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Minimum Component Truly Mixed Mode First Order Universal Filter Employing EXCCTA

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Abstract: A mixed mode first order universal filter (FO-UF) has been proposed in this study. One Extra X Current Conveyor Transconductance Amplifier (EXCCTA), one capacitor and two resistors are used to design the filter. The main attributes of the filter include (i) electronic tunability (ii) ability to work in all four modes of operation (iii) cascadability (iv) availability of low pass (LP), high pass (HP) and all pass (AP) responses simultaneously. By incorporating the filter to design the second order current mode and trans-admittance mode filters, the filter's practicability is investigated. To determine how component spread and frequency-dependent current and voltage transfer gains affect the filter's operation, non-ideal analysis is conducted. The layout of the EXCCTA occupies an area of 51.47*23.33µm2 and it is designed and validated using 180nm GPDK in Cadence software. The FO-UF functions at ±1.25V supply at a frequency of 16.23MHz. Experimental analysis using off the shelf integrated circuits (ICs), the AD844 and CA3080 is also conducted to validate the proposed design.

Keywords: current mode; filter; current conveyor; universal filter; analog

Minimalna komponenta mešanega načina univerzalnega filtra prvega reda z uporabo EXCCTA

Izvleček: V študiji je predlagan univerzalni filter prvega reda (FO-UF) z mešanim načinom delovanja. Za zasnovo filtra so uporabljeni ojačevalnik EXCCTA (Extra X Current Conveyor Transconductance Amplifier), kondenzator in dva upora. Glavne lastnosti filtra so: (i) elektronska nastavljivost (ii) sposobnost delovanja v vseh štirih načinih delovanja (iii) kaskadnost (iv) razpoložljivost odzivov nizke prepustnosti (LP), visoke prepustnosti (HP) in vseh prepustnosti (AP) hkrati. Z vključitvijo filtra v zasnovo tokovnega režima drugega reda in filtrov s prehodno prepustnostjo je raziskana praktična uporabnost filtra. Da bi ugotovili, kako razširjenost komponent in od frekvence odvisni tokovni in napetostni prenosni dobički vplivajo na delovanje filtra, je izvedena neidealna analiza. Postavitev EXCCTA zavzema površino 51,47*23,33 µm2 ter je zasnovana in potrjena z uporabo 180 nm GPDK v programski opremi Cadence. FO-UF deluje pri napajanju ±1,25 V in frekvenci 16,23 MHz. Za potrditev predlagane zasnove je izvedena tudi eksperimentalna analiza z uporabo razpoložljivih integriranih vezij AD844 in CA3080.

Ključne besede: tokovni način; filter; tokovni ojačevalnik; univerzalni filter; analogni

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1 Introduction

Any signal processing system must have universal active frequency selective filters as a fundamental component. The analog active filters are employed to carryout multiple signal processing tasks like noise removal, phase correction, avoid aliasing by analog to digital converters (ADCs) or digital to analog converters (DACs). They are also an integral part of audio processing, telecommunications, and instrumentation systems. The analog filters [1-2] are also employed in image processing for removing noise or sharpening edges of the images. Current mode (CM) active components are the most favoured for the construction of multifunction filters because they have higher order linearity, a wider bandwidth, a straightforward design, and better performance in LVLP conditions [3–4]. The all-pass filters are utilised in the construction of multiphase oscillators, high quality factor (Q) bandpass filters, and for phase correction and equalization [5, 6]. Differential voltage current conveyor (DVCC) [15], operational transconductance amplifier (OTA) [6], inverting-current conveyor (ICCII) [8–9], current differencing transconductance amplifiers (CDTA) [18] and second-generation voltage conveyor (VGC) [6] are a few examples of analog active blocks (ABBs) used in the design. Many first order universal or all pass filter topologies can be found in the literature[5-37]. Table 1 presents the comparative analysis of some filters reported in the literature. Mixed-signal processing systems require interaction between current-mode and voltage-mode (VM) circuits. This requirement can be met by employing transadmittance-mode (TAM) and transimpedance-mode (TIM) circuits that not only perform signal processing, but also facilitate distortion-free interfacing between CM and VM units with the advancement of technology mixed-mode systems are being developed which require the interaction between CM and VM circuits by acting as a bridge. The mixed-mode first order universal filter that can provide LP, HP and AP filter functions in CM, VM, TAM and TIM modes of operation is needed for mixed signal system implementation.

It is found during the study that the filters presented in [6-9, 11-12, 16, 23, 31, 36, 37] utilizes more than one active block. The designs in [14, 15, 19, 20, 23, 27, 30-32] require three or more passive components. Floating passive elements are necessary for the filter architectures in [7-10, 12, 13, 15, 20, 23, 30-32]. The filter designs found in [5, 27] involve use of several capacitors. The literature review suggests that the majority of filters have the following flaws (i) large numbers of active analog blocks (ii) operation in a single mode (iii) excessive use of passive elements (iv) use of floating passive components (v) lack of on chip tuning.

In this study, we present a single mixed mode first order universal filter based on the extra X current conveyor transconductance amplifier (EXCCTA) [33] that can generate all three filter responses concurrently. The suggested filter can function in trans-admittance (TAM), trans-impedance (TIM), voltage mode (VM), and current mode (CM).

2 Proposed EXCCTA mixed mode universal filter

The EXCCTA is a versatile active analog block [33] that has inbuilt tunability property. The functional diagram of EXCCTA is presented Figure 1 and the current-voltage relations are given by Equations (1-4).

$$V_{XP} = V_{XN} = V_Y \tag{1}$$

$$I_{XP} = I_{ZP+} = -I_{ZP-} \tag{2}$$

$$I_{XN} = I_{ZN+} = -I_{ZN-} \tag{3}$$

$$I_{O+} = -I_{O-} = g_m \left(V_{ZP+}\right) \tag{4}$$

The designed EXCCTA mixed mode filter is presented in Figure 2. The design requires one EXCCTA, one capacitor and two resistors for implementation. The resistors are implemented using MOSFET based active resistors [34]. The filter operates in all four modes without requiring any change in the topology.

The filter key characteristics are (i) electronic tunability (ii) operation in all four modes (iii) cascadability (iv) usage of a limited number of active blocks and passive components (v) low input impedance in CM and TIM operation (vi) high input impedance in VM and TAM operation (vii) simultaneous availability of LP, HP, and AP responses. Equations (5–17) give the filter transfer function for each of its four operating modes.

