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Electronically Tunable Multifunction Current Mode Filter Employing Grounded Capacitors

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Abstract: In this paper, a new single input multi output (SIMO) filter is presented that works in current mode (CM). The universal filter is designed using a recently proposed highly versatile active building block the extra X current conveyor transconductance amplifier (EXCCTA). The design employs two EXCCTAs, two capacitors and one resistor. The designed filter uses grounded passive elements which is advantageous for fabrication. The design can provide all the five responses i.e., high-pass (HP), band-pass (BP), low-pass (LP), all-pass (AP), and band-stop (BS) simultaneously. In addition, it provides an independent electronic tunability of angular frequency (ω) and quality factor (Q). Moreover, there is no requirement of passive component matching. The non-ideal and sensitivity analysis of the filter is done to get a measure of the effect of the process and components variation on the functioning of the filter. The simulation results are obtained using Cadence software employing 0.18 µm CMOS technology parameters from Silterra Malaysia at a supply voltage of ±1.25 V also the layout of the EXCCTA is designed. The proposed filter is validated by designing it for a frequency of 16.07MHz. Additionally, the Spice macro model of the commercially available integrated circuits (ICs) AD844 and LM13700 are used to further test the feasibility of the proposed filter.

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

Elektronsko nastavljiv večfunkcijski filter v tokovnem načinu z ozemljenimi kondenzatorji

Izvleček: V članku je predstavljen nov enovhodni večizhodni filter (SIMO), ki deluje v tokovnem načinu (CM). Univerzalni filter je zasnovan z uporabo nedavno predlaganega zelo vsestranskega aktivnega gradnika - transkondukcijskega ojačevalnika z dodatnim tokom X (EXCCTA). Zasnova uporablja dva EXCCTA, dva kondenzatorja in en upor. Zasnovani filter uporablja ozemljene pasivne elemente, kar je ugodno za izdelavo. Zasnova lahko hkrati zagotavlja vseh pet odzivov, tj. visokoprepustni (HP), pasovni (BP), nizkoprepustni (LP), vseprepustni (AP) in pasovno zaporo (BS). Poleg tega omogoča neodvisno elektronsko nastavitev kotne frekvence (ω) in faktorja kakovosti (Q). Poleg tega ni potrebe po usklajevanju pasivnih komponent. Vplivi sprememb procesa in komponent na delovanje filtra so bili izmerjeni s pomočjo neidealne analize in analize občutljivosti filtra. Rezultati simulacije so pridobljeni s programsko opremo Cadence, pri čemer so uporabljeni parametri tehnologije CMOS 0,18 µm podjetja Silterra Malaysia pri napajalni napetosti ±1,25 V. Zasnovana je tudi postavitev EXCCTA. Predlagani filter je potrjen za frekvenco 16,07 MHz. Poleg tega sta za nadaljnje testiranje izvedljivosti predlaganega filtra uporabjena makro modela Spice komercialno dostopnih integriranih vezij (IC) AD844 in LM13700.

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

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1 Introduction

From the last few decades, the designing of current mode (CM) analog filters has gained popularity among researchers due to their versatility and wide applicability. Their applications can be easily found in high-speed communication, instrumentation, sound system, control engineering, and electroacoustic etc.[1-4]. Presently universal filters designed using low voltage low power (LVLP) techniques are in demand because of the emergence of portable battery-operated devices. A universal filter circuit provides all the five filter responses, i.e. high-pass (HP), low-pass (LP), band-pass (BP), band-stop (BS), and all-pass (AP), from the same topology[3]. Furthermore, universal filters can be categorized as single input multi output (SIMO)[1, 3], multi-input multi output (MIMO)[1, 5] and multi input single output (MISO) [6, 7] filters. Second order filters have wider range of applications, so their design is an important area of research. Considering the benefits current mode (CM) circuits have in terms of higher bandwidth, good dynamic range and low power dissipation, the proposed universal filter is designed using the CM active block. Several SIMO universal filters were designed employing different CM active blocks by researchers in the literature[2, 4, 5, 8-30]. Some of these active blocks are differential voltage current conveyor (DVCC) [2, 8], current conveyor transconductance amplifier (CCTA) [9], current follower transconductance amplifier (CFTA) [11], operational floating current conveyor (OFCC) [24], third generation current conveyor (CCIII)[10], second generation current conveyor (DOCCII) [8, 9, 13], four terminal floating nullor transconductance amplifier (FTFNTA) [21], and extra x current conveyor transconductance amplifier[27], voltage differencing current conveyor. A comparative study of some exemplary designs of CM SIMO filters is done based on the following parameters (i) Number of analog building blocks required (ABBs) (ii) Number of Passive Components employed (iii) Grounded passive components used in the design (iv) the filter has low input impedance (v) all responses are available through explicit high impedance terminals (vi) responses available (vii) electronic tunability feature present (viii) independent control of quality factor and pole frequency (ix) design frequency. The Table 1 presents the comparative analysis. The available designs have some limitations in terms of cascading feature, number of passive elements, number of floating passive components, independent tunability of frequency and quality factor and simultaneous availability of all five filter responses as mentioned below.

- Low output impedance due to which cascading is not possible [9, 10, 26, 27].
- High input impedance which is undesirable for cascading [8-10, 12, 18, 14-26, 30].
- More than two active elements are employed for the design [8, 11, 12, 13, 15, 17, 19, 28, 30].
- Angular frequency and quality factor are not independently tunable [8-10, 12, 16, 17, 19, 24, 26-28].
- Fabrication is difficult due to the availability of floating passive elements [10, 12].

