Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 47, No. 4(2017), 211 – 221

A Novel Mix-Mode Universal Filter Employing a Single Active Element and Minimum Number of Passive Components

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Abstract: A Novel biquadratic mixed mode tunable universal filter is presented. The mix mode filter is based on a new versatile active element dual X current conveyor differential input transconductance amplifier (DXCCDITA). The filter is capable of realizing high pass (HP), low pass (LP), band pass (BP), notch pass (NP) and all pass (AP) responses in voltage mode (VM), current mode (CM) and trans-impedance mode (TIM). In trans-admittance (TAM) mode the filter can realize HP and BP responses. The striking feature of the design is that it is the first reported mix mode Multi Input Single Output (MISO) filter employing a single active element for the design. Only a few passive elements are required for the design (two capacitors and two resistors). The second resistor is required only for obtaining TIM filter response. By properly exciting the filter structure with appropriate current or voltage signals the filter response in all four modes can be obtained. Additionally, VM response can be obtained both in inverting and non-inverting form simultaneously. The pole frequency and quality factor of the filter are tunable. The analysis of non-idealities and sensitivity is conducted to further study the effect of process variability on the filter response. The filter is simulated in Spice using 0.35µm CMOS model parameters obtained from TSMC. Additionally, the DXCCDITA is also constructed using commercially available integrated circuits (ICs) AD844 and LM13700. The ideal and measured results of the filter for Voltage mode are given to further validate its performance.

Keywords: Current mode; Current conveyor; Cascadable; Mix Mode; Tunable

Nov univerzalen filter z mešanim načinom delovanja z enim aktivnim elementom in minimalnim številom pasivnih komponent

Izvleček: Predstavljen je nov dvokvadrantni univerzalen in nastavljiv filter v mešanem načinu. Filter temelji na novem prilagodljivem aktivnem dvojnem X tokovnem diferencialnem transkonduktančnem ojačevalniku (DXCCDITA). Deluje lahko v visoko, nizko ali pasovno prepustnem načinu (HP, LP ali BP) ter tokovnem, napetostnem ali transimpedančnem načinu (CM, VM, TIM). Je prvi dizajn filtra, ki omogoča mešan način delovanja z le enim aktivnim elementom. Uporabljeni so le štirje pasivni elementi (dva upora in dva kondenzatorja), pri čemer je drugi upor potreben le za doseganje TIM odziva. S pravim tokovno napetostnim vzbujanjem lahko filter deluje v vseh štirih načinih. Dodatno, VM način omogoča simultan invertiran in neinvertiran odziv. Filter je simuliran v SPICE okolju v 0.35µm CMOS tehnologiji. DXCCDITA filter je realiziran s komercialnimi integriranimi vezji AD844 in LM13700. Validacija je prikazana na osnovi simuliranih in merjenih vrednosti v napetostnem načinu delovanja.

Ključne besede: Tokovni način; tokovni ojačevalnik; kaskade; mešan način

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1 Introduction

Filters are an integral part of almost every electronic system and so their synthesis and development remains an ever evolving field. They find applications in signal processing, bio-medical, instrumentation, communication systems etc. Among various filter structures universal filters are the most versatile as all the standard filter functions can be derived from them [1]. They serve as standalone solution to many filtering needs.

Owing to their inherent advantage of wide bandwidth, high slew rate, low power consumption, simple circuitry and excellent linearity [1-3] current conveyors (CC) are widely used in electronic design. Moreover, the requirement of low voltage low power operation put forward by portable electronic devices and the energy harvesting systems [4] etc. further encourages the use of CC. In the present day mixed mode design environment where many systems interact, many times the need arises for the current mode and voltage mode circuits to be connected together. This requirement can be met by employing trans-admittance mode (TAM) and trans-impedance mode (TIM) filter structures which can serve as the interface providing distortion free interaction. Although a number of TAM and TIM filter structures can be found in the literature but a single topology providing the CM, VM, TAM and TIM responses will be an added advantage in terms of area and power requirements. In the past two decades, a number of mixed mode filters have been proposed utilizing different current mode active elements like dual output current controlled current conveyor (DOCCCII), multi output current conveyor (MOCCII) [3], current controlled current conveyor transconductance amplifier (CCCCTA) [3], Current feedback operational amplifiers (CFOA) [3], fully differential current conveyor (FDCCII) [3], differential difference current conveyor and digitally programmable current conveyor (DPCCII) [3] etc.

The filter structures can be classified in three basic groups single input multi output (SIMO) [9], multi input multi output (MIMO) [5], multi input single output (MISO) [6]. The mix mode filters can be categorized based on many criteria like number of active elements utilized, number of passive components employed, requirement of components matching, whether the filter is tunable, number of filter responses realized in each mode, cascadability of the filter etc. The designs in [5, 6, 7, 8, 11, 12, 13, 17] require three or more active elements which results in large chip area and increased parasitic effects. The filter topologies in [10, 14, 16] requires two active elements but four or more passive elements. The mix mode filters in [5, 7, 8, 11] cannot realize all standard filter responses in all the four modes. In addition, filter structures in [6, 12, 13, 14, 16] did not posses inbuilt tuning capability. A comprehensive comparison of some of the exemplary mix mode filter designs with the proposed filter is presented in Table 1. The literature survey shows that except [15] no other single active element based filter to date exists that can function in all the four modes. Furthermore, the design of [15] is MIMO type filter which uses a complex building block, the FDCCII and did not posses inbuilt tuning property and cascadability for all responses in any mode. The filter in [15] requires a matching condition

Table 1: Comparison of the proposed filter with state of art filter topologies available in the literature

