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VD-EXCCII Based Mixed Mode Biquadratic Universal Filter Employing Grounded Capacitors

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Abstract: A recently developed active building block (ABB), namely Voltage Differencing Extra X current conveyor (VD-EXCCII), is used to design an electronically tunable mixed-mode universal filter. The filter provides low pass (LP), high pass (HP), band pass (BP), band reject (BR), and all pass (AP) responses in voltage-mode (VM), current-mode (CM), trans-impedance-mode (TIM), and trans-admittance-mode (TAM). The filter employs two VD-EXCCIIs, three resistors, and two capacitors. The attractive features of the filters include: (i) ability to operate in all four modes, (ii) use of grounded capacitors, (iii) tunability of Q factor independent of pole frequency, (iv) low output impedance for VM and TIM mode, (v) high output impedance explicit current output for CM and TAM and (vi) no requirement for double/negative input signals (voltage/current) for response realization. The VD-EXCCII and its layout is designed and validated in Cadence virtuoso using 0.18µm process design kit (PDK) at supply voltage of ±1.25 V. The operation of filter is examined at 16.42 MHz frequency. The non-ideal gain and sensitivity analysis is also carried out to study the effect of process and components spread on the filter performance. The obtained results bear a close resemblance with the theoretical findings.

Keywords: Analog signal processing; mixed-mode filter; current conveyor; VD-EXCCII

VD-EXCCII na osnovi mešanega načina bikvadratičnega univerzalnega filtra, ki uporablja ozemljene kondenzatorje

Izvleček: Nedavno razviti aktivni gradnik (ABB), in sicer napetostni diferenčni pretvornik Extra X (VD-EXCCII), se uporablja za zasnovo elektronsko nastavljivega univerzalnega filtra z mešanim načinom delovanja. Filter omogoča odzive nizke prepustnosti (LP), visoke prepustnosti (HP), pasovne prepustnosti (BP), pasovne zavrnitve (BR) in vse prepustnosti (AP) v napetostnem (VM), tokovnem (CM), trans-impedančnem (TIM) in trans-admitančnem (TAM) načinu. Filter uporablja dva VD-EXCCII, tri upore in dva kondenzatorja. Privlačne lastnosti filtrov so: (i) možnost delovanja v vseh štirih načinih, (ii) uporaba ozemljenih kondenzatorjev, (iii) nastavljivost faktorja Q neodvisno od frekvence polov, (iv) nizka izhodna impedanca za način VM in TIM, (v) visoka izhodna impedanca z eksplicitnim izhodnim tokom za CM in TAM ter (vi) ni potrebe po dvojnih/negativnih vhodnih signalih (napetost/tok) za realizacijo odziva. VD-EXCCII in njegova postavitev sta zasnovana in potrjena v Cadence virtuoso z uporabo 0,18µm kompleta za načrtovanje procesov (PDK) pri napajalni napetosti ±1,25 V. Delovanje filtra je preverjeno pri frekvenci 16,42 MHz. Izvedena je tudi analiza neidealnega ojačanja in občutljivosti, da bi preučili vpliv razširjenosti procesa in komponent na delovanje filtra. Dobljeni rezultati so zelo podobni teoretičnim ugotovitvam.

Ključne besede: Obdelava analognih signalov; filter v mešanem načinu; tokovni transporter; VD-EXCCII

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1 Introduction

Recently, the Current-mode active building blocks (ABBs) are widely used for analog signal processing applications. The CM ABBs show greater linearity, wide bandwidth, simple structure, low power consumption, and enhanced dynamic range [1-6]. The universal frequency filters find a broad application spectrum in communication, control, instrumentation, data acquisition systems (in the analog front-end), biomedical signal processing, oscillator design, etc. [1, 2, 5, 7]. With the advancement of technology, mixed-mode systems are being developed, requiring interaction between CM and VM circuits. This task can be accomplished by TAM and TIM filters that not only perform signal processing, but also provide interfacing between VM and CM systems by acting as a bridge [8, 9]. The development of mixed-mode universal filters that can provide LP, HP, BP, BR, and AP filter functions in CM, VM, TAM, and TIM modes of operation is needed for mixed-signal system implementation.

