0 of 4.5 MHz. The results of the AC simulation for the LPF, HPF, and BPF responses of the circuit in Fig. 3 are given in Fig. 14, while the NF and APF responses are shown in Figs. 15 and 16, respectively. The THD variations for the LPF, HPF, BPF, and APF responses in Fig. 3 are calculated at 2 MHz, 15 MHz, 6.37 MHz, and 4.5 MHz, respectively. A graph illustrating these variations with a 1 kΩ resistor connected to the output is presented in Fig. 17. Both filters consume 3.36 mW power. In addition, Table V presents a comparison among the proposed filters and previously published CFOA-based filters.

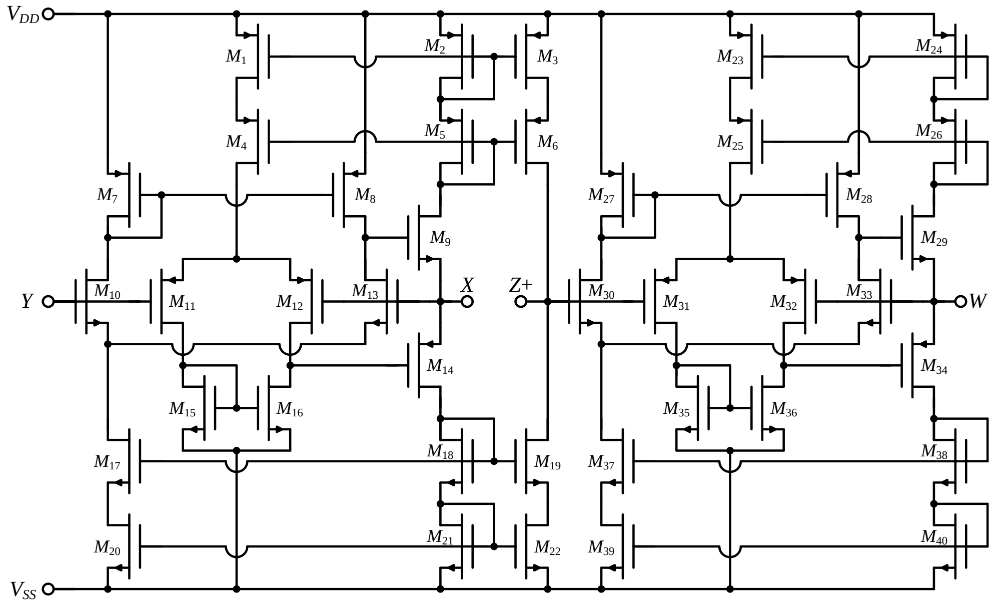

Fig. 5. MOS transistor-based realisation of the CFOA.

TABLE III. THE DIMENSIONS OF THE NMOS AND PMOS TRANSISTORS.

MOS Transistors		**Aspect Ratios (*W*/*L*)**
PMOS Transistors	M_1-M_6, M_{11} M_{12}, M_{23}-M_{26} M_{31}, M_{32}	30 μm/0.36 μm
	M_7, M_8, M_{27}, M_{28}	6 μm/0.36 μm
	M_{14}, M_{34}	20 μm/0.36 μm
NMOS Transistors	M_9, M_{29}	10 μm/0.36 μm
	M_{10}, M_{13} M_{17}-M_{22}, M_{30} M_{33}, M_{37}-M_{40}	15 μm/0.36 μm
	M_{15}, M_{16} M_{35}, M_{36}	2 μm/0.36 μm

TABLE IV. THE PARASITIC IMPEDANCES AND NONIDEAL GAINS.

Parasitic Impedances	**Nonideal Gains**
$R_X \cong 1\ \Omega$	$\alpha \cong 1$
$R_Z \cong 2.62\ \text{M}\Omega$	$f_\alpha \cong 280$ MHz
$R_W \cong 1\ \Omega$	$\beta \cong 0.978$
$C_Y \cong 35$ fF	$f_\beta \cong 1.56$ GHz
$C_Z \cong 99$ fF	$\eta \cong 0.978$ $f_\eta \cong 1.47$ GHz