Reference	Filter responses realized				Number/Type of Active Block	Passive Elements used	
	VM	CM	TAM	TIM		C	R
5	LP, BP, HP, NP	LP, BP, HP, NP	LP, BP, HP, NP	LP, BP, HP, NP	4/CCCII	2	0
6	All Five	All Five	All Five	All Five	7/CCII	2	8
7	LP, BP, HP	All Five	All Five	LP, BP, HP	3/CCCCTA	2	0
8 Fig. 4	Not Realized	All Five	Not Realized	All Five	2/CCII, 1/MOCCII	2	3
9	All Five	All Five	Not Realized	Not Realized	2/DO-CCCII	2	0
10	All Five	All Five	All Five	All Five	2/CCCII	2	2
11	LP, HP, BP	LP, HP, BP	LP, HP, BP	LP, HP, BP	5/MOCCCII	2	0
12	All Five	All Five	All Five	All Five	4/CFOA	2	9
13	Not Realized	All Five	Not Realized	All Five	3/MOCCII	2	5
14	All Five	All Five	All Five	All Five	3/DDCC	2	4
15	All Five	All Five	HP, BP	All Five	1/FDCCII	2	3
16	All Five	All Five	All Five	All Five	1/FDCCII, 1/DDCC	2	6
17	All Five	All Five	All Five	All Five	4/MOCCCII	2	0
Proposed	All Five	All Five	HP, BP	All Five	1/DXCCDITA	2	2

to realize AP response in all three modes. Moreover, excessive number of Input/output terminals are used in the design. In addition, the circuit cannot be constructed using the off the shelf popular ICs AD844 which is a slight disadvantage since every time it is not possible to fabricate the concept. The proposed filter on the other hand can be readily constructed using AD844 [33] and LM13700 [34] making it possible to test our design in hardware or employ the design in practical applications. Furthermore, the proposed mix mode filter realizes non-inverting responses in all four modes unlike [15]. The proposed filter is further compared with the state of the art recently published filter structures using single active elements to highlight the merits of the structure. The survey shows that majority of the single active element based implementations work in a single mode. The Table 2 presents the detailed comparison.

In this research the authors propose a mixed mode universal filter synthesized by single DXCCDITA [35]. The filter uses only two capacitors and two resistors. The second resistor is required only for obtaining TIM filter response. The filter can be termed as MISO since for a particular mode all the filter responses are obtained from a single node. By proper excitation with appropriate current or voltage signals the filter structure can perform in all four modes. The filter is capable of realizing all five standard filter responses in VM, CM and TIM modes. Additionally, in VM both inverting and non-inverting outputs are available simultaneously. In TAM mode the filter can realize HP and BP responses. The merits of the filter includes (i) it is the first reported MISO type mix mode filter using single active element (ii) no matching for VM, TAM, CM (HP, BP) and TIM (LP, BP) responses (iii) tunability of pole frequency via bias current (iv) use of minimum number of passive elements (v) availability of VM output at low impedance node (vi) availability of CM and TAM output at high impedance node (vii) low active and passive sensitivities (viii) provision for independent control of frequency and bandwidth (ix) provision for gain tuning in TIM mode. The simulations in 0.35µm technology parameters obtained from TSMC are conducted to test the performance of the filter. The DXCCDITA utilized in the filter design is also constructed using ICs AD844 and LM13700 to further validate the filter design.

2 Dual X current conveyor differential Input transconductance amplifier (DXCCDITA)

The proposed Dual X current conveyor differential Input transconductance amplifier (DXCCDITA) [35] is functionally a connection of DXCCII and OTA. The new block carries features of CCII, ICCII and tunable transconductor in one single architecture which is also simple to implement as an integrated circuit. The Voltage current characteristics of the developed DXCCDITA are given in matrix Equation 1 and the block diagram is presented in Fig. 1.

Table 2: Comparison of the proposed filter with state of art MISO filter topologies available in the literature

Reference	Type of Active Block	Filter responses realized	Number of Capacitors/ Resistors Used	Matching Condition	Number/Type of Filtering Modes realized	Whether Tunable	Is output available from a single Node
18	CCII	LP, HP, BP, NP ,AP	2C/3R	Yes	1/VM	No	No
19 Fig. 16	DVCCII	LP, BP	2C/3R	No	1/VM	No	Yes
20 Fig. 4	FDCCII	LP, HP, BP, NP ,AP	2C/2R	No	1/VM	No	Yes
21 Fig. 8	DDCCTA	LP, HP, BP, NP ,AP	2C/1R	No	1/CM	Yes	No
22	VDIBA	LP, HP, BP, NP ,AP	2C/1R	No	1/VM	Yes	No
23	VDTA	LP, HP, BP, NP ,AP	2C/1R	No	1/VM	Yes	Ye
24	VDTA	LP, HP, BP, NP ,AP	2C/1R	No	1/VM	Yes	Yes
25	VD-DIBA	LP, HP, BP, NP ,AP	2C/1R	No	1/VM	Yes	Yes
26	CDBA	LP, HP, BP, NP ,AP	4C/4R	Yes	1/VM	No	Yes
27	CFOA	LP, HP, BP, NP ,AP	2C/3R	Yes	1/VM	No	Yes
28	CDTA	LP, HP, BP, NP, AP	2C/3R	Yes	1/CM	Yes	Yes
29	CFOA	LP, HP, BP, NP ,AP	2C/3R	Yes	1/VM	No	Yes
30	CDBA	LP, HP, BP, NP, AP	2C/5R	Yes	1/VM	No	Yes
31	CCII	LP, HP, BP, NP, AP	2C/2R	Yes	2/VM, CM	No	No
32 Fig. 2	FDCCII	LP, HP, BP, NP ,AP	2C/2R	No	1/CM	No	No
Proposed	DXCCDITA	LP, HP, BP, NP, AP (only HP, BP in TAM)	2C/2R	No (Only CM Mode)	4/CM, VM,TIM,TAM	Yes	Yes

$$\begin{bmatrix} I_Y \\ V_{XP} \\ V_{XN} \\ I_{ZP1} \\ I_{ZP2} \\ I_{ZN1} \\ I_{ZN2} \\ I_{0+} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & g_m & 0 & -g_m & 0 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_{XP} \\ I_{XN} \\ V_{ZP1} \\ V_{ZP2} \\ V_{ZN1} \\ V_{ZN2} \\ V_O \end{bmatrix}. \qquad (1)$$