***Table 1**: Comparative studey of the CM SIMO universal filters*

References	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
[8]	DVCC (3)	4R+2C	Yes	No	Yes	All five	No	No	22.5MHz
[9]	CCTA (1)	2R+2C	Yes	No	No	All five	Yes	No	1MHz
[10]	CCIII (1)	2R+2C	No	No	No	LP, BP	No	No	562.7kHz
[11]	CFTA (4)	2C	Yes	Yes	Yes	All five	Yes	Yes	153kHz
[12]	MOCCII (3)	5R+2C	No	No	Yes	All five	No	No	281.35kHz
[13]	CCII (3)	3R+2C	Yes	Yes	Yes	All five	No	Yes	1MHz
[15]	ZC-CFTA (4)	2C	Yes	Yes	Yes	All five	Yes	Yes	159kHz
[16]	ZC-CITA (2)	2C	Yes	Yes	Yes	All five	Yes	No	1.026MHz
[17]	MOCCII (3)	2R+2C	Yes	Yes	Yes	All five	No	No	1kHz
[18]	VDCC (2)	2R+2C	Yes	No	Yes	All five	Yes	Yes	1.06MHz
[19]	MOCCII (3)	2R+2C	Yes	Yes	Yes	All five	No	No	436.2kHz
[24]	MO-OFC (2)	2R+2C	Yes	No	Yes	All five	No	No	1.5MHz
[25]	DXMOCCII (2)	2R+2C	Yes	No	Yes	All five	Yes	Yes	2.65MHz
[25]	DXMOCCII (2)	1R+2C	Yes	No	Yes	All five	Yes	Yes	2.65MHz
[26]	VDCC (1)	2R+2C	Yes	No	No	All five	Yes	No	8.91MHz
[27]	EXCCTA (1)	1R+2C	Yes	Yes	No	All five	Yes	No	2.054MHz
[28]	CFTA (3)	2C	Yes	Yes	Yes	All five	Yes	No	6.4MHz
[29]	DXMOCCII (2)	3R+2C	Yes	Yes	Yes	All five	No	Yes	1.203MHz
[30]	MOCCII (3)	3R+2C	Yes	No	Yes	All five	No	Yes	100MHz
Proposed	EXCCTA (2)	1R+2C	Yes	Yes	Yes	All five	Yes	Yes	16.07MHz

- All five responses of filters are missing [10].
- Capacitor is connected to low impedance node which will degrade high frequency performance [25].

This paper describes the design of a SIMO filter by making use of two EXCCTA, two grounded capacitors and one resistor. It provides all five responses concurrently and it features independent control of angular frequency (ω) and quality factor (Q) via transconductance of the EXCCTA. Another important advantage of the filter is that the outputs are available explicitly from high impedance terminals which are essential for cascading point of view. The design is validated using Cadence design software and the simulations results are found to be in closely following the expected theoretical results.

2 Extra X Current Conveyor Transconductance Amplifier (EXCCTA)

The Extra X current conveyor transconductance amplifier (EXCCTA) is functionally an improved and more versatile version of extra x current conveyor (EXCCII) [31]. The EXCCTA[27] includes features of current and voltage followers and operational transconductance amplifier (OTA) making it more versatile. The voltage current (V-I) characteristics of the developed EXCCTA are given in Equations (1-5) and the block diagram is presented in Figure 1.

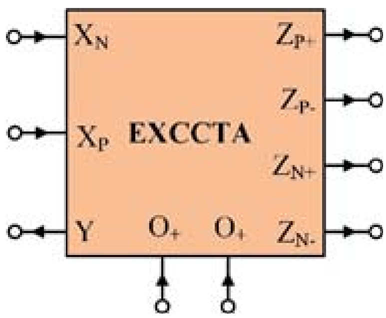

Figure 1: Block Diagram of EXCCTA

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

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

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

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

The expression for transconductance (g_m) is given in Equation 5.

$$g_m = \sqrt{\mu_n C_{OX} \frac{W}{L} I_B} \tag{5}$$

Where C_{QX} is the gate oxide capacitance, μ_n is the mobility of electrons in NMOS, g_m denotes the transconductance of OTA set via bias current I_B and W/L is the aspect ratio of the transistors.

The CMOS implementation of the EXCCTA as proposed in[27] is presented in Figure 2. The Y terminal is high impedance voltage input node and X_P & X_N low impedance voltage output/current input nodes. The O_+, Z_{P+} & Z_{N+} terminals are high impedance current output nodes. The number of current output terminals (I_{ZP+}, I_{ZP-}, I_{ZN+}, I_{ZN-}, O_+, O_-) can be increased by simply adding two MOS transistors.