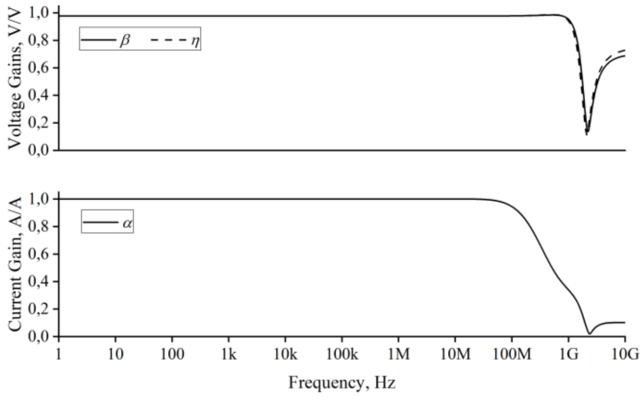

Fig. 6. The nonideal gains versus frequency.

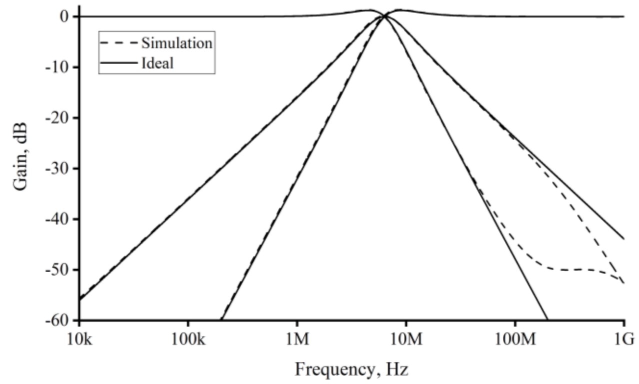

Fig. 7. AC responses for LPF, HPF, and BPF in Fig. 2.

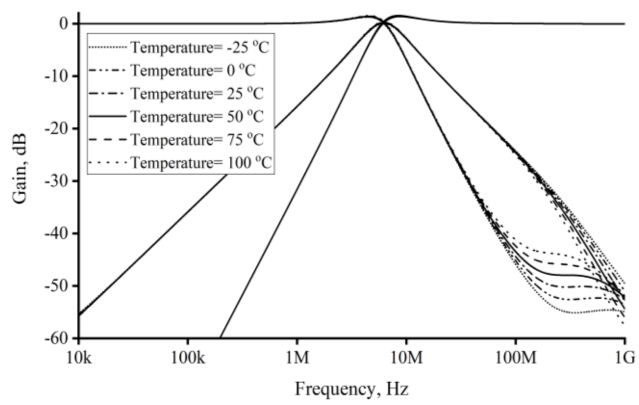

Fig. 8. AC temperature results for the CM filter in Fig. 2.

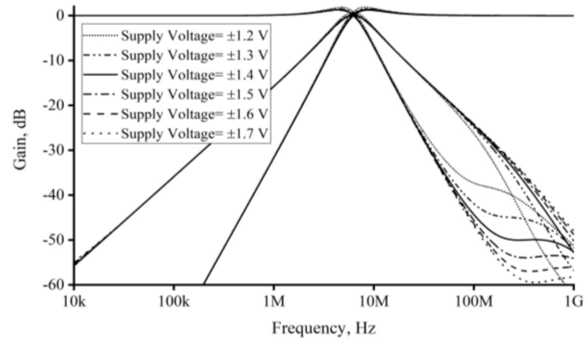

Fig. 9. Supply voltage simulation results for LPF, HPF, and BPF in Fig. 2.

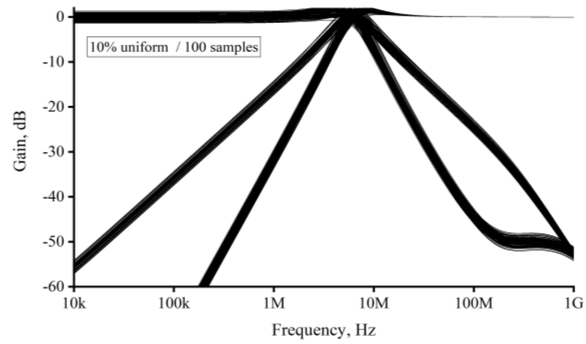

Fig. 10. MC simulation results for the LPF, HPF, and BPF in Fig. 2.