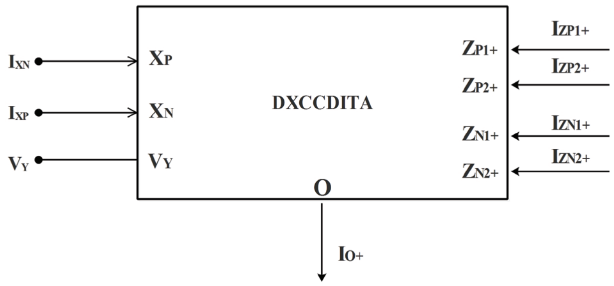

Figure1: Block diagram of DXCCDITA

The CMOS implementation of DXCCDITA is presented in Fig.2. It is a eight terminal active element. The first stage consists of DXCCII transistors (M1-M24). The voltage at Y appears at V_{XP} and in inverted form at V_{XN}. The current input at V_p node is transferred to nodes Z_{P1} and Z_{P2}. In the same way the input current from X_N node is transferred to Z_{N1} *and* Z_{N2}. The second stage is composed of OTA transistors. The transconductance is realized using transistors (M25-M34).The output current of the trans-conductor depends on the voltage difference between voltages at terminals Z_{P1} and Z_{N1}. Assuming saturation region operation for all transistors and equal W/L ratio for transistors M25 and M26 the output current I_o of the OTA is given by Equation 2.

$$I_O = g_{mi}\left(V_{ZP1} - V_{ZN1}\right) = \left(\sqrt{2I_{Bias}K_i}\right)\left(V_{ZP1} - V_{ZN1}\right) \qquad (2)$$

Where, the transconductance parameter $K_i = \mu C_{ox} W/_{2L}$, (i=25, 26) W is the effective channel width, L is the effective length of the channel, C_{ox} is the gate oxide capacitance per unit area andμ is the carrier mobility. It is evident from (2) that the transconductance can be tuned by the bias current thus imparting tunability to the structure.

3 The Proposed Single Active Element Mixed Mode Filter

The proposed mix mode universal filter is presented in Fig. 3. The filter utilizes two resistors and two capacitors. The second resistor R_2 is only needed to obtain TIM response. The VM, CM and TAM responses can be obtained using only three passive elements. The filter can realize all five generic filter responses in VM, CM, TIM while it can realize HP, BP functions in TAM mode of operation.

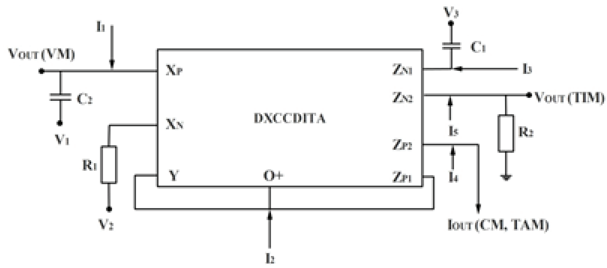

Figure 3: Mix Mode filter topology

3.1 Voltage Mode Operation

In voltage mode operation the input currents I_1 to I_5 are set to zero. The filter transfer function is given in Equation 3. The filter is capable of realizing all five standard filter functions. The input excitation sequence is given

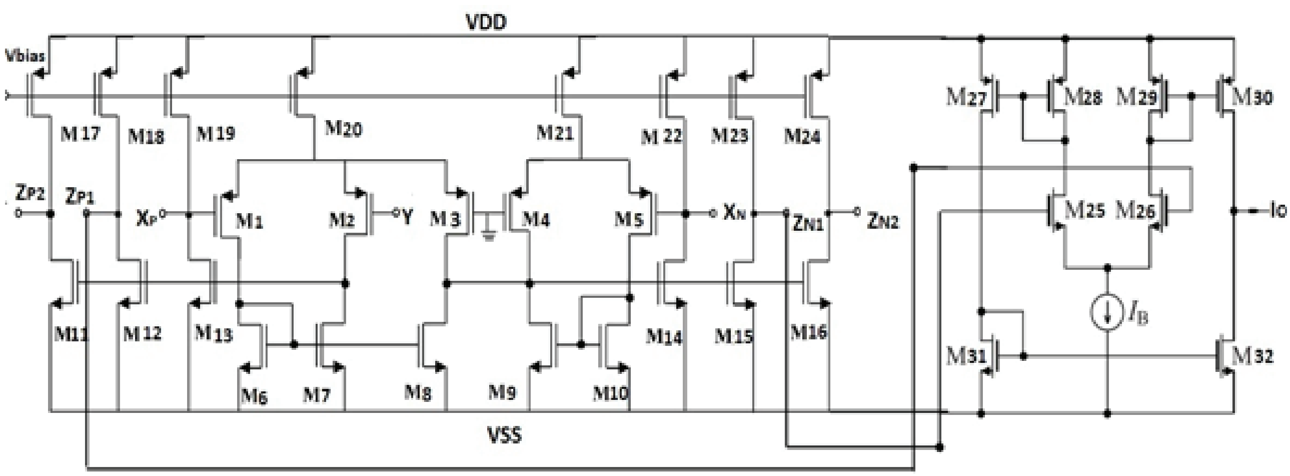

Figure 2: CMOS Implementation of DXCCDITA

in Table 3. The output of the filter is available at low impedance X_P terminal. It is worth emphasizing that by tapping the output from X_N node inverting VM response can also be obtained simultaneously which is an added advantage of the filter. In addition, in VM LP response both the capacitors are grounded which is again an advantage.