3 Proposed EXCCTA based CM SIMO filter

The proposed current mode SIMO filter is shown in Figure 2. It employs two EXCCTA, one grounded resistor and two grounded capacitors which is advantageous for fabrication point of view. The filter is fully cascadable having low input impedance and high output impedance. Additionally, the pole frequency and quality factor of the filter can be independently tuned via bias current of the OTA. Another important design feature

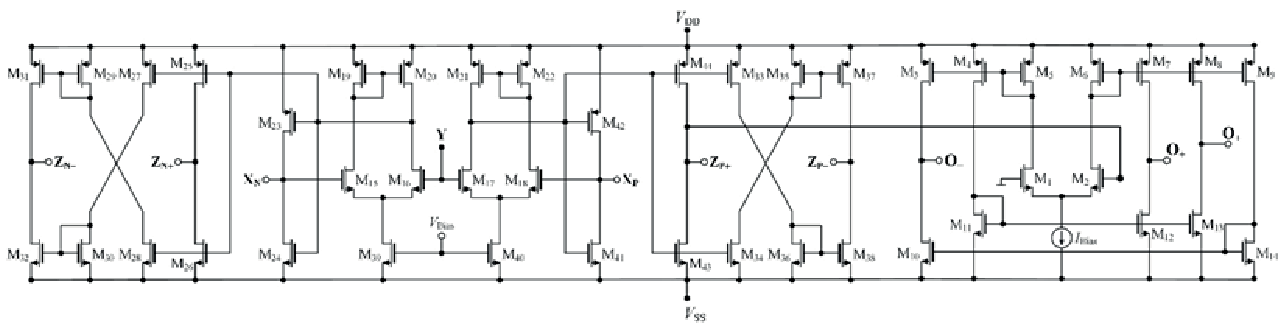

Figure 2: CMOS implementation of EXCCTA

is the use of only positive current output terminals as it avoids the use of additional MOS transistors for current reversal and improves accuracy.

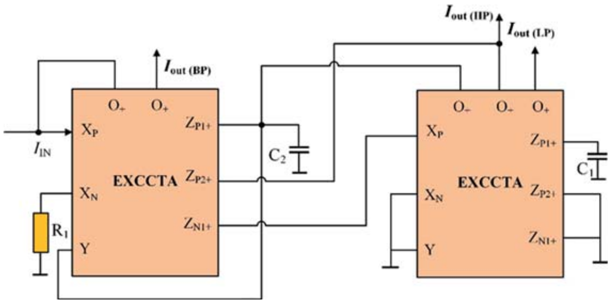

Figure 3: Proposed SIMO universal filter

The analysis of the filter circuit yields the transfer functions of all the five filter responses as given in Equations (6-10). The expression of quality factor and pole frequency of the filter are presented in Equations (11-13).

$$\frac{I_{HP}}{I_{IN}} = -\frac{S^2C_1C_2R_1}{S^2C_1C_2R_1 + SC_1R_1g_{m2} + g_{m1}} \tag{6}$$

$$\frac{I_{LP}}{I_{IN}} = -\frac{g_{m1}}{S^2C_1C_2R_1 + SC_1R_1g_{m2} + g_{m1}} \tag{7}$$

$$\frac{I_{BP}}{I_{IN}} = +\frac{SC_1R_1g_{m2}}{S^2C_1C_2R_1 + SC_1R_1g_{m2} + g_{m1}} \tag{8}$$

$$\frac{I_{NP}}{I_{IN}} = \frac{-S^2C_1C_2R_1 - g_{m1}}{S^2C_1C_2R_1 + SC_1R_1g_{m2} + g_{m1}} \tag{9}$$

$$\frac{I_{AP}}{I_{IN}} = \frac{-S^2C_1C_2R_1 - g_{m1} + SC_1R_1gm_2}{S^2C_1C_2R_1 + SC_1R_1gm_2 + g_{m1}} \tag{10}$$

$$f_o = \frac{1}{2\pi}\sqrt{\frac{g_{m1}}{C_1C_2R_1}} \tag{11}$$

$$Q = \frac{1}{g_{m2}}\sqrt{\frac{g_{m1}C_2}{C_1R_1}} \tag{12}$$

$$BW = \frac{1}{2\pi}\frac{g_{m2}}{C_2} \tag{13}$$

From equation (11) to (12), it is very clear that we can independently tune the quality factor of the filter without affecting the frequency (*f*) which means that *f* and Q are orthogonally tunable.

4 Non - ideal and sensitivity analysis

The imperfections present in the MOS transistors leads to improper transfer of current and voltage signals which leads to a shift in the V-I transfer characteristics of the EXCCTA from the ideal one. This results in the shift in the frequency and quality factor of the designed filter. The frequency dependent current, voltage and transconductance transfer gains are considered for the analysis as they are the major contributor. Considering the non-ideal gains the V-I relations of the EXCCTA will be modified to I_Y=0, $V_{XP} = \beta_p(s)V_Y$, $V_{XN} = \beta_N(s)V_Y$, $I_{ZP+} = \alpha_p(s)I_{XP}$, $I_{ZN+} = \alpha_N(s)I_{XN}$, $I_{0+} = \gamma g_m V_{ZP+}$, where $\beta_{P/N}$ is non-ideal voltage transfer gain, $\alpha_{P/N}$ is non-ideal current transfer gain and γ is non-ideal transconductance transfer gain. Ideally $\beta_{P/N} = \alpha_{P/N} = \gamma = 1$.