Several designs of single-input multi-output (SIMO) and multi-input single-output (MISO) mixed-mode filters have been proposed in the literature that employ CM ABBs. A detailed comparison of the MISO filters with the proposed design is presented in Table 1, based on the following important measures of comparison: (i) number of CM-ABBs employed, (ii) the number of passive components needed, (iii) employment of all

Table 1: Comparative study of the state-of-the-art MISO Mixed mode filter designs with the proposed filter

References	Mode of Operation	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)
[10]	MISO	6-OTA	2C	Yes	N.A.	No	No	No	Yes	Yes	Yes	-
[6]	MISO	7-CCII	2C+8R	No	Yes	No	Yes	No	Yes	Yes	No	-
[11]	MISO	3-CCII	3C+4R+ 2-switch	No	No	No	Yes	No	Yes	Yes	No	-
[12]	MISO	4-OTA	2C	Yes	N.A.	No	No	No	Yes	Yes	Yes	2.25 MHz
[17]	MISO	5-OTA	2C	Yes	N.A.	No	Yes	No	Yes	No	Yes	1.59 MHz
[35]	MISO	2-MOCCCII	2C+2R	No	Yes	Yes	Yes	No	Yes	Yes	Yes	1.27 MHz
[38]	MISO	CFOA	2C+3R	No	No	Yes	No	No	Yes	No	No	12.7MHz
[20]	MISO	4-MOCCCII	2C	Yes	N.A.	No	Yes	Yes	Yes	No	Yes	-
[37]	MISO	1-FDCCII	2C+2R	No	Yes	No	No	No	Yes	Yes	No	10 MHz
[43]	MISO	2-VDTA	2C	Yes	N.A	Yes	No	No	Yes	Yes	Yes	1 MHz
[30]	MISO	1-FDCCII+1-DDCC	2C+6R	No	Yes	Yes	Yes	No	Yes	No	No	1.59 MHz
[29]	MISO	5-DVCC	2C+5R	Yes	Yes	Yes	Yes	No	Yes	Yes	No	1MHz
[45]	MISO	4-CCII	2C+4R	Yes	Yes	Yes	No	No	Yes	Yes	No	31.8 MHz
[26]	MISO	5-OTA	2C	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	3.390 MHz
[27]	MISO	3-DDCC	2C+4R	No	Yes	No	Yes	No	Yes	Yes	No	3.978 MHz
[45]	MISO	1-EXCCCII	2C	No	N.A.	Yes	No	No	Yes	No	Yes	23 MHz
[47]	MISO	4-ZC-CCTA	2C	No	N.A.	No	Yes	No	Yes	No	Yes	7.5 MHz
[40]	MISO	2-EXCCTA	2C+4R	No	Yes	Yes	Yes	No	Yes	Yes	Yes	7.622 MHz
[42]	MISO	2-VD-DVCC	2C+3R	No	Yes	Yes	Yes	No	Yes	Yes	Yes	5.305 MHz
[44]	MISO	2-VDBA	2C+2R	No	Yes	Yes	No	Yes	No	Yes	Yes	1.52 MHz
[41]	MISO	1-VD-EXCCII	2C+2R	No	Yes	Yes	Yes	No	Yes	Yes	Yes	8.08 MHz
This Works	MISO	2-VD-EXCCII	2C+3R	No	Yes	Yes	Yes	No	Yes	Yes	Yes	16.42 MHz

***Full** nomenclature of the mentioned ABBs in Tables 1 in alphabetical order: CCII: Second-generation current conveyor, CFOA: Current feedback operational amplifier, DDCC: Differential difference current conveyor, DVCC: Differential voltage current conveyor, EXCCCII: Extra x current controlled current conveyor, EXCCTA: Extra x Current conveyor transconductance amplifier, FDCCII: Fully differential second-generation current conveyor, MOCCCII: Multi output current controlled current conveyor, OTA: Operational transconductance amplifier, VD-DVCC: Voltage differencing differential voltage current conveyor, VDBA: Voltage differencing buffered amplifier, VDTA: Voltage differencing transconductance amplifier, ZC-CCTA: Z copy-current conveyor transconductance amplifier.