The expression for pole frequency is given in Equation 11. It can be concluded for the transfer function analysis for VM, TAM and TIM modes that the filter gain can be adjusted by changing the value of the resistor without disturbing the frequency. The resistors can be implemented using MOSFETS making the frequency and gain electronically tunable.

2.1 Operation in CM and TAM

In CM operation the filter did not require any resistors for implementation. In the TAM mode of operation, the

Table 1: Comparative analysis of first order filters

Reference	Number of Active Block	Passive components count		Low input impedance (CM /TIM) or High input impedance (VM/TAM)	High output impedance (CM/ TAM) or Low output impedance (VM/TIM) for AP response	Tunability	Mode of Operation	Universal Filter	Employment of Floating Passive Components
		R	C						
[5]	DXCCTA-1	0	2	Yes	Yes	Yes	CM	Yes	No
[6]	OTA-2	1	1	Yes	No	Yes	VM	Yes	No
[7]	CCII-2	1	1	Yes	Yes	No	CM	Yes	Yes
[8]	ICCII-2	1	1	No	Yes	No	CM	No	Yes
[9]	ICCII-2	0	1	No	Yes	Yes	CM	Yes	Yes
[10]	DXCCDITA-1 (APF-1)	0	1	Yes	Yes	Yes	VM	No	Yes
[11]	MO-CCII-2	1	1	Yes	Yes	No	CM	Yes	No
[12]	Subtractor-2	1	1	Yes	Yes	No	VM	No	Yes
[13]	ZC-VDCC (Fig.2)-1	1	1	No	Yes	Yes	CM	No	No
[14]	DV-DXCCII-1	3	1	Yes	No	No	VM	No	Yes
[15]	DVCC-1	2	1	Yes	No	No	VM	Yes	Yes
[16]	CCII-2	1	1	Yes	Yes	No	CM	No	No
[17]	DXCCTA-1	0	1	Yes	Yes	Yes	CM	No	No
[18]	CDTA-1	0	1	Yes	Yes	Yes	CM	No	No
[19]	DXCCII-1 (Fig.2)	2	1	Yes	No	No	VM	No	No
[20]	DVCC-1	2	1	No	Yes	No	VM	No	Yes
[21]	VCII-2	3	1	Yes	Yes	No	VM/CM	No	Yes
[27]	DX-MOCCII	2	2	No	Yes	No	CM	Yes	No
[30]	CFOA-2 (Fig.1 a)	3	1	No	Yes	No	VM	No	Yes
[31]	VCII-2	2	1	Yes	Yes	No	VM/CM	Yes	Yes
[32]	LT-1228-1	2	1	No	Yes	Yes	VM	Yes	Yes
[34]	EXCCTA-1	0	1	Yes	Yes	Yes	CM	Yes	No
[35]	VDDDA-1	0	1	Yes	Yes	Yes	VM	Yes	No
[36]	DDTA-2	1	1	Yes	Yes	Yes	VM	Yes	No
[37]	CCCII-2	0	1	Yes	Yes	Yes	CM	Yes	No
Proposed	EXCCTA-1	1	1	Yes	Yes	Yes	CM, VM, TAM, TIM	Yes	No

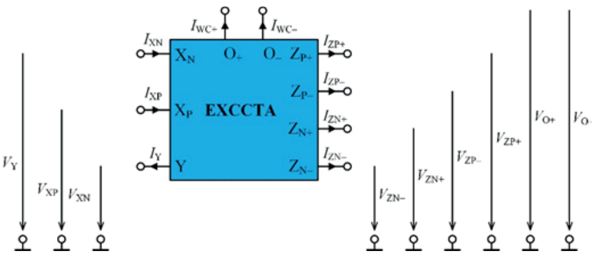


Figure 1: Functional diagram of EXCCTA

filter employs one active resistor (R_1) for voltage to current conversion. In both CM and TAM modes the filter provides all three responses simultaneously. The transfer functions and relation of pole frequency for LP, HP and AP responses are given by Equations (5-11).

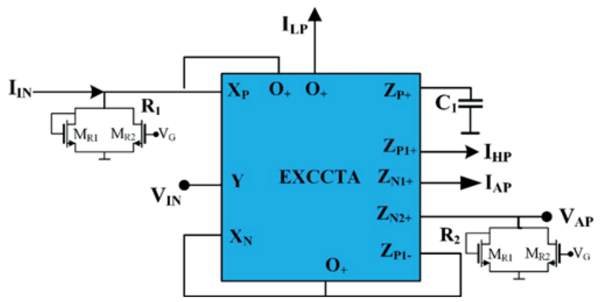


Figure 2: Mixed Mode First Order universal filter

$$I_{HP(CM-Mode)} = \frac{-sC}{sC + g_m} \qquad (5)$$

$$I_{LP(CM-Mode)} = \frac{-g_m}{sC+g_m} \quad (6)$$

$$I_{AP(CM-Mode)} = -\left[\frac{sC-g_m}{sC+g_m}\right] \quad (7)$$

$$I_{HP(TAM-Mode)} = \frac{1}{R_1} * \left[\frac{sC}{sC+g_m}\right] \quad (8)$$

$$I_{LP(TAM-Mode)} = \frac{1}{R_1} * \left[\frac{-g_m}{sC+g_m}\right] \quad (9)$$

$$I_{AP(TAM-Mode)} = \frac{1}{R_1} * \left[\frac{sC-g_m}{sC+g_m}\right] \quad (10)$$

$$f_o = \frac{1}{2\pi} * \left[\frac{g_m}{C}\right] \quad (11)$$

It can be seen from Equations (8-10) that the gain of the TAM filter is $(H_o = \frac{1}{R_1})$ that can be tuned by varying the resistance value of the active resistor. In TAM configuration the filter offers dual tunability of frequency and gain.

2.2 Operation in VM and TIM

In the TIM mode of operation, the input will be current, and the output will be voltage. To operate in this mode the filter requires one active resistor at the output for current to voltage conversion. For the sake of simplicity only AP voltage output responses are shown in the Figure 2. The same process will be followed to get LP and HP responses. Since the active MOSFET resistors require less chip area it will have negligible effect on the chip area.