$$V_{Out(VM)} = \frac{V_1 S^2 C_1 C_2 \, {}^{R_1}\!/_{g_m} - V_2 + V_3 S C_1 R_1}{S^2 C_1 C_2 \, {}^{R_1}\!/_{g_m} + S C_1 R_1 + 1} \qquad (3)$$

Table 3: Input Excitation sequence for VM realization

V_{Out} (VM)	V_1	V_2	V_3	Matching Required
LP	0	-1	0	No
HP	1	0	0	No
BP	0	0	1	No
NP	1	-1	0	No
AP	1	-1	-1	No

3.2 Current Mode Operation

In current mode the voltages V_1 to V_3 are set to zero. Hence all the passive elements are grounded. The input currents are applied as shown in Fig. 3. It is to be noted that input current I_5 and resistance R_2 are not needed for CM operation so only four current inputs are necessary to achieve five standard filter responses. The transfer function is presented in Equation 4 and filter excitation sequence is given in Table 5. All the outputs are available at high impedance Z_{P2} node which is good for cascadability.

3.3 Trans-Impedance Mode Operation

In TIM mode the voltages V_1 to V_3 are set to zero grounding all the passive elements. In TIM mode an extra resistor is needed to obtain the output. In this mode input current I_4 is not required. To realize HP and NP responses a matching condition of $R_1 = 1/g_M$ is required which can be easily set by fixing R_1 and changing the bias current of the trans-conductor. The analysis of the filter leads to the transfer function as given in Equation 5. The excitation sequence of the filter is given in Table 5. The gain of the filter can be varied by changing the value of R_2 which is an advantage.

Table 4: Input Excitation sequence for CM realization

I_{Out}	I_1	I_2	I_3	I_4	Matching Required
LP	-1	0	-1	0	$C_1=C_2$
HP	0	-1	0	0	No
BP	0	0	1	0	No
NP	0	0	-1	1	$C_1=C_2$
AP	0	0	-2	1	$C_1=C_2$

Table 5: Input Excitation sequence for TIM realization

V_{Out}(TIM)	I_1	I_2	I_3	I_5	Matching Required
LP	0	0	-1	0	No
HP	1	0	1	1	$R_1=1/g_M$
BP	1	0	0	0	No
NP	1	0	0	1	$R_1=1/g_M$
AP	1	-1	0	1	$R_1=R_2=1/g_M$
AP (alternative option to make filter gain tunable)	2	0	0	1	$R_1=1/g_M$

3.4 Trans-Admittance Mode Operation

In TAM operation the filter transfer function is given in Equation 6. The filter can only realize HP and BP functions. The excitation table is given in Table 6. The output of the filter is available at high impedance Z_{P2} node.

$$I_{Out(TAM)} = \frac{-V_1\left(S^2 C_1 C_2 R_1 + SC_2\right) - V_2\left(SC_2\right) + V_3\left(S^2 C_1 C_2 R_1\right)}{S^2 C_1 C_2 \, {}^{R_1}\!/_{g_M} + SC_1 R_1 + 1} \qquad (6)$$

I_{Out}(TAM)	V_1	V_2	V_3	Matching Required
HP	0	0	1	No
BP	0	-1	0	No

$$I_{Out(CM)} = \frac{I_4(S^2 C_1 C_2 \, {}^{R_1}\!/_{g_M} + SC_1 R_1 + 1) - I_1\left(SC_1 R_1 + 1\right) - I_2(S^2 C_1 C_2 \, {}^{R_1}\!/_{g_M}) + I_3(SC_2 R_1)}{S^2 C_1 C_2 \, {}^{R_1}\!/_{g_M} + SC_1 R_1 + 1} \qquad (4)$$

$$V_{Out(TIM)} = \frac{I_5(S^2 C_1 C_2 \, {}^{R_1 R_2}\!/_{g_M} + SC_1 R_1 R_2 + R_2) - I_1\left({}^{SC_1 R_2}\!/_{g_M}\right) + I_2\left({}^{SC_1 R_1}\!/_{g_M}\right) - I_3(R_2)}{S^2 C_1 C_2 \, {}^{R_1}\!/_{g_M} + SC_1 R_1 + 1} \qquad (5)$$

The expression for pole frequency, quality factor and bandwidth for all four modes are given in Equations 7-9. It can be inferred by examining the equations that if R_1 or $R_M(1/g_M)$ is varied but their ratio is kept constant then frequency can be varied independent of the quality factor. This can be easily achieved by changing R_1 and adjusting the bias current of transconductance amplifier. The frequency and bandwidth also enjoy non interactive tuning capability through R_1 and R_M.

$$\omega_P = \sqrt{\frac{1}{C_1 C_2 R_1 R_M}} \tag{7}$$

$$Q = \sqrt{\frac{R_M C_2}{C_1 R_1}} \tag{8}$$

$$BW = 1 / R_M C_2 \tag{9}$$

where $R_M = 1/g_M$ is the transconductance of the transconductance amplifier.