**N.A.-Not applicable

grounded passive components, (iv) no requirement for resistive matching except for obtaining AP response, (v) provision to control quality factor (Q) independent of the centre frequency, (vi) ability to provide all five filter responses in all four modes of operation, (vii) low output impedance for VM and TIM modes, (viii) availability of explicit current output in CM and TAM, (ix) no requirement for double/negative input signals (voltage/current), (x) inbuilt tunability, and (xi) test frequency. The MISO filter structures [3, 6, 8-29] employ ABBs in excess of two. The filter structures in [3, 6, 9, 11, 18, 21, 27, 29-32] require more than five passive components. The filter designs in [3, 6, 9, 11, 18, 21, 27, 30-42] do not employ all grounded passive components. The filters in [3, 6, 9-12, 16, 17, 20, 23, 24, 27, 30, 33, 36-39] do not provide quality factor tuning independent of frequency. The filter structures [6, 8, 10, 12-14, 16, 19, 21, 23, 28, 32, 33, 36-38, 43, 44] do not provide all five filter responses in VM, CM, TAM, and TIM operation. The filter structures [3, 6, 9, 11, 14, 18, 21, 27-34, 37-39] lack inbuilt tunability. The literature survey shows that a limited number of truly mixed-mode filters are available, and additional novel mixed-mode filter structures are needed to fill this technological void.

In this research, Voltage Differencing Extra X current conveyor (VD-EXCCII) is utilized to design mixed-mode filters. The design requires two VD-EXCCIIs, two capacitors, and three resistors. The striking features of the proposed filter are: (i) ability to work in all four modes of operation, (ii) provision for inbuilt tunability, (iii) the filter enjoy low active and passive sensitivities, and (iv) use of all grounded capacitors. Besides these, the filters enjoy all the properties (iv-x) mentioned in Table 2. The design of the VD-EXCCII is done in Cadence Virtuoso using 0.18µm PDK. The simulation results are in close agreement with the theoretical predictions.

2 Voltage differencing extra X current conveyor (VD-EXCCII)

The proposed Voltage Differencing Extra X current conveyor (VD-EXCCII) is derived by connecting extra X second generation current conveyor (EXCCII) [46] and operational transconductance amplifier (OTA). The first stage comprises OTA followed by the CCII with two current input terminals. The developed active element has characteristics of CCII and tunable OTA in one structure. The voltage-current (V-I) characteristics of the developed VD-EXCCII are presented in Equations (2.1-2.4) and the block diagram is presented in Fig. 1.