In VM mode operation two resistors are required, one at the input side and other at the output. As is clear from Equations (12-17). The VM and TIM modes offer dual tunability. The filter frequency can be controlled by OTA transconductance (g_m) and gain can be changed by active resistors (R_2/R_1). For VM mode the filter gain $(H_o = \frac{R_2}{R_1})$ and for TIM the gain is ($H_o = R_2$).

$$V_{HP(VM-Mode)} = \frac{R_2}{R_1} * \left[\frac{sC}{sC+g_m}\right] \quad (12)$$

$$V_{LP(VM-Mode)} = \frac{R_2}{R_1} * \left[\frac{-g_m}{sC+g_m}\right] \quad (13)$$

$$V_{AP(VM-Mode)} = \frac{R_2}{R_1} * \left[\frac{sC-g_m}{sC+g_m}\right] \quad (14)$$

$$V_{HP(TIM-Mode)} = -R_2 * \left[\frac{sC}{sC+g_m}\right] \quad (15)$$

$$V_{LP(TIM-Mode)} = -R_2 * \left[\frac{-g_m}{sC+g_m}\right] \quad (16)$$

$$V_{AP(TIM-Mode)} = -R_2 * \left[\frac{sC-g_m}{sC+g_m}\right] \quad (17)$$

3. Non-ideal analysis of the filter

The major contributing factors for the deviation in frequency performance of the EXCCTA are the frequency dependent current and voltage transfer gains, $\boldsymbol{\alpha}_i(s)$ and $\beta_i(s)$ respectively, where $\alpha(s) = \alpha_0/(1 + s/\omega_\alpha)$ and $\beta(s) = \beta_0/(1 + s/\omega_\beta)$. Ideally, $\alpha_0 = \beta_0 = 1$ and $\omega_\alpha = \omega_\beta = \infty$. The γ symbolizes the inaccuracy in the transconductance transfer of the OTA. If the non-ideal gains are considered the V-I relationships of the EXCCTA are transformed to $I_Y = 0$, $V_{XP} = \beta_P(s)V_Y$, $V_{XN} = \beta_N(s)V_Y$, $I_{ZP+} = \alpha_p(s)\, I_{XP}$, $I_{ZP-} = \alpha_p'(s)\, I_{XP}$, $I_{ZN+} = \alpha_N(s)\, I_{XN}$, $I_{ZN-} = \alpha_N'(s)\, I_{XN}$, $I_{0+} = \gamma g_m V_{ZP+}$, $I_{0-} = \gamma' g_m V_{ZP+}$.

The reanalysis of the all-pass filter including the effect of frequency dependent current and voltage transfer gains results in the modified transfer functions and pole frequency expression as presented in Equations (18-20). For the sake of brevity only non-ideal AP responses of all modes are included.

$$I_{AP(CM-Mode)} = -\frac{sC\alpha_N\alpha_P\beta_P - \alpha_P\alpha_N\beta_P\gamma' g_m}{sC+\alpha_P\gamma' g_m} \quad (18)$$

$$I_{AP(TAM-Mode)} = \frac{1}{R_1} * \frac{sC\alpha_N\alpha_P\beta_P - \alpha_P\alpha_N\beta_P\gamma' g_m}{sC+\alpha_P\gamma' g_m} \quad (19)$$

$$V_{AP(VM-Mode)} = \frac{R_2}{R_1} * \left[\frac{sC\alpha_N \alpha_P \beta_P - \alpha_P \alpha_N \beta_P \gamma' g_m}{sC + \alpha_P \gamma' g_m} \right] \quad (20)$$

$$V_{AP(TIM-Mode)} = -R_2 * \left[\frac{sC\alpha_N \alpha_P \beta_P - \alpha_P \alpha_N \beta_P \gamma' g_m}{sC + \alpha_P \gamma' g_m} \right] \quad (21)$$

$$f_o = \frac{1}{2\pi} * \left[\frac{\alpha_P \gamma' g_m}{C} \right] \quad (22)$$

4. Simulation results

The EXCCTA employed in the design of FO-UF is designed in 180nm GPDK in Cadence Virtuoso analog design environment at a supply voltage of ±1.25V. The CMOS implementation of EXCCTA is presented in Figure 3. The width and length of the EXCCTA transistors can be found in [34]. The width to length ratio of MOSFET active resistors are 8.6 µm /1.8µm. The layout of the EXCCTA is designed and verified as presented in Figure 4. It occupies an area of 51.47*23.33µm^2.

4.1 Analysis of the first order universal filter:

By fixing I_{Bias} = 100µA and C_1 = 10pF, the filter is configured for a frequency of 16.23MHz. First, the CM operation is examined. The input is applied at the X_p terminal, while the Y node is connected to ground. Figure 5 presents the ideal and simulated LP and HP responses. Figure 6 shows the AP configuration gain and phase response. The AP gain and phase response for various bias currents are presented in Figure 7 to demonstrate the filter tunability property. Figure 8 depicts the Lissajous curve to further verify the phase relationship between the input and output signals. The illustration shows that there is a 90° phase difference between the input and output signals. The filter transient analysis performance for an input sinusoidal signal of 40µA (p-p) at a frequency of 16.23 MHz is shown in Figure 9. The Monte Carlo mismatch analysis is done by incorporating the models provided in the GPDK for MOSFETs and MIM Capacitor, the statistical analysis is performed for 200 runs to examine the impact of process variables on the performance of the filter. The results presented in Figure 10 show satisfactory performance with little variation. The total harmonic distortion (THD) of the CM AP configuration is measured for different input signal amplitudes. The Figure 11 shows that the THD remains within acceptable range till 80µA input range.