By considering the effect of EXCCTA non-idealities on the designed filter the expression of quality factor and angular frequency are modified as given in Equations 14-15.

$$f_o = \frac{1}{2\pi}\sqrt{\frac{\alpha_N\alpha_P\beta_P\gamma g_{m1}}{C_1C_2R_1}} \tag{14}$$

$$Q = \frac{1}{g_{m2}}\sqrt{\frac{\alpha_N\beta_P g_{m1}C_2}{\alpha_P\gamma C_1R_1}} \tag{15}$$

The active and passive sensitivities of the proposed are evaluated and presented below.

$$-S^{\omega}_{C_1} = -S^{\omega}_{C_2} = -S^{\omega}_{R_1} = S^{\omega}_{\gamma} = S^{\omega}_{\beta_P} = S^{\omega}_{\alpha_N} = S^{\omega}_{\alpha_P} = S^{\omega}_{g_1} = \frac{1}{2},$$

$$S^{Q}_{C_2} = -S^{Q}_{C_1} = -S^{Q}_{R_1} = -S^{Q}_{\gamma} = -S^{Q}_{\alpha_P} = -S^{Q}_{\gamma} = S^{Q}_{\beta_P} = S^{Q}_{g_1} = S^{Q}_{\alpha_N} = \frac{1}{2}$$

$$S^{Q}_{g_2} = -1$$

It is clear from analysis that all the sensitivities are unity or below which is the required condition. Hence the proposed filter has good performance in terms of sensitivity.

5 Parasitic study

The effect of EXCCTA parasitic elements on the performance of the filter is carried out in this section. The EXCCTA parasitic elements are shown in Figure 4. At Y terminal the parasitic resistance and capacitance appear in parallel (R_Y\\$C_Y$), same is the case with parasitic elements at Z_P, Z_N and O+ terminals where the parasitic elements appear in parallel as follows: (R_{ZP}\\$C_{ZP}$), ($R_{ZN}$\\

C_{ZN}), and (R_{O+}\\C_{O+}). The parasitic associated with low impedance X_P and X_N terminals appear as a resistors R_{XP} and R_{XN} in series with an inductor. The inductive effect is dominant at a very high frequency so it is ignored in this analysis.

Adding the EXCCTA parasitic elements in the proposed filter the node capacitance and resistance will me modified as $C_2' = (C_2 \backslash\backslash C_Y \backslash\backslash C_{ZP1+} \backslash\backslash C_{O+})$, $C_1' = (C_1 \backslash\backslash C_{ZP1+})$, $R_1' = (R_1 \backslash\backslash R_{XN})$. The modified tranfer functions of the filter including the parasitics are presented in Equations 16-22. The change in the total node capacitance and resistance majorly result in the deviation.One advantage of this topology is that the capacitors are connected with the high impedance nodes and the resistor is connected with the low impedance node. The capacitors will absorb the parasitic capacitance and the connected resistance will absorb the parasitic series resistance they by reducing the effect on the performance.

$$\frac{I_{HP}}{I_{IN}} = -\frac{S^2 R_1' C_1' C_2'}{S^2 R_1' C_1' C_2' + S R_1' C_1' g_{m2} + g_{m1}} \qquad (16)$$

$$\frac{I_{LP}}{I_{IN}} = -\frac{g_{m1}}{S^2 R_1' C_1' C_2' + S R_1' C_1' g_{m2} + g_{m1}} \qquad (17)$$

$$\frac{I_{BP}}{I_{IN}} = +\frac{S R_1' C_1' g_{m2}}{S^2 R_1' C_1' C_2' + S R_1' C_1' g_{m2} + g_{m1}} \qquad (18)$$

$$\frac{I_{NP}}{I_{IN}} = \frac{-S^2 R_1' C_2' C_1' - g_{m1}}{S^2 R_1' C_1' C_2' + S R_1' C_1' g_{m2} + g_{m1}} \qquad (19)$$

$$\frac{I_{AP}}{I_{IN}} = \frac{-S^2 R_1' C_2' C_1' - g_{m1} + S R_1' C_1' gm_2}{S^2 R_1' C_1' C_2' + S R_1' C_1' g_{m2} + g_{m1}} \qquad (20)$$

$$f_o = \frac{1}{2\pi}\sqrt{\frac{g_{m1}}{R_1' C_1' C_2'}} \qquad (21)$$

$$Q = \frac{1}{g_{m2}}\sqrt{\frac{g_{m1} C_2'}{R_1' C_1'}} \qquad (22)$$

6 Simulation results

To validate the proposed resistor less CM SIMO filter it is designed and simulated in Cadence virtuoso design software. The EXCCTA is designed in 0.18 µm Silterra Malaysia technology at a supply voltage of ±1.25V. The width and length of the transistors used are given in Table 2. The transconductance of the OTA was fixed 1.02 mS by selection the bias current I_{bias} = 120 µA. The layout of the EXCCTA is presented in Fig. 5. It is drawn using the nhp and php high performance MOS transistors from the Silterra library and occupies chip area of 65*26µm^2.