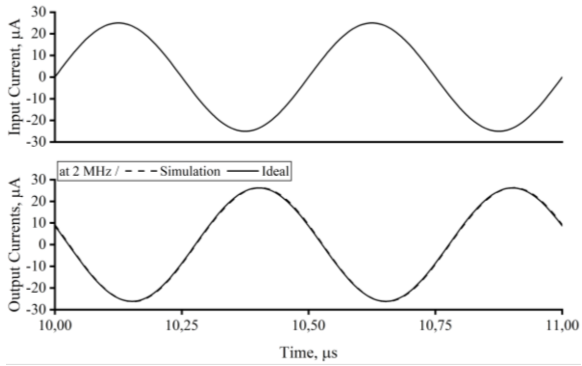

Fig. 11. Results of the transient simulation for the LPF in Fig. 2 at $f = 2$ MHz.

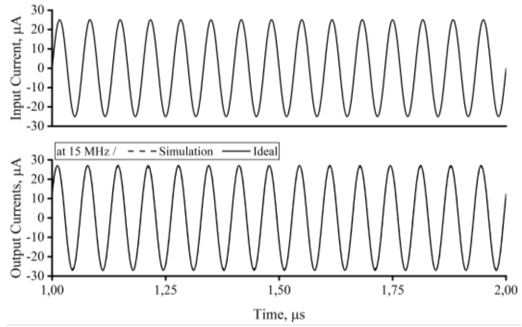

Fig. 12. Results of the transient simulation for the HPF in Fig. 2 at f = 15 MHz.

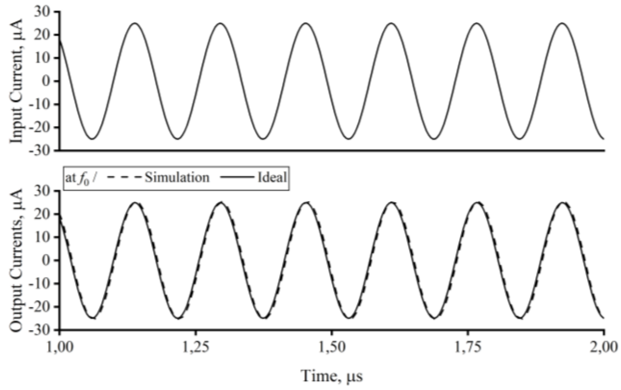

Fig. 13. Results of the transient simulation for the BPF in Fig. 2 at $f = f_0$.

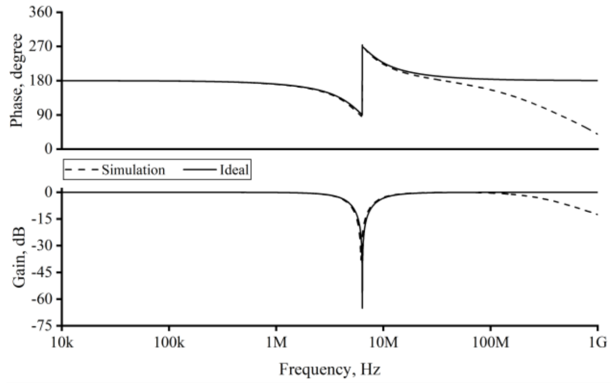

Fig. 15. AC responses for the NF in Fig. 3.

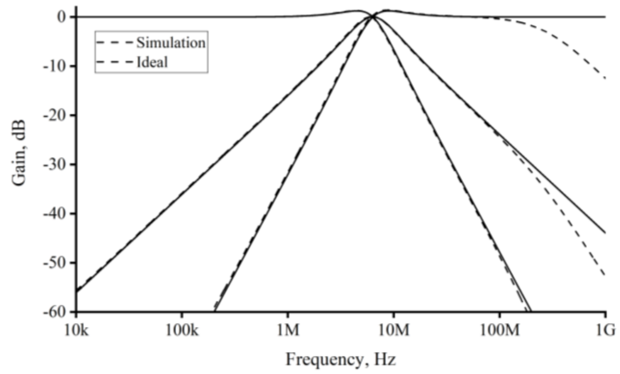

Fig. 14. AC responses for LPF, HPF, and BPF in Fig. 3.