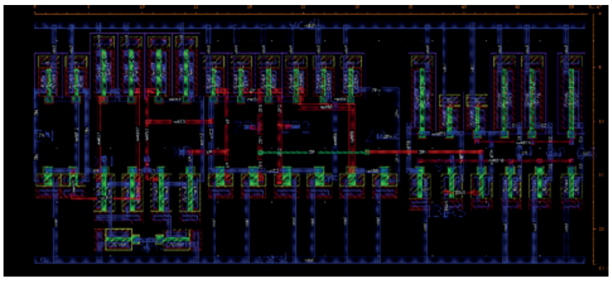


Figure 4: The layout of EXCCTA in 180nm technology

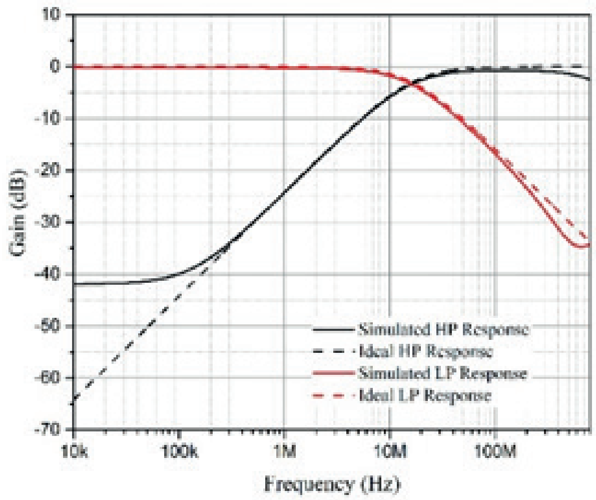


Figure 5: Frequency responses of CM HP and LP configuration

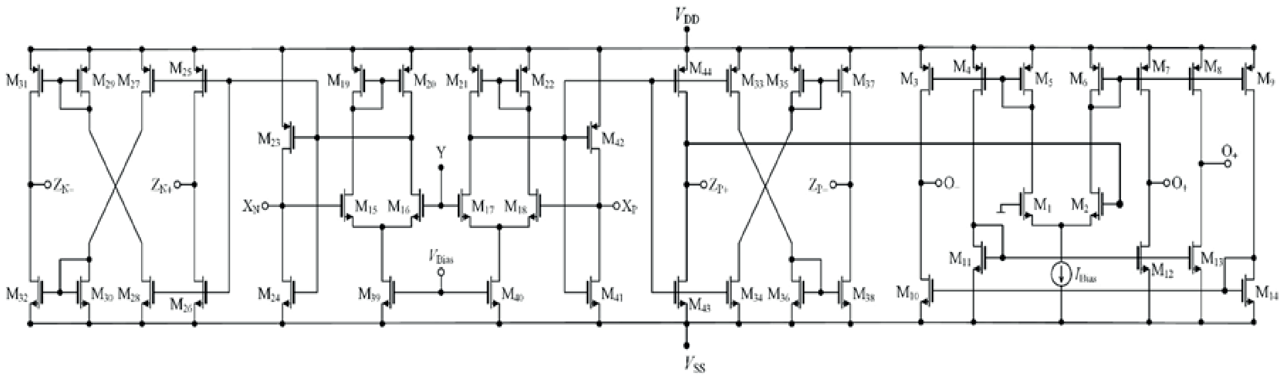


Figure 3: The CMOS implementation of EXCCTA

(a)

(b)

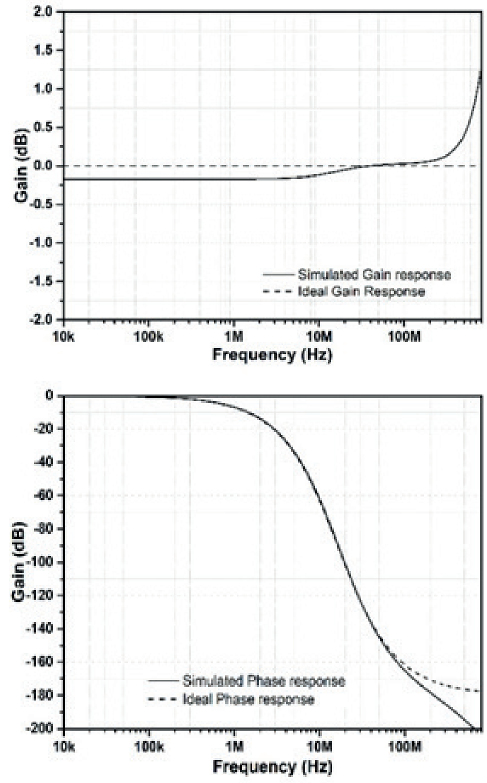


Figure 6: Frequency response of CM AP configuration: (a) Gain (b) Phase

(a)

(b)

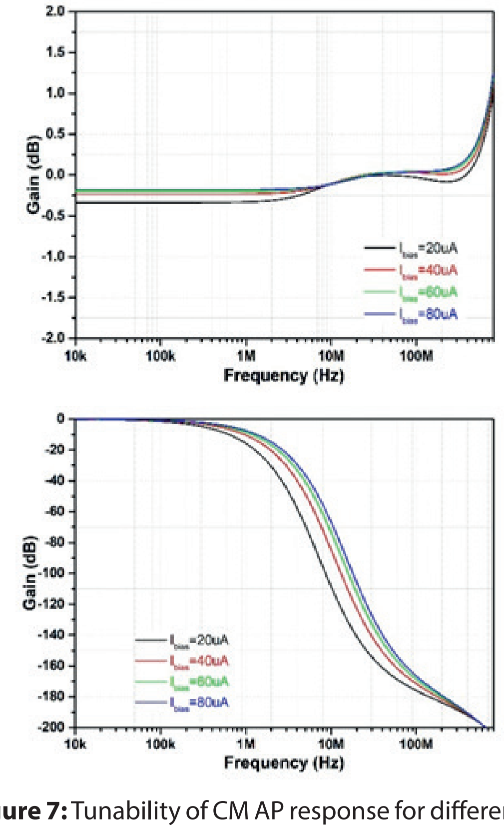


Figure 7: Tunability of CM AP response for different values of bias currents: (a) Gain (b) Phase