The property of tunability allows changing the pole frequency of the filter without changing the passive components and it is also advantageous for cancelling out the variations in the pole frequency caused due to slight change in capacitance values during fabrication. The tuning can be achieved by changing the bias current of the OTA, any variation in the pole frequency introduced due to random variations in capacitance and device parasitics can be easily nullified. Moreover, the two resistors can be designed using the MOS transistors [36-37] this will impart dual tunability to the filter structure hence by properly tuning the control voltage of the MOS resistors and the bias current of the transconductance amplifier changes in the capacitance values can be easily accommodated.

4 Non-Ideal Analysis

In this section the Non-idealities of the DXCCDITA are considered and their influence on the proposed mix mode filter circuit is analyzed. A simplified non-ideal model of DXCCDITA is presented in Fig. 5 for analysis. The most important aspects contributing to the deviations in frequency performance are the non-ideal frequency dependent current and voltage transfer gains $a_i(s)$ and $b_i(s)$, where $a_i(s) = a_{0i}/(1 + s/w_{ai})$ and $b_i(s) = b_{0i}/(1 + s/w_{bi})$. Ideally, $a_i = b_{0i} = 1$ and $w_{ai} = w_{\beta I} = \infty$. Another

$$\begin{bmatrix} I_Y \\ V_{XP} \\ V_{XN} \\ I_{ZP1} \\ I_{ZP2} \\ I_{ZN1} \\ I_{ZN2} \\ I_{0+} \end{bmatrix} = \begin{bmatrix} (sC_Y + \frac{1}{R_Y}) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \beta_P(s) & Z_{XP} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\beta_N(s) & 0 & Z_{XN} & 0 & 0 & 0 & 0 & 0 \\ 0 & \alpha_P(s) & 0 & (sC_{ZP1} + \frac{1}{R_{ZP1}}) & 0 & 0 & 0 & 0 \\ 0 & \alpha_P(s) & 0 & 0 & (sC_{ZP2} + \frac{1}{R_{ZP2}}) & 0 & 0 & 0 \\ 0 & 0 & \alpha_N(s) & 0 & 0 & (sC_{ZN1} + \frac{1}{R_{ZN1}}) & 0 & 0 \\ 0 & 0 & \alpha_N(s) & 0 & 0 & 0 & (sC_{ZN2} + \frac{1}{R_{ZN2}}) & 0 \\ 0 & 0 & 0 & \gamma g_m & 0 & -\gamma g_m & 0 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_{XP} \\ I_{XN} \\ V_{ZP1} \\ V_{ZP2} \\ V_{ZN1} \\ V_{ZN2} \\ V_O \end{bmatrix} \tag{10}$$

$$V_{Out(VM)} = \frac{\alpha_P V_1 S^2 A - \alpha_N V_2 + V_3 SB}{\alpha_P \beta_P S^2 A + SB + \alpha_N \beta_N} \tag{11}$$

Where, $A = C_1 C_2 R_1 / g_m$, $B = C_1 R_1$

$$I_{Out(CM)} = \frac{I_4(\alpha_P \beta_P S^2 A + SB + \alpha_N \beta_N) - I_1 \alpha_P \left(\alpha_P \beta_P S^2 A + BS + \alpha_N \beta_N\right) + I_1(\alpha_P \beta_P S^2 A) - I_2 \beta_P (S^2 A) + I_3 \beta_P (SC_2 R_1)}{\alpha_P \beta_P S^2 A + BS + \alpha_N \beta_N} \tag{12}$$

$$V_{Out(TIM)} = \frac{I_5(\alpha_P \beta_P S^2 R_2 A + SBR_2 + \alpha_N \beta_N R_2) - I_1 \alpha_P \alpha_N \beta_N \left(SC_1 R_2 / g_m\right) + I_2 \alpha_N \beta_N \left(SB / g_m\right) + I_3 \alpha_N \beta_N (R_2)}{\alpha_P \beta_P S^2 A + BS + \alpha_N \beta_N} \tag{13}$$

$$I_{Out(TAM)} = \frac{V_1 \left(\alpha_P \beta_P S^3 C_1 C_2 C_2 R_1 / g_m\right) - V_2 \left(\alpha_N \beta_P SC_2\right) - \alpha_P SC_2 V_1 + V_3 \beta_N \left(S^2 C_1 C_2 R_1\right)}{\alpha_P \beta_P S^2 A + BS + \alpha_N \beta_N} \tag{14}$$

important performance parameter is the associated parasitics at the X nodes which can be quantified as $Z_{XP} = Z_{XN} = R_{X(N,P)} + sL_{X(N,P)}$. The parasitic resistances and capacitance associated with the Y and Z nodes are R_{ZP}, R_{ZN} and R_Y, while the associated capacitances are C_{ZP}, C_{ZN} and C_Y. There ideal values are equal to zero. γ represents the transconductance transfer inaccuracy of the OTA while R_o and C_o are parasitics at the OTA output. The modified V-I relations of DXCCDITA including the non-ideal gains and parasitic elements are given in Equation 10. Considering only the effect of the non-ideal gains the transfer functions, pole frequency and quality factor of the above filter will be modified as presented in Equations 11-16.

$$\omega_P = \sqrt{\frac{\alpha_N \beta_N}{C_1 C_2 R_1 R_M \alpha_P \beta_P}} \tag{15}$$

$$Q = \sqrt{\frac{R_M C_2 \alpha_N \beta_N \alpha_P \beta_P}{C_1 R_1}} \tag{16}$$