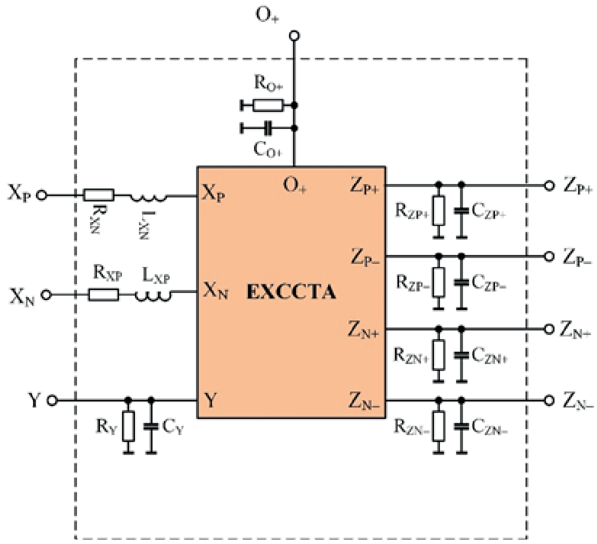

Figure 4: Non-ideal equivalent circuit model of the EXCCTA

Table 2: Width and Length of the MOS transistors

Transistors	Width (µm)	Length (µm)
M1-M2, M5-M6	1.8	0.36
M3, M4, M7, M8, M9	5.4	0.36
M10-M14	1.8	0.72
M15-M18	3.06	0.36
M19-M22	10	0.36
M23, M25, M27, M29, M31, M35, M37, M33, M42, M44	2.16	0.36
M24, M25, M28, M41, M43, M34	0.72	0.72
M30, M32, M36, M38	1.08	0.72

The pole frequency of the filter is fixed at 16.07 MHz and quality factor to 1.2 by setting passive component values as R_1 = 1kΩ, $C_1 = C_2$ = 10 pF and g_m = 1.02 µS. The LP, HP, BP and NP responses of the CM SIMO filter are presented in Fig. 6. The AP gain and phase response is given in Fig. 7. The simulated frequency for CM-AP is found to be 15.75 MHz leading to 2% error. The power dissipation of the filter is found to be 3.29mW.