$$I_W = I_{WC+} = -I_{WC-} = g_m \left(V_P - V_N\right), \tag{2.1}$$

$$V_{XP} = V_{XN} = V_W, \tag{2.2}$$

$$I_{XP} = I_{ZP+} = -I_{ZP-}, \tag{2.3}$$

$$I_{XN} = I_{ZN+} = -I_{ZN-}. \tag{2.4}$$

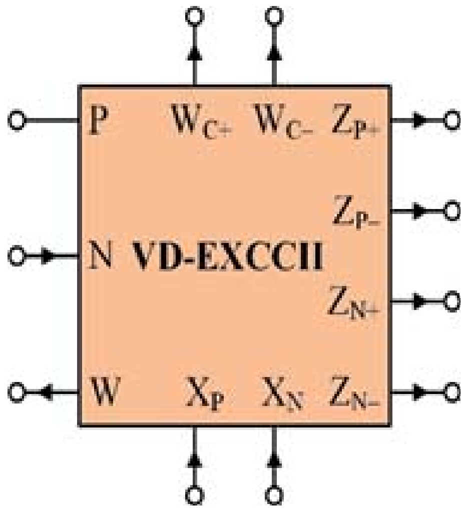

Figure 1: Block Diagram of VD-EXCCII

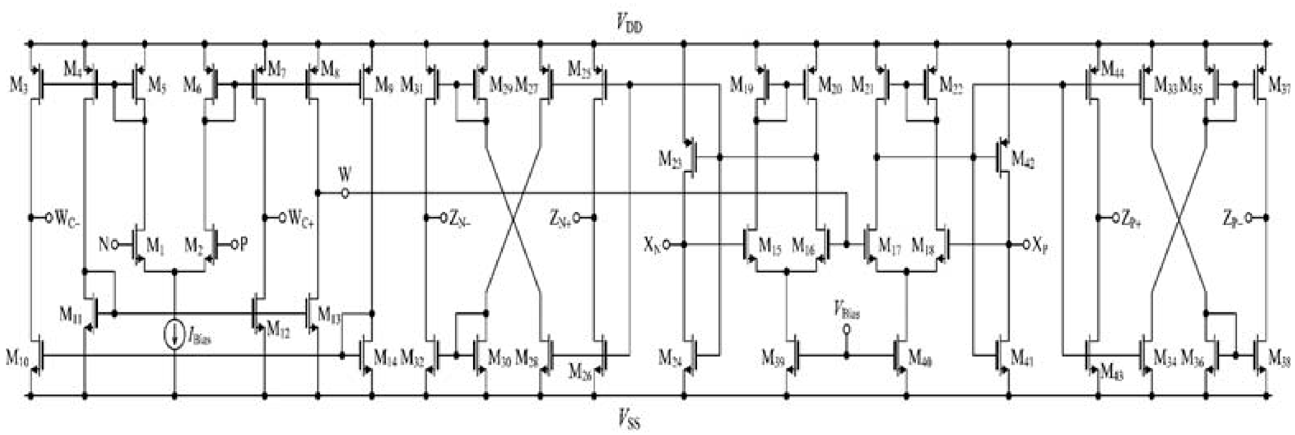

Figure 2: CMOS implementation of VD-EXCCII

The CMOS implementation of VD-EXCCII is given in Figure 2. The first stage consists of OTA MOS transistors (M1-M14). The output current of the OTA depends on the voltage difference ($V_P - V_N$). Assuming that all transistors are operating in saturation region and transistors (M1-M2) have equal width to length ratio, the output current is given by Equation 2.5. The second stage is made up of hybrid voltage and current followers (M15-M44). The voltage developed at node W is transferred to nodes X_P and X_N. In the same way, the input current from X_P node is transferred to Z_{P+} and Z_{P-}. Furthermore, the input current from X_N node is transferred to Z_{N+} and Z_{N-}. The current following in Z_N and Z_P terminals are independent of each other. The class AB output stage is utilized in the output stage as it is suitable for low voltage operation and better dynamic range [2].

$$I_W = I_{WC+} = -I_{WC-} = g_{mi}\left(V_P - V_N\right) = \left(\sqrt{2I_{Bias}K_i}\right)\left(V_P - V_N\right), \quad (2.5)$$

$K_i = \mu C_{ox} W/2L$, (i = 1, 2) is the transconductance parameter, W is the effective channel width, L is the effective length of the channel, C_{ox} is the gate oxide capacitance per unit area and μ is the carrier mobility.

3 Proposed electronically tunable mixed-mode universal filter

The proposed filter, as shown in Fig. 3, requires two VD-EXCCIIs, two capacitors, and three resistors. The filter offers low output impedance for VM and TIM mode of operation. In addition, the CM and TAM responses are available from explicit high impedance terminals. Furthermore, the capacitors are connected to high impedance terminals to absorb the parasitics associated with the terminals. Among the three resistors, two are connected to the low resistance X terminals to accommodate the parasitic resistance. The main drawback of the filter is the use of two floating resistors, but given the advantages of the filter, this can be accommodated. Moreover, floating resistors can be easily implemented in CMOS technology. The important features of the filter include: (i) ability to provide all five filter responses in all four modes of operation, (ii) employment of a minimum number of passive components, (iii) use of grounded capacitors, (iv) no requirement for resistive matching except for AP response, (v) low output impedance in VM and TIM configuration, (vi) no need for capacitive matching, (vii) availability of explicit current output in CM and TAM, (viii) no requirement for double/negative input signals (voltage/current), (xi) independent control of Q and f_0 and (xi) inbuilt tunability. The operation of the filter in all modes is explained below.