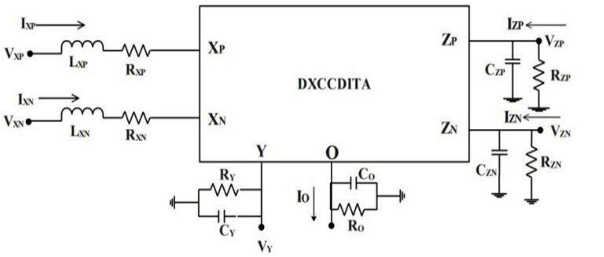

Figure 4: Non-Ideal model of DXCCDITA

The sensitivity analysis of the filter is also carried out to get a measure of active and passive sensitivities of the filter. It can be deduced from the analysis that the filter has low sensitivities.

$$-S_{R1}^{\omega} = -S_{C2}^{\omega} = -S_{C1}^{\omega} = S_{gm}^{\omega} = \frac{1}{2}$$

$$-S_{R1}^{Q} = S_{C2}^{Q} = -S_{C1}^{Q} = -S_{gm}^{Q} = \frac{1}{2}$$

$$-S_{\alpha P}^{\omega} = -S_{\beta P}^{\omega} = -S_{R1}^{\omega} = -S_{C2}^{\omega} = -S_{C1}^{\omega} = S_{\alpha N}^{\omega} = S_{\beta N}^{\omega} = S_{gm}^{\omega} = \frac{1}{2}$$

$$S_{\alpha P}^{Q} = S_{\beta P}^{Q} = -S_{R1}^{Q} = S_{C2}^{Q} = -S_{C1}^{Q} = S_{\alpha N}^{Q} = S_{\beta N}^{Q} = -S_{gm}^{Q} = \frac{1}{2}$$

5 Simulation results

In order to establish the performance of the proposed dual X current conveyor differential input transconductance amplifier (DXCCDITA) it was designed in 0.35 µm parameters from TSMC. The circuit was simulated in SPICE to measure the important design metrics. The aspect ratios of the transistors are given in Table 7. The supply voltages are kept at $V_{DD} = -V_{SS} = 1.5$V. The bias voltage was fixed at $V_{bias} = 0.55$V. The bias current of OTA was set to 50 µA which resulted in a transconductance of $g_m = 0.1$ mS. The proposed active element is characterized using the method stated in [38]. The performance parameters of the active block are summarised in Table 8.

Table 7: Aspect Ratios of the Transistors

Transistor	Width (W µm)	Length (L µm)
M1- M2	1.4	0.7
M3- M5	2.8	0.7
M6- M7	2.4	0.7
M8- M10	4.8	0.7
M11-M24	9.6	0.7
M25-M32	2	1

Table 8: Performance Parameters of the Proposed DXCCDITA

Voltage Gain (V_{XP}/V_Y)	0.98
Voltage Gain (V_{XN}/V_Y)	0.95
Current Gain (I_{ZP}/I_{XP})	1.05
Current Gain (I_{ZN}/I_{XN})	1.05
DC Voltage transfer range	±400mV
DC Current Transfer range (I_{ZP})	±60µA
DC Current Transfer range (I_{ZN})	±60µA
Voltage Transfer B.W. (V_{XP}/V_Y)	632MHz
Voltage Transfer B.W. (V_{XN}/V_Y)	728MHz
Current Transfer B.W. (I_{ZP}/I_{XP})	932MHz
Current Transfer B.W. (I_{ZN}/I_{XN})	1.32GHz
Parasitic Resistance at X_P node R_{XP}	71.1Ω
Parasitic Resistance at X_N node R_{XN}	38.2 Ω
Resistance at Z_N node R_{ZN}	305K Ω
Resistance at Z_P node R_{ZP}	305 K Ω
Resistance at O node Z_0	1.05M Ω

The operation of the filter in voltage mode is analyzed first. The filter is designed for unit quality factor (Q=1) and pole frequency of 318.30KHz by selecting the passive components values as R_1 =10KΩ, C_1 = 50pF, C_2 = 50pF the bias current is set at I_{bias} = 50µA. The filter responses are given in Fig. 5-6. Next, the tunability of the filter is examined by varying the bias current and observing the BP response. It can be inferred from the Fig. 7 that the filter is perfectly tunable. The total harmonic distortion (THD) of the filter is evaluated and plotted for different signal amplitudes as shown in Fig. 8. It can be seen that THD is within acceptable limit for wide range of voltage signal amplitudes. To study the effect of process variability on the filter performance Monte

Carlo analysis, assuming Gaussian distribution, for 10% deviation in capacitor values (C_1&C_2) is conducted for 100 runs as shown in Fig. 9. It can be deduced from the figure that there is only slight deviation from the expected value which can be easily nullified by adjusting the bias current of the filter as discussed in the preceding section.