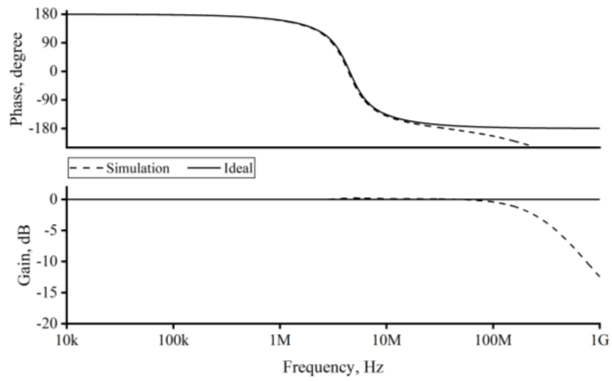

Fig. 16. AC responses for APF in Fig. 3.

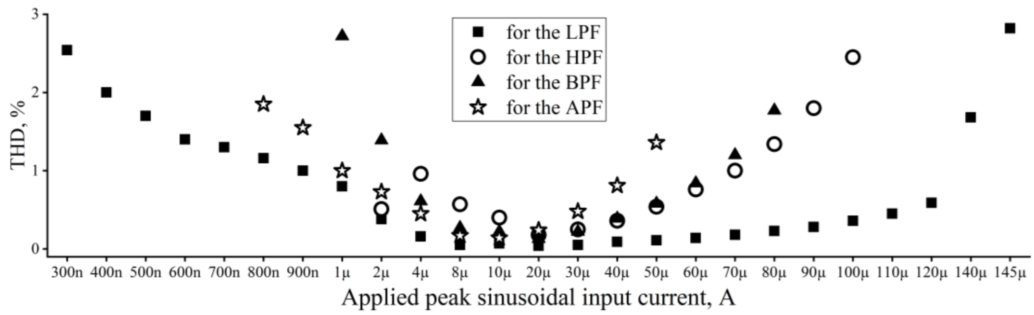

Fig. 17. THD values for LPF, HPF, BPF, and APF in Fig. 3.

TABLE V. A COMPARISON OF THE PROPOSED FILTERS WITH SIMILAR ONES IN THE LITERATURE.

References (Figure)	**# of CFOA**	**Use inverting CFOA**	**Comprise floating capacitor(s)**	**Include more than three resistors**	**Universality**	**Include switch**	**Have complex responses**	***X* terminal capacitor**	**Technology**	**Supply voltages (V)**	**Power dissipation (mW)**
[2] (Fig. 7)	6	No	Yes	Yes	Yes	No	No	No	AD844	NA	NA
[3] (Fig. 1)	1	No	No	Yes	Yes	No	Yes	No	AD844	24	NA
[4] (Fig. 1)	1	No	Yes	No	Yes	No	Yes	No	AD844	24	NA
[5] (Fig. 1)	1	No	No	No	Yes	No	Yes	No	AD844	24	NA
[6] (Fig. 5)	3	No	Yes	No	Yes	No	No	Yes	AD844	NA	NA
[7] (Fig. 7)	2	No	Yes	No	No	No	No	No	0.13 µm	1.8	1.96
[8] (Fig. 1)	1	No	No	No	No	No	No	No	AD844	NA	NA
[9] (Fig. 2a)	3	Yes	No	Yes	Yes	No	No	No	AD844	NA	NA
[10] (Fig. 1)	4	No	No	Yes	Yes	Yes	No	No	AD844	24	NA
[11] (Fig. 5)	3	No	No	Yes	Yes	No	No	Yes	AD844	NA	NA
This work (Fig. 2)	2	No	Yes*	No	Yes	No	No	Yes*	0.18 µm	2.8	3.36
This work (Fig. 3)	2	No	No	No	Yes	No	No	No	0.18 µm	2.8	3.36

*Note: * - It is valid if high output impedance HPF/NF/APF responses are required. Otherwise, the answer is No. NA: not available.*

V. EXPERIMENTAL WORKS

As an example, frequency-domain and time-domain experiments of the BPF shown in Fig. 2 are carried out in which commercially available active devices such as AD844s [12] are utilised. The experimental circuit with AD844s and passive elements is shown in Fig. 18. In the experiments conducted for the BPF, all resistors are set to 4.7 kΩ and all capacitors to 220 pF, resulting in an ideal resonance frequency of $f_0 \cong 153.9$ kHz. The supply voltages for AD844s are chosen to be ±7.5 V. The results of the AC experiment for the BPF are shown in Fig. 19, while the experimental results in the time domain, obtained by applying a sinusoidal input current of 1 V peak-to-peak current at f_0, are shown in Fig. 20.