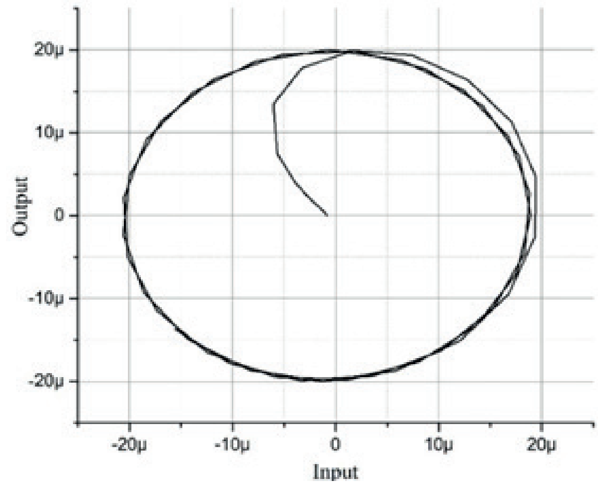


Figure 8: Lissajous patters for CM AP configuration

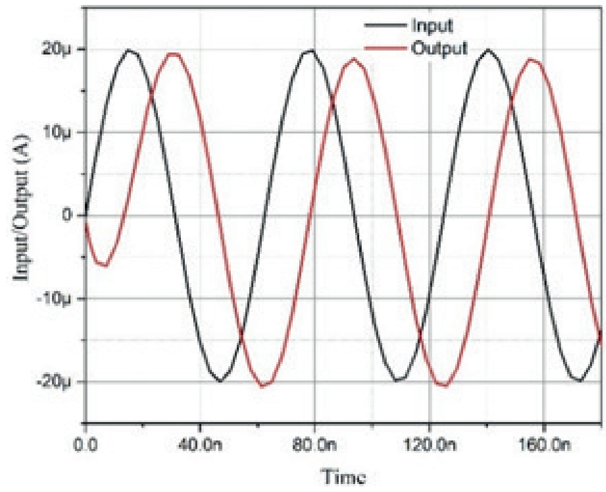


Figure 9: Time domain analysis of CM AP configuration

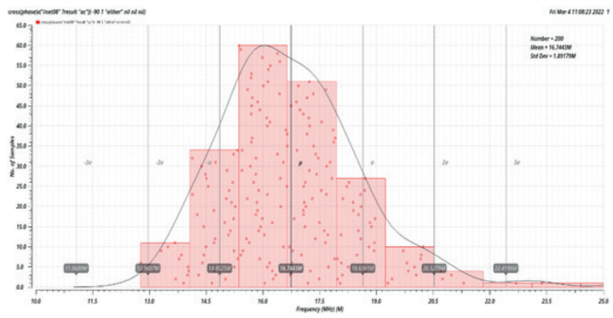


Figure 10: Monte Carlo analysis of CM AP configuration

Next, the VM operation of the filter is examined. The input voltage is applied at Y node. The Figure 12 presents the LP and HP response in VM configuration. To obtain the LP and HP gain responses a 1kΩ active MOSFET resistor is attached to the output terminal of the filter. The value of the active resistor can be controlled by setting the control voltage (V_G). The AP gain and

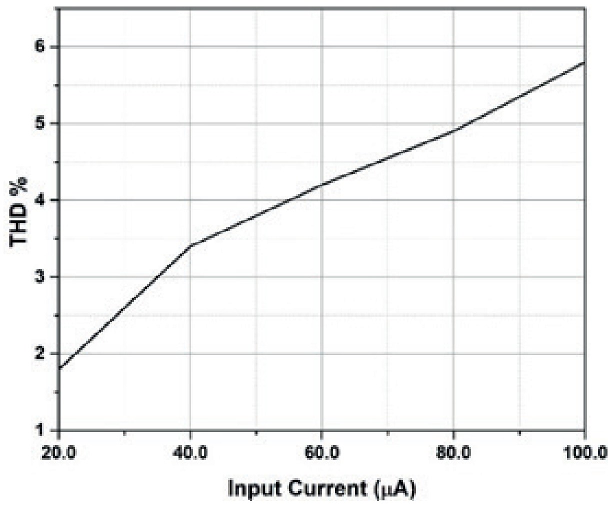


Figure 11: Total harmonic distortion of CM AP configuration

phase responses are presented in Figure 13. The time domain results of an input sinusoidal voltage signal of 400mV(p-p) at 16.23MHz is shown in Figure 14. The Monte Carlo analysis results for 200 runs as presented in Figure 15 indicate negligible effect of process variations on the AP filter response.

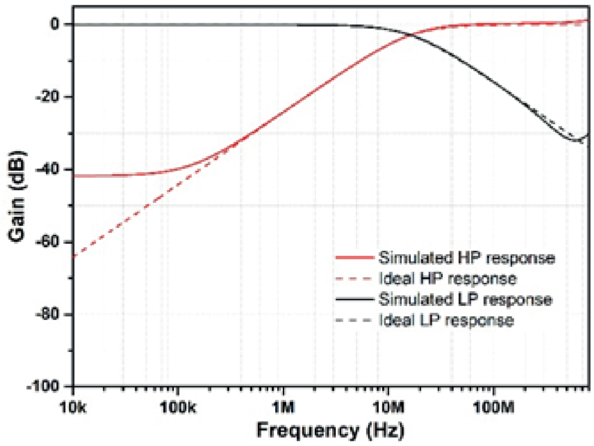


Figure 12: Frequency responses of VM HP and LP configuration

The LP, HP and AP responses for the TAM and TIM configurations are shown in Figures 16-17. The value of the active resistor was set at 1kΩ for the analysis. The analysis of the responses indicates the correct functioning of the designed filter in mixed mode configuration. The THD of the VM AP filter configuration is also measured for different input signal amplitudes. The Figure 18 shows that the THD remains within acceptable range till 160mV input range.