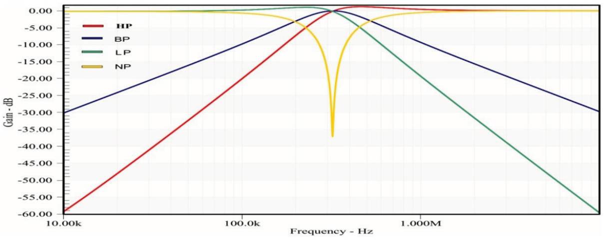

Figure 5: VM filter responses

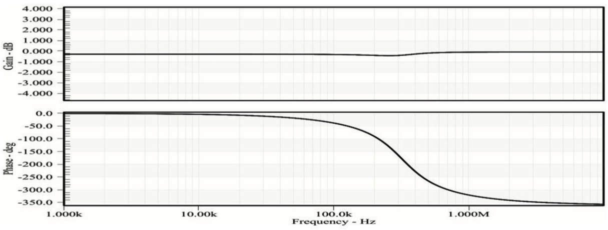

Figure 6: VM All Pass filter gain and phase response

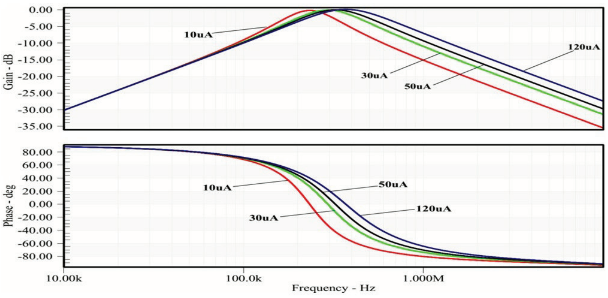

Figure 7: Band pass response of VM filter for different bias currents

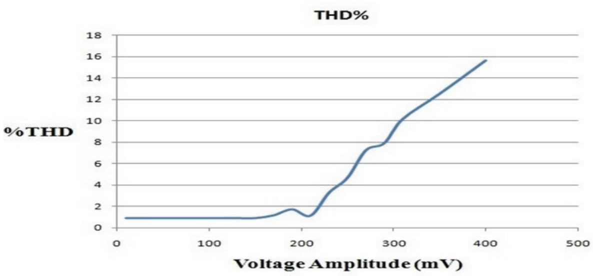

Figure 8: Total Harmonic Distortion of filter in voltage mode operation for BP response

The current mode filter is now designed for a pole frequency of 318.30 KHz by selecting R_1 = 10KΩ, C_1 = 50pF, C_2 = 50pF the bias current is set at I_{bias} = 50µA.

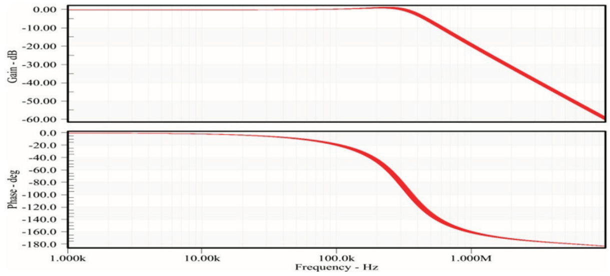

Figure 9: Monte Carlo analysis of the low pass response for 10% variation in capacitance value

The response of the filter is given in Fig. 10-11. The total harmonic distortion (THD) of the filter is evaluated and plotted for different signal amplitudes as shown in Fig. 12. It can be seen that THD is less than 1.5% for wide range of signal amplitudes.

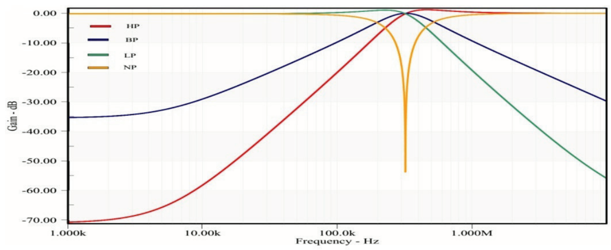

Figure 10: CM filter responses

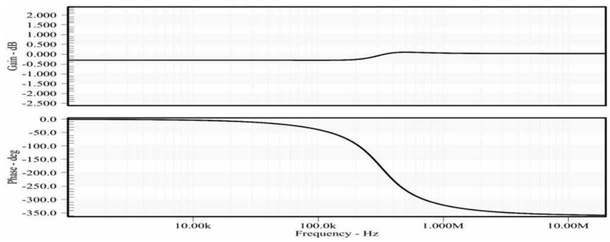

Figure 11: CM All Pass filter gain and phase response

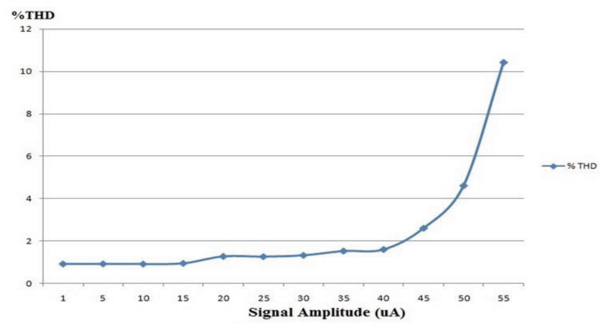

Figure 12: Total Harmonic Distortion of filter in current mode operation for BP response

Now the TIM response is analysed. The passive elements are fixed at R_1=R_2=10KΩ, C_1 = 50pF, C_2 = 50pF. The bias current is selected as I_{bias} = 50µA(g_M = 0.1ms) to satisfy the condition of $R_1 = 1/g_M$. The resulting pole frequency is 318.30 KHz. The responses of the filter are shown in Fig. 13-14.

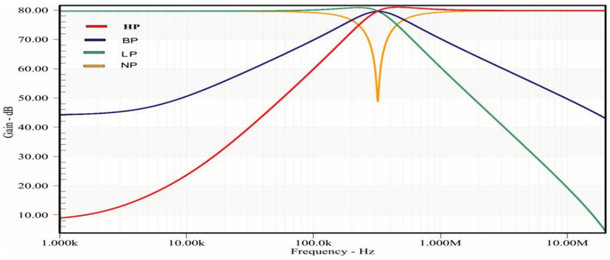

Figure 13: TIM filter responses

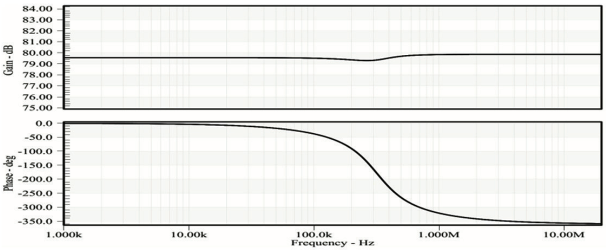

Figure 14: CM All Pass filter gain and phase response

To further validate the performance of the proposed topology. The DXCCDITA is constructed using the commercially available ICs AD844 and LM13700. The possible implementation of DXCCDITA is given in Fig. 15.