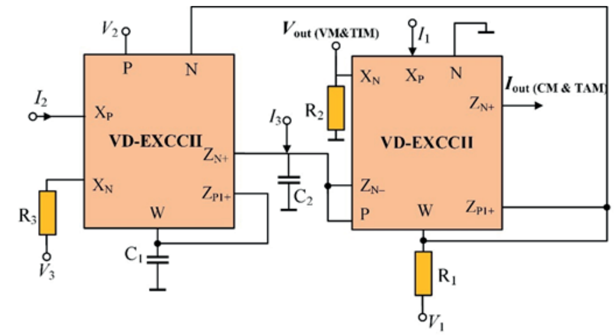

Figure 3: Proposed Mixed-mode Filter

3.1 Operation in VM and TAM mode

In this mode of operation, the inputs currents ($I_1 - I_3$) are set to zero. The filter is excited with input voltages ($V_1 - V_3$) as per the sequence given in Table 2. The transfer functions for VM/TAM and expressions for quality factor and pole frequency are given in Equations (3.1-3.4).

$$V_{out(VM)} = \frac{s^2C_1C_2R_2R_3V_1 - sC_1g_{m1}R_2R_1V_3 + R_1g_{m1}R_2g_{m2}V_2}{s^2C_1C_2R_2R_3 + sC_1g_{m1}R_3R_1 + R_1g_{m1}R_2g_{m2}} \quad (3.1)$$

For all pass response, a simple resistive matching of ($R_3 = R_2$) is required, which is easy to achieve.

$$I_{out\,(\mathrm{TAM})} = \frac{V_{out(VM)}}{R_2} = $$
$$= \frac{1}{R_2} * \left[\frac{s^2C_1C_2R_2R_3V_1 - sC_1g_{m1}R_2R_1V_3 + R_1g_{m1}R_2g_{m2}V_2}{s^2C_1C_2R_2R_3 + sC_1g_{m1}R_3R_1 + R_1g_{m1}R_2g_{m2}}\right], \quad (3.2)$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g_{m1}g_{m2}R_1}{C_1C_2R_3}}\ , \quad (3.3)$$

$$Q = R_2\sqrt{\frac{C_2g_{m2}}{C_1g_{m1}R_1R_3}}\ . \quad (3.4)$$

Table 2: Excitation Sequence for VM and TAM

Response	Inputs			Matching Condition	Filter Gain Constants
	V_1	V_2	V_3		
LP	0	1	0	No	1
HP	1	0	0	No	1
BP	0	0	1	No	1
BR	1	0	1	No	1
AP	1	1	1	$R_2 = R_3$	1

3.2 Operation in CM and TIM mode:

In this mode of operation, all input voltages ($V_1 - V_3$) are set to zero. The input currents ($I_1 - I_3$) are applied according to Table 3. The transfer functions for TIM and CM are given in Equations (3.5) and (3.6).

$$V_{out(TIM)} = R_1\left[\frac{-s^2C_1C_2R_2R_3I_1 + sC_1R_3g_{m1}R_2I_3 - g_{m1}R_2I_2}{s^2C_1C_2R_2R_3 + sC_1g_{m1}R_3R_1 + R_1g_{m1}R_2g_{m2}}\right] \quad (3.5)$$

$$I_{out(CM)} = \frac{V_{out(TIM)}}{R_2} = \frac{R_1}{R_2}\left[\frac{-s^2C_1C_2R_2R_3I_1 + sC_1R_3g_{m1}R_2I_3 - g_{m1}R_2I_2}{s^2C_1C_2R_2R_3 + sC_1g_{m1}R_3R_1 + R_1g_{m1}R_2g_{m2}}\right] \quad (3.6)$$

In Equation 3.6 for $R_1 = R_2$ the filter gain constants are $H_{oHP} = 1,\ H_{oLP} = \frac{1}{R_1g_{m2}}, H_{oBP} = 1$ by adjusting these parameters the filter gain can be adjusted.