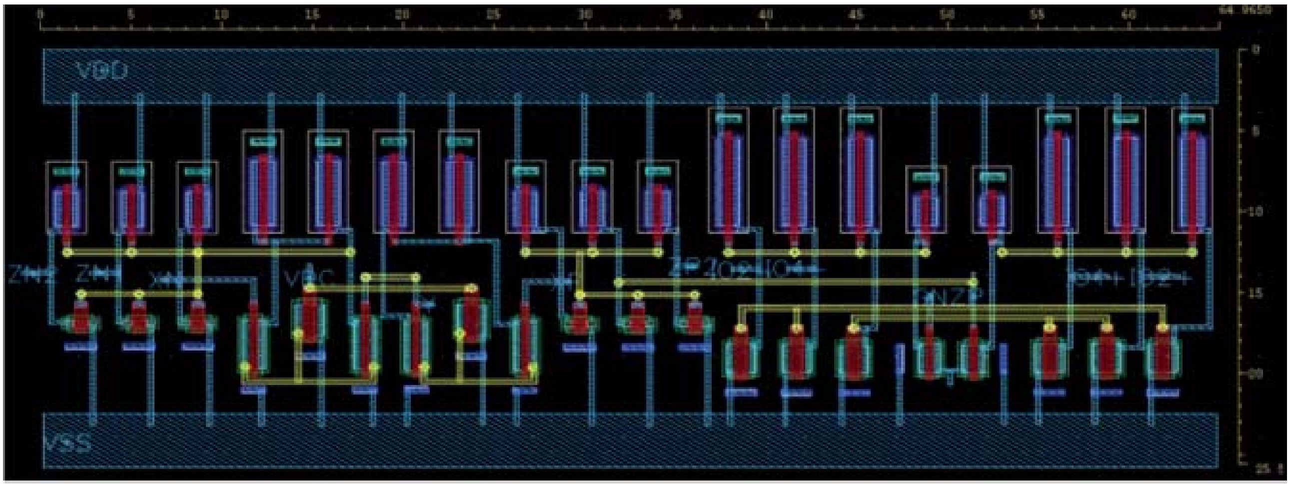

Figure 5: Layout of the EXCCTA

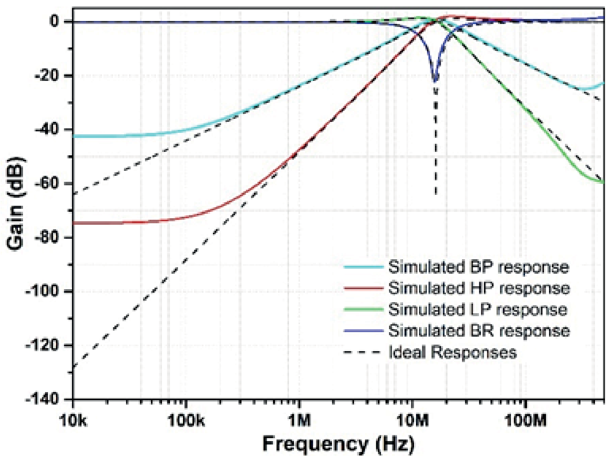

Figure 6: The ideal and simulated results of the SIMO filter

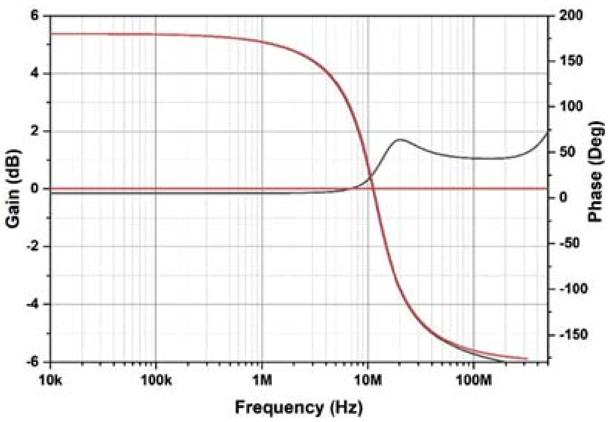

Figure 7: The AP gain and phase response of the SIMO filter

To establish the signal processing capability of the proposed filter a sine wave of frequency 16.07MHz and 100µA(p-p) amplitude is applied and the BP response of the filter is monitored as presented in Fig.8. It can be seen the filter output is accurate in terms of phase and magnitude. The Monte Carlo analysis is performed to measure the effect of device parameter variations and process spread on the performance of the filter. The Monte Carlo analysis is done for 200 runs using the mismatch models provided in the PDK for MOSFETs. As can be seen from Figure 8 the mean frequency is found to be 15.79 MHz which is close to designed frequency. Also, the frequency spread is small for majority of the samples so it can be concluded that the filter exhibits acceptable performance with minimum deviation under process variations. It can also be seen from the plot in Fig. 9 that minimum and the maximum frequency are 14.9MHz and 16.81MHz respectively. The phase plot of the all-pass response for the Monte Carlo analysis is presented in Fig. 10.

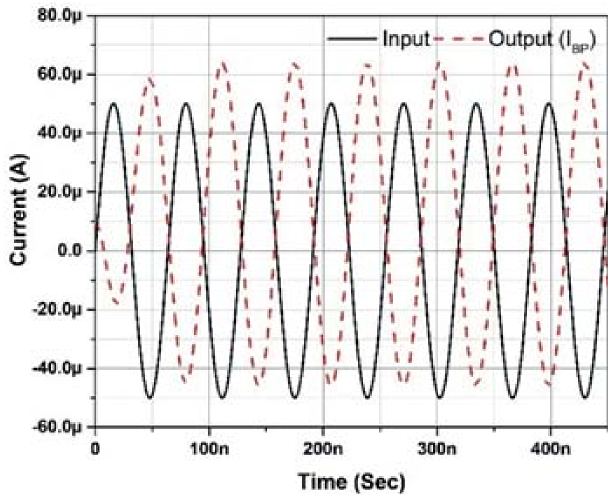

Figure 8: Time domain results for BP configuartion

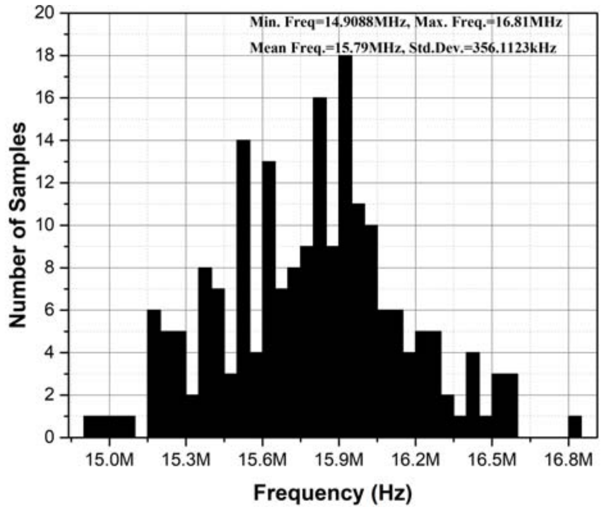

Figure 9: The Monte Carlo analysis results for AP confoguartion

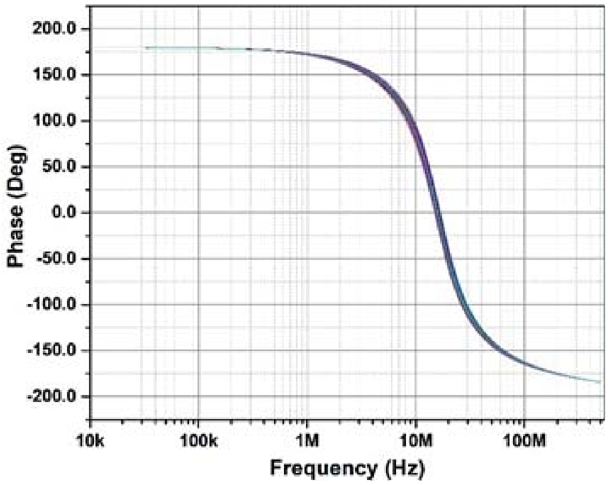

Figure 10: The Monte Carlo analysis plot of the phase response of AP configuartion

The variation of the quality factor independent of the pole frequency is examined for different values of I_{Bias2} ranging from I_{Bias2} =20μA(g_{m2} = 463μS), I_{Bias2} =50μA(g_{m2} = 681μS), I_{Bias2} =80μA(g_{m2} = 910μS) and I_{Bias2} =120μA(g_{m2} = 1.02μS) while keeping I_{Bias1} constant as presented in Fig. 11. The quality factor of the filter chages as per Equation 12 due to the change in the transcoducatnnce (g_{m2}). The effect of temperature variation on the functioning of the filter is examined by analysing the BP response under different temperature values ranging from 0° to 100°C. It can be inferred for the graph in Fig. 12(a-b) that although the filter frequency decreases with increase in temperature it is close to theoretical value within 20° to 60°C. Theoretically, the frequency of the filter should not change with temperature, but the frequency of the filter decreases due to rise in temperature because of the decrease in OTA transconductance (g_m). Two main contributing factors that influence the transconductance are the threshold voltage (V_t) and carrier mobility.The total harmonic distortion (THD) of the filter is measured for different input current amplitudes as presented in Fig. 13. The THD remains within acceptable limit of 5% for significant input current range.