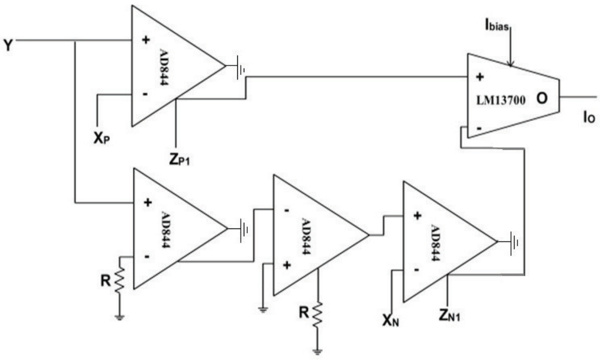

Figure 15: Implementation of the DXCCDITA from the commercially available ICs

The hardware implemented DXCCDITA is then used to measure the VM filter responses. The Agilent technologies MSO-X 3024A oscilloscope, IDL-800 digital lab prototype board, and Agilent technologies function generator were used in the test setup. The passive components values selected were C_1 = 560pF, C_2 = 560pF, R_1 = 10KΩ. The supply voltage are kept at $V_{DD} = -V_{SS}$ = 5V. The theoretical pole frequency of the filter is found to be 28.420 KHz. The ideal and measured filter responses are given in Fig. 16 (a-d). The all pass response is given in Fig. 17 (a-b).

a) b) c) d)

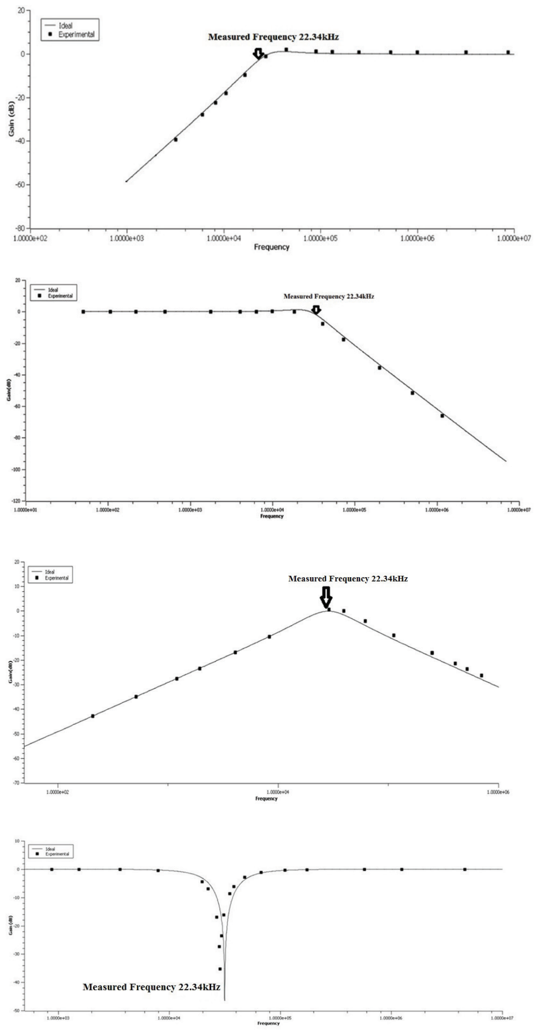

Figure 16: The VM filter responses constructed using the AD844 and LM13700 ICs

a) b)

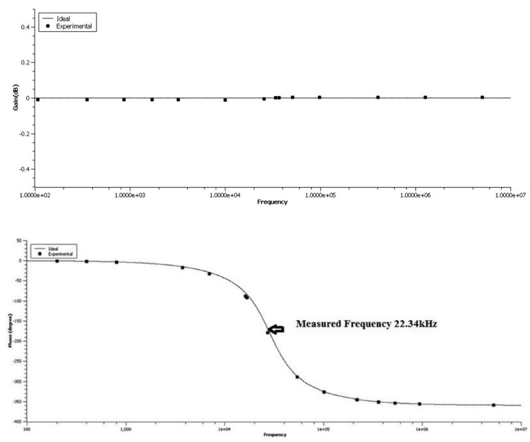

Figure 17: The VM filter all pass response constructed using the AD844 and LM13700 ICs (a)Gain (b) Phase

6 Conclusion

A novel minimum component MISO type mix mode universal filter is presented. The filter is designed using a single DXCCDITA as active element. To the best knowledge of the authors the reported filter is the first MISO type mix mode single active element based implementation capable of working in all four modes. The filter can realize all five standard responses in voltage mode, current mode and trans-impedance modes. The filter gives HP and BP responses in trans-admittance mode. No components matching condition are required in any mode except for trans-impedance mode (LP, NP, AP) and current mode (LP, NP, AP) responses. The filter offers low impedance voltage mode output and high impedance current and trans-admittance mode output leading to cascadability. The pole frequency, quality factor and bandwidth of the filter are tunable. There is a provision for gain adjustment of the filter in trans-impedance mode as well. The filter also enjoys low active and passive sensitivities. The experimental results are also given to validate the theory.

7 Acknowledgement

The authors gratefully acknowledge the support provided by UKM internal grant (GUP-2015-021) and grant from ministry of education (FRGS/2/2014/TK03/UKM/02/1) for this study.

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Arrived: 09. 06. 2017
Accepted: 14. 09. 2017