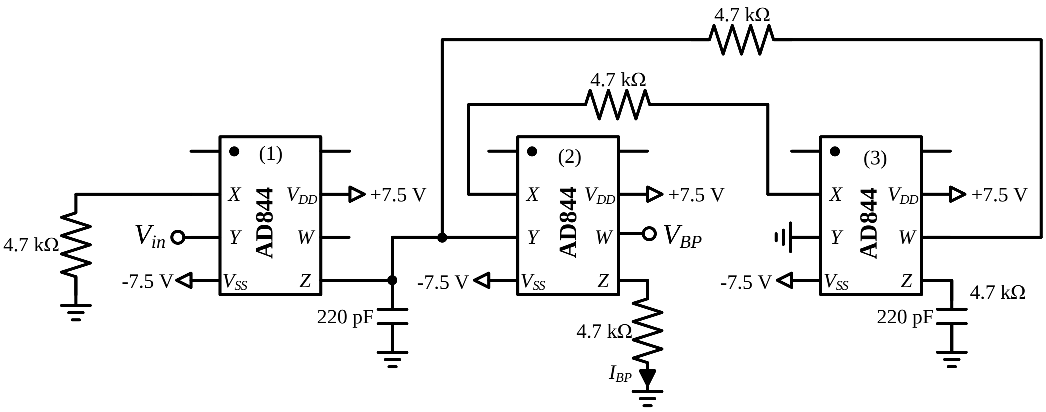

Fig. 18. The experimental circuit for the BPF in Fig. 2.

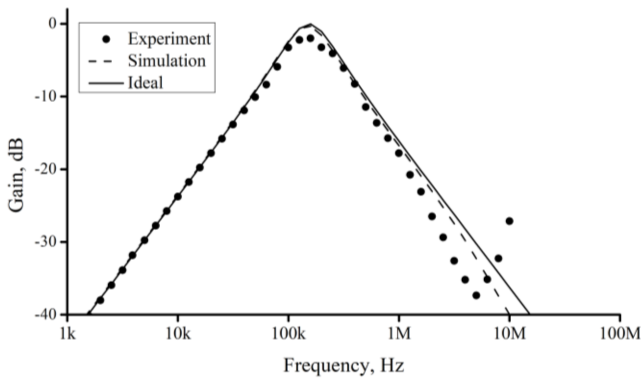

Fig. 19. AC experimental results for the BPF in Fig. 2.

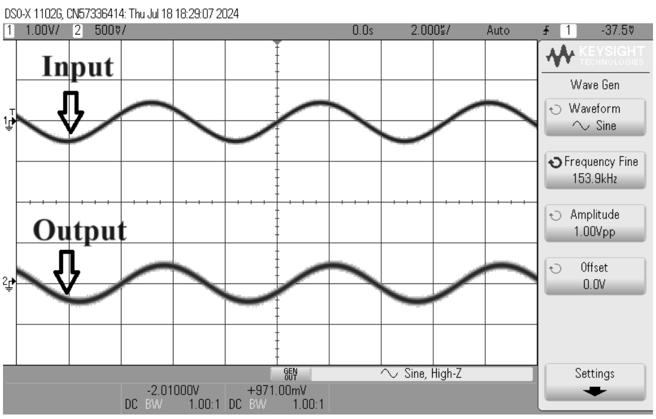

Fig. 20. Experimental results in the time domain for the BPF in Fig. 2.

VI. CONCLUSIONS

This work proposes two universal CM filter circuits that offer flexibility in generating universal filter responses, including LPF, HPF, BPF, NF, and APF responses. The proposed single-input CM filter simultaneously delivers LPF, HPF, and BPF responses without the need of passive component matching, with tunable gain for both the LPF and BPF responses. By combining output currents in specific configurations, NF and APF responses can also be obtained, but passive element matching conditions and extra CFOAs are needed to obtain high output impedance responses. The three-input CM filter generates all five filter responses if the inputs are appropriately selected. However, passive component matching is required for the second proposed filter to achieve HPF, NF, and APF responses. The second filter circuit is designed with two grounded capacitors, making them suitable for IC technology, while maintaining low active and passive sensitivities. Negligibly small differences are observed among the ideal, simulation, and experimental results of the proposed circuits. Both filters are expected to be beneficial in applications such as telecommunications, radio frequency systems, biomedical devices, audio processing, industrial control systems, radar and satellite communication, high-speed data transmission, etc. due to their versatility, gain, and low sensitivity.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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