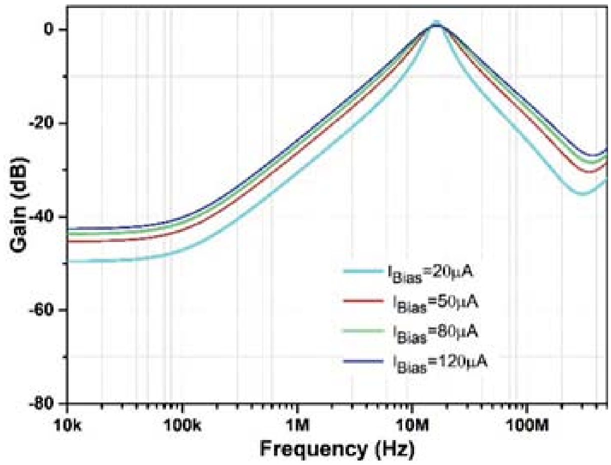

Figure 11: BP quality factor tuning

(a)

(b)

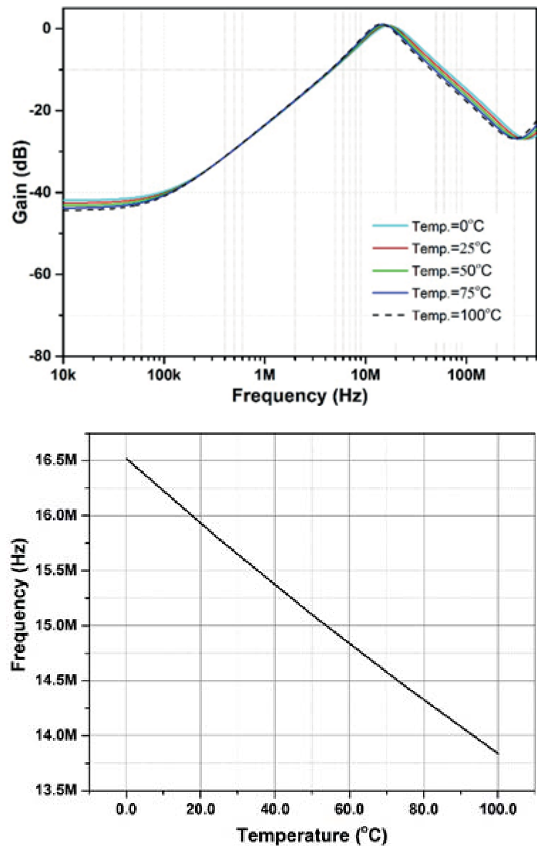

Figure 12: Effect of temperature on the filter performance (a) BP response (b) BP frequency variation

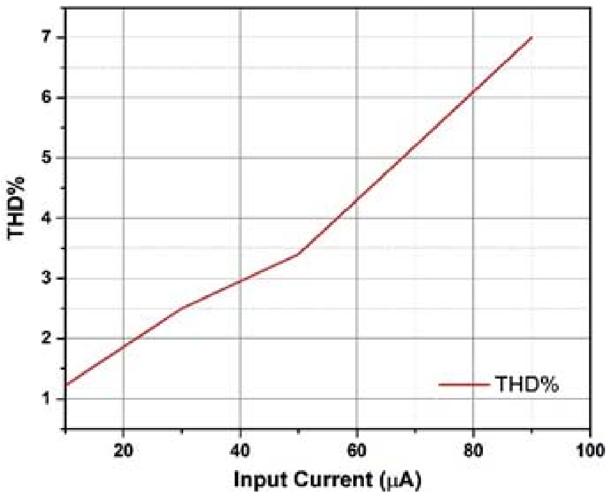

Figure 13: Variation of total harmonic distortion with applied input current

The frequency tunability of the filter is shown by varying the bias currents (I_{Bias1} and I_{Bias2}) of the OTAs simultaneously. It can be seen from Figure 14 that the filter frequency changes with change in the bias currentss also it is observed that there is slight change in the quality factor of filter due to change in the transconductnace (g_{m2}). The change in the quality factor can be nullified by accordingly setting the value of R_1 or setting the value of g_{m2}.

7 Implementation using commercially ICs

To further investigate the workability of the filter it is designed using commercially available ICs. The be-

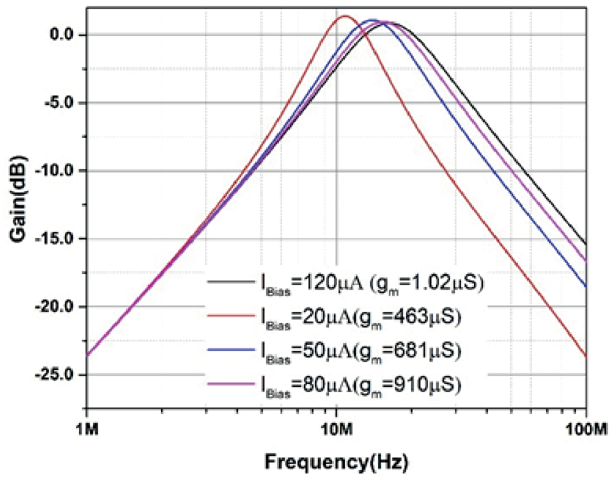

Figure 14: Variation of filter frequency with bias currents of the OTA

havioural models of the current feedback operational amplifier (AD844) and OTA (LM13700) provided by the manufacturer are used in the study. The PSPICE software is used for the analysis. The authors want to mention that the IC based implementation is done for the proof of concept as the fabricated chip is not available for experimental validation. The Figure 15 presents the implementation of the filter.