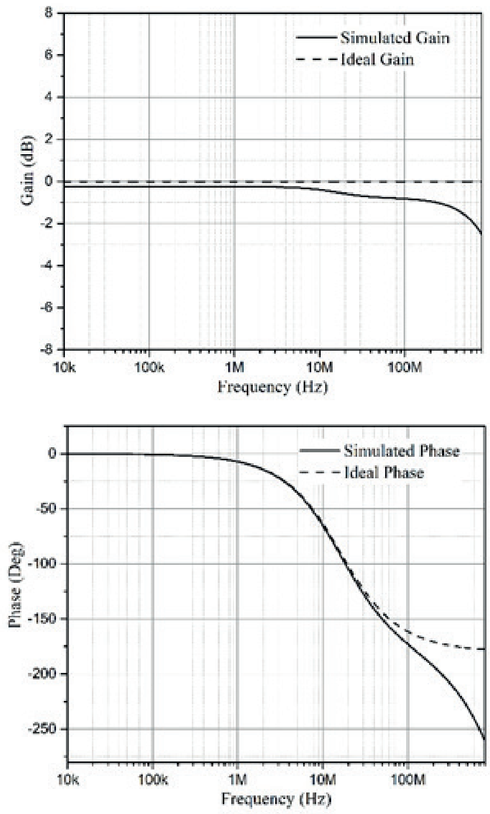


Figure 13: Frequency response of VM AP configuration: (a) Gain (b) Phase

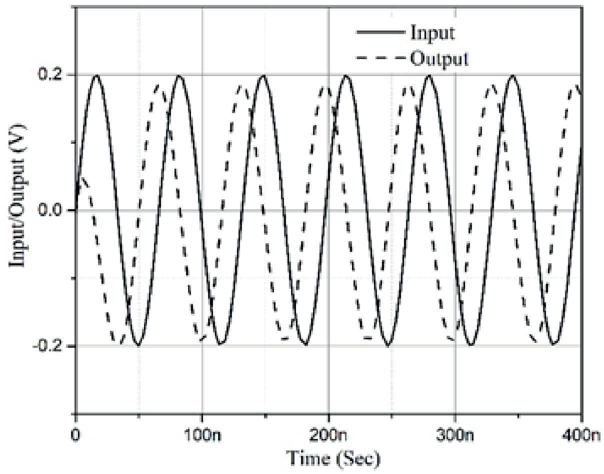


Figure 14: Time domain analysis of CM AP configuration

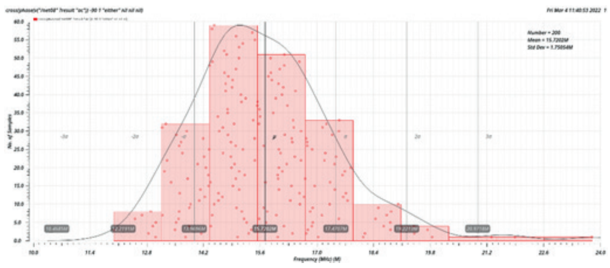


Figure 15: Monte Carlo analysis of VM AP configuration

(a)

(b)

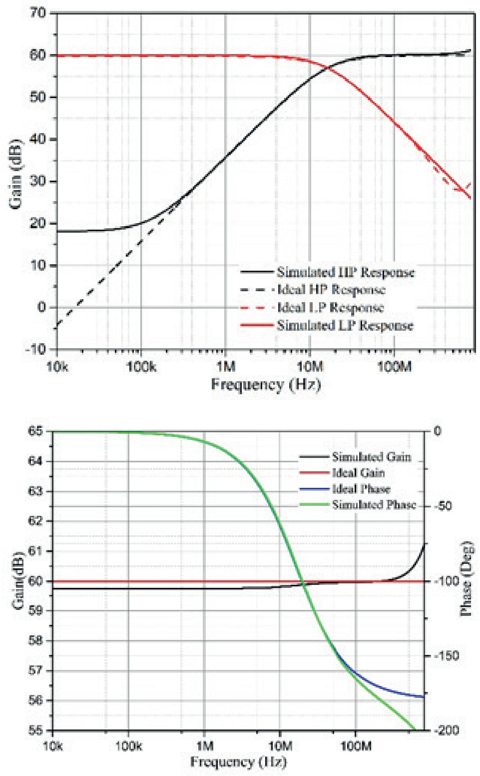


Figure 16: Frequency responses of TIM configuration (a) HP and LP (b) AP

(a)

(b)

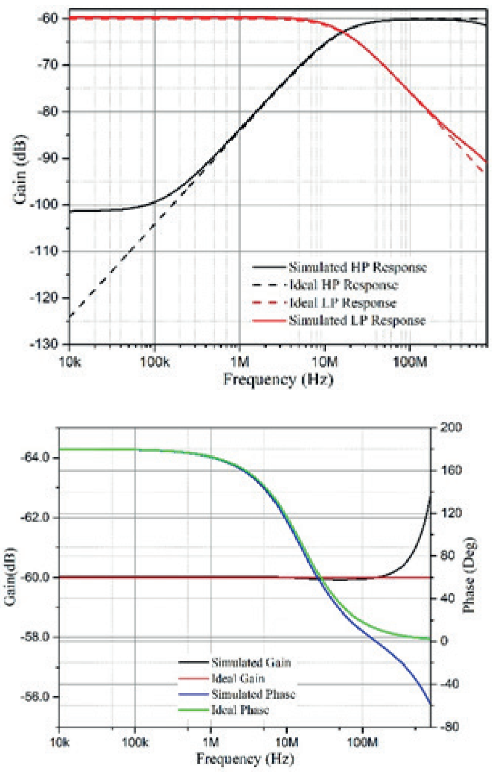


Figure 17: Frequency responses of TAM configuration: (a) HP and LP (b) AP

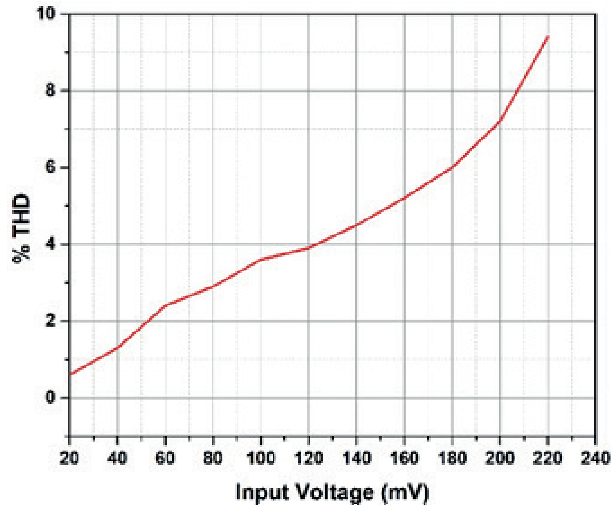


Figure 18: Total harmonic distortion of VM AP configuration

(a)

(b)

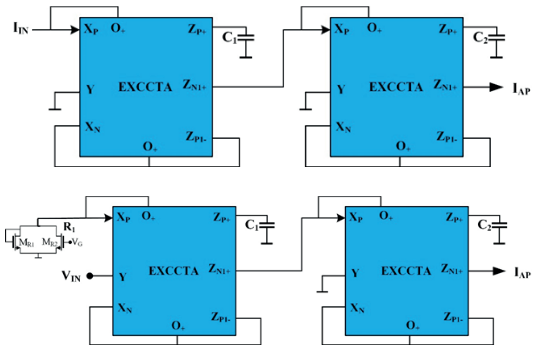


Figure 19: Second order AP filters obtained by direct cascading (a) CM (b) TAM

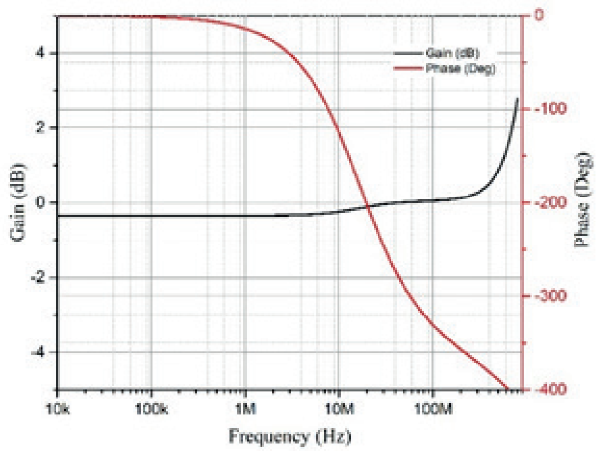


Figure 20: Frequency response of CM Second order AP configuration

4.2 Design of second order CM and TAM Filters

Second order CM and TAM mode filters are designed to verify the cascadeability of the proposed filter. The proposed all pass filter is cascaded together to achieve

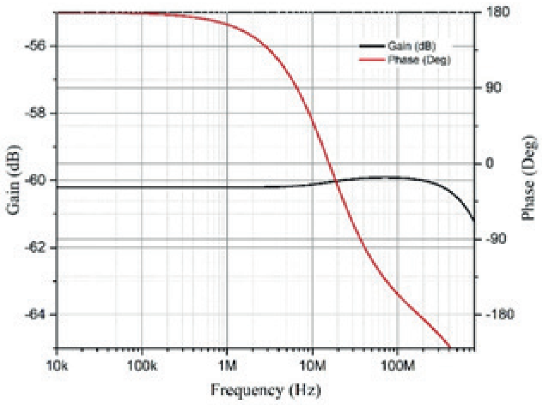


Figure 21: Frequency response of TAM Second order AP configuration

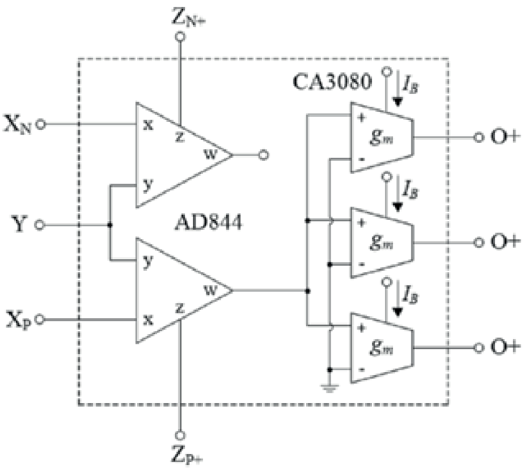


Figure 22: Implementation of EXCCTA using off the shelf ICs

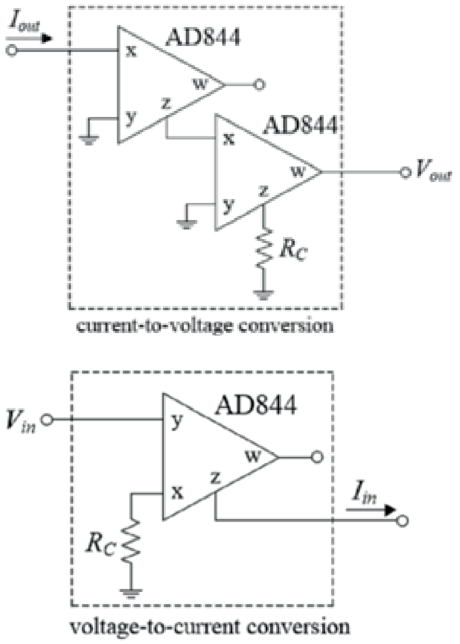


Figure 23: Current to voltage (V-I) and Voltage to current (V-I) converters

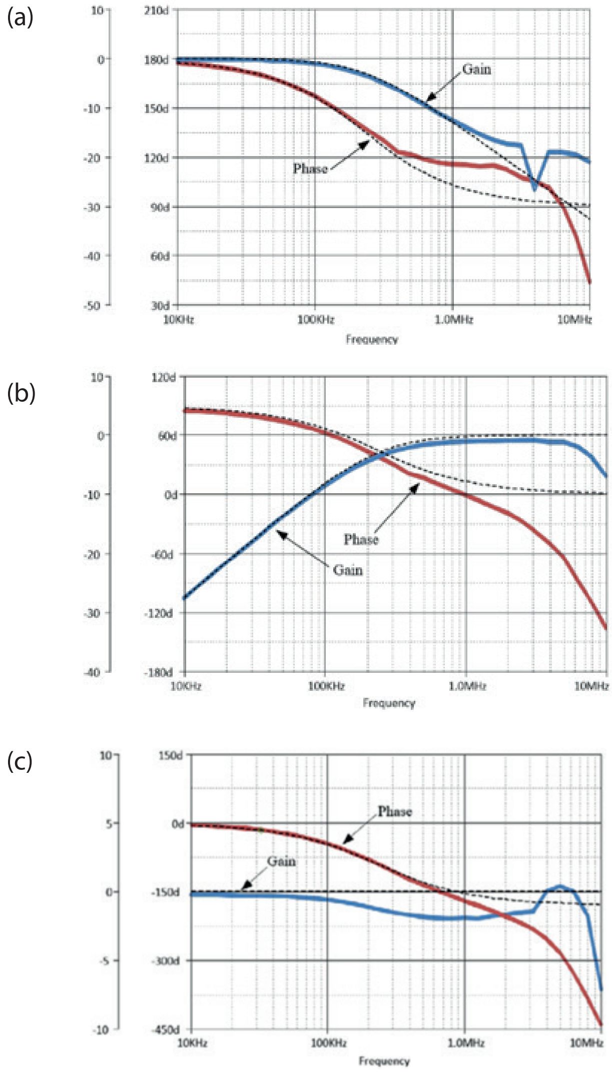


Figure 24: Frequency response of CM configuration: (a) LP (b) HP (c) AP

the second order AP filter as shown in Figure 19(a-b). The second CM and TAM filters are tested at a frequency of 16.23MHz by choosing $C_1 = C_2 = 10pF$ and $I_{bias1,2} = 100\mu A$. For $C_1 = C_2 = C$ and $g_{m1} = g_{m2} = g_m$ the pole frequency expression of the filter will be identical to the one given in Equation 11. The Figures 20-21 present the frequency domain results of the designed filters which validates the cascadeability of the filters.

4.3 Experimental analysis

To further establish the practical feasibility of the proposed designs experimental analysis using commercially available integrated circuits AD844 [10] and CA3080 is done. The EXCCTA is realised as presented in Figure 22.