The filter frequency is set at 225kHz by setting OTA transconductance at 2mS and passive component values at R_1 = 1 kΩ, C_1 = C_2 = 1nF. The frequency domain analysis of the filter is done as presented in Figure 16. The close relationship between the ideal and simulated results verify the feasibility of the proposed design.

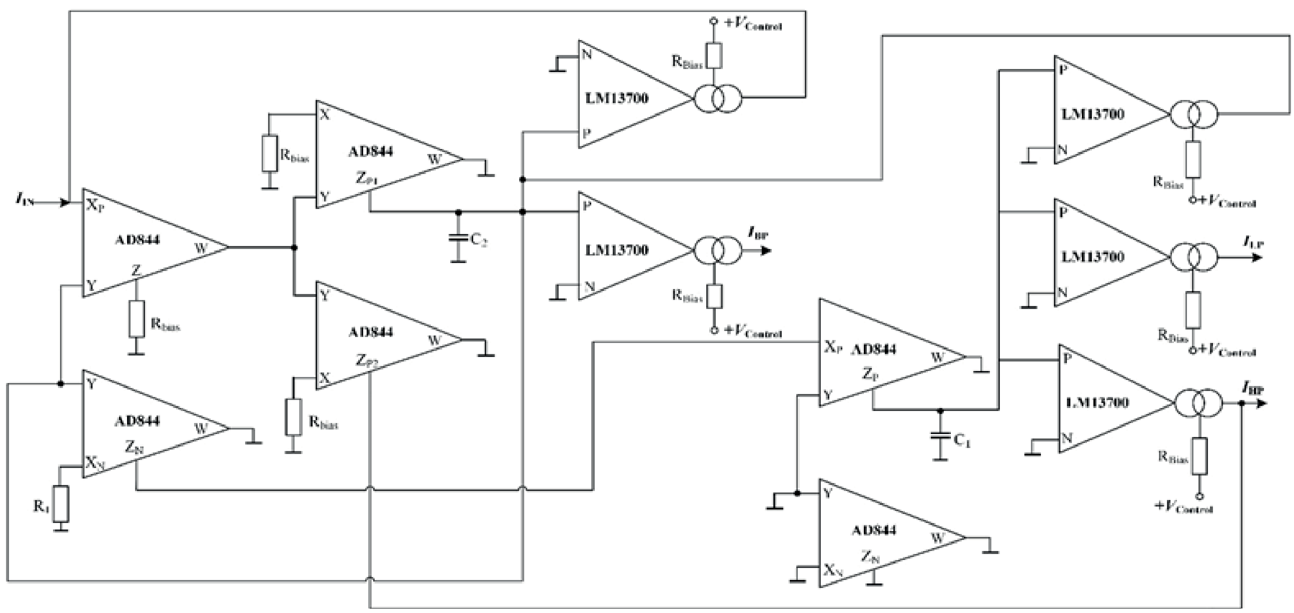

Figure 14: Implementation of the proposed filter using commercially available ICs AD844 and LM13700

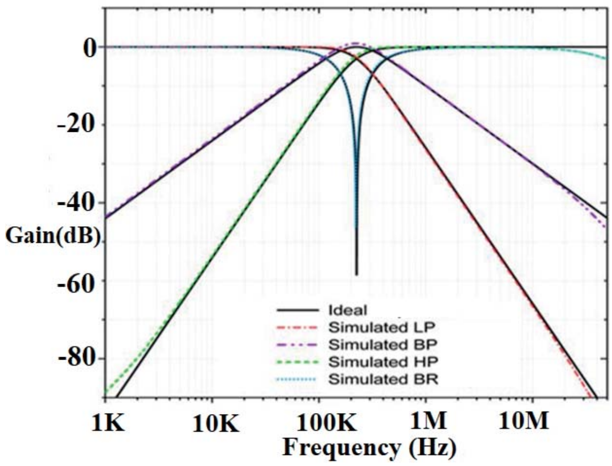

Figure 16: Frequency response of the filter obtained using AD844 and LM13700

8 Conclusion

This paper presents a new EXCCTA based electronically tunable SIMO filter. The filter employs two EXCCTA, one resistor and two grounded capacitors. Presented SIMO filter has inbuilt tunability and can realize all five filter responses simultaneously. The EXCCTA is designed in Cadence Virtuoso software and extensive simulations are carried out to examine and validate the proposed filter. The proposed filter has all the advantages mentioned in Table 1.The filter is designed for a frequency of 16.07 MHz at ±1.25 V supply. The Monte Carlo analysis shows that the frequency deviation is within acceptable limits. Furthermore, the THD is within 5% for considerable current input signal range. The simulation results are found consistent with the theoretical predictions.

9 Conflicts of interest

The authors declare no conflict of interest.

10 Acknowledgement

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