The results are obtained with $g_m = 1mA/V$, $R_1 = 1k\Omega$ and $C_1 = 680$ pF at supply voltage of ±5V which results in $f_o =$

234.5 kHz. The current to voltage (V-I) and voltage to current (V-I) converters used for obtaining the results are presented in Figure 23. The value of the converting resistance R_C = 1Ω k. A sinusoidal signal of 50mA(p-p) at 234kHz is applied to the filter for testing. The frequency domain results for CM mode LP, HP and AP are presented in Figure 24. The transient analysis results are given in Figure 25. The Fourier transforms results are also shown in Figure 26.

(a)

(b)

(c)

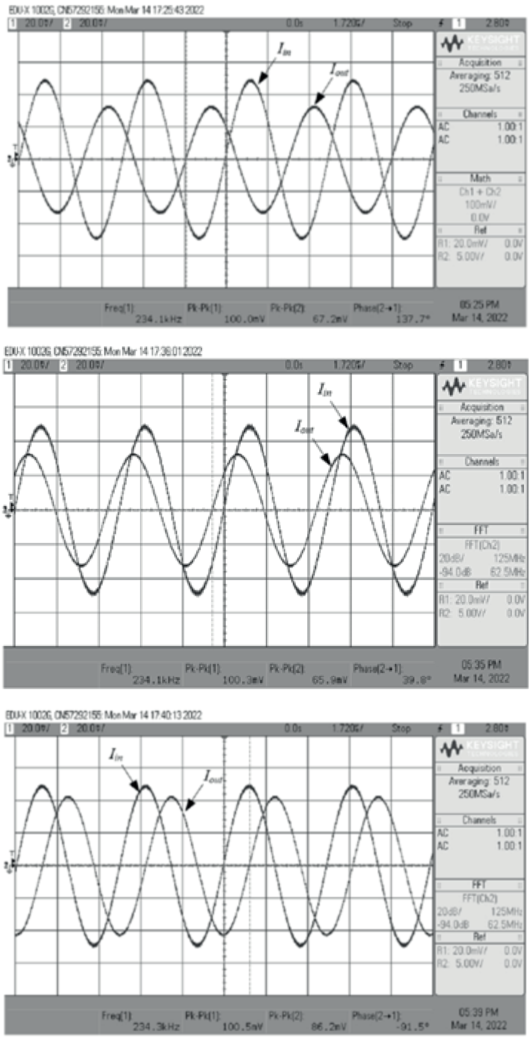
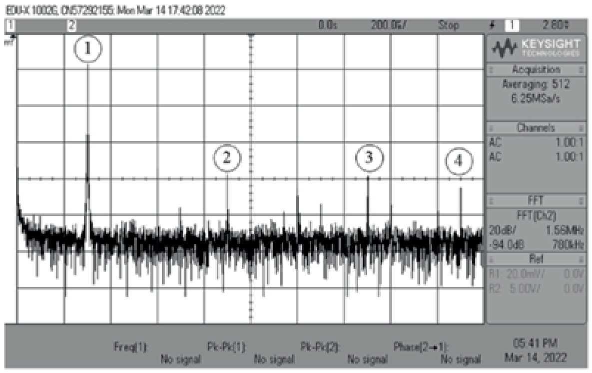


Figure 25: Time domain Analysis of CM configuration: (a) LP (b) HP (c) AP

Similarly, frequency domain results for TAM LP, HP and AP are presented in Figure 27. Analysis of the results reveal that the proposed mixed mode FO-UF works as expected.

5 Conclusion

The manuscript presents a topology of mixed mode first order universal filter using EXCCTA. The filter employs single grounded capacitor and two active MOS-



No.	Frequency (kHz)	Gain (dB)
1	234.05	-33.86
2	704.34	-92.64
3	1173.12	-93.21
4	1486.68	-117.8

Figure 26: Fourier transforms results of CM AP configuration

(a)

(b)

(c)

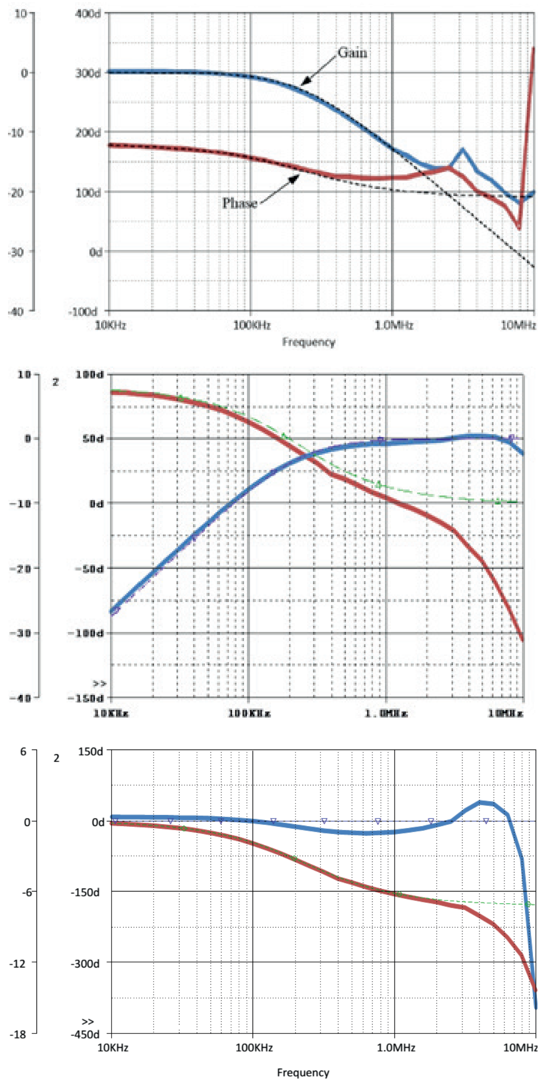


Figure 27: Frequency response of CM configuration: (a) LP (b) HP (c) AP

FET resistors for implementation. The filter can operate in VM, CM, TAM and TIM modes and provide LP, HP and AP responses. The filter is cascadable and did not require any matching condition for passive components. The filter enjoys tunability of filter frequency and gain. The non-ideal gain and sensitivity analysis of the filter is also conducted to gauge their effect on the performance of the filter. The filter is validated at a frequency of 16.23MHz and the layout of the EXCCTA is also designed and verified. The experimental validation using off the shelf ICs is also conducted for the proof of concept.

6 Acknowledgement

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7 Conflicts of Interest

The authors declare no conflict of interest.

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