Table 3: Input current excitation sequence

Response	Inputs			Matching Condition	Filter Gain Constants
	I_1	I_2	I_3		
LP	0	1	0	No	$\frac{1}{R_1g_{m2}}$
HP	1	0	0	No	1
BP	0	0	1	No	1
BR	1	1	0	No	1
AP	1	1	1	$g_{m1}R_2 = 1$, $R_2 = R_1$	1

4 Non-ideal gain and sensitivity analysis

The non-ideal effects that influence the response of the VD-EXCCII are the frequency-dependent non-ideal current ($\alpha_{P/N}$, $\alpha'_{P/N}$), voltage ($\beta_{P/N}$), and transconductance transfer (γ, γ›) gains. These non-ideal gains result in a change in the current and voltage signals during transfer leading to an undesired response. Taking into account the non-ideal gains, the V-I characteristics of the VD-EXCCII in (3.1-3.4) will be modified as follows: $I_W = 0$, $V_{XP} = \beta_P V_W$, $V_{XN} = \beta_N V_W$, $I_{ZP+} = \alpha_p I_{XP}$, $I_{ZP-} = -\alpha'_p I_{XP}$, $I_{ZN+} = \alpha_N I_{XN}$, $I_{ZN-} = \alpha'_N I_{XN}$, $I_W = I_{WC+} = \gamma g_m(V_P - V_N)$, $I_{WC-} = -\gamma' g_m(V_P - V_N)$, where $\beta_{Pm} = 1 - \varepsilon_{vPm}$, $\beta_{Nm} = 1 - \varepsilon_{vNm}$, $\alpha_{Pm} = 1 - \varepsilon_{iPm}$, $\alpha_{Nm} = 1 - \varepsilon_{iNm}$, $\gamma_m = 1 - \varepsilon_{g_m m}$, and $\gamma'_m = 1 - \varepsilon'_{g_m m}$, for $m = 1, 2$, which refers to the number of VD-EXCCIIs. Here, ε_{vPm}, ε_{vNm}($|\varepsilon_{vPm}|$, $|\varepsilon_{vNm}|$«1) denote voltage tracking error, ε_{iPm}, ε_{iNm} ($|\varepsilon_{iPm}|$, $|\varepsilon_{iNm}|$«1), denote current tracking errors, and $\varepsilon_{g_m m}$, , ε›$_{g_m m}$ ($|\varepsilon_{g_m m}|$, $|\varepsilon$›$_{g_m m}|$«1) denote transconductance errors of the VD-EXCCII.

The non-ideal analysis considering the effect of non-ideal current, voltage, and transconductance transfer gains is carried out for (VM, CM, TAM and TIM) configurations to see its effect on the transfer function, f_0, and Q of the proposed filter. The modified expressions of filter transfer functions, f'_0, and Q' are presented in Equations (4.1) to (4.6). The procedure to perform the non-ideal analysis can be found in [42].

$$V'_{out(VM-Mode)} = \left[\frac{s^2C_1C_2R_2R_3V_1 - s\alpha_{N1}\ \gamma_1 g_{m1}R_1R_2C_1V_3 + V_2\alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}{s^2C_1C_2R_2R_3 + \alpha'_{N2}\beta_{N2}\ \gamma g_{m1}SC_1R_3R_1 + \alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}\right] \quad (4.1)$$

$$I'_{out(TAM-Mode)} = \frac{\alpha_{N2}\beta_{N2}}{R_2}\left[\frac{s^2C_1C_2R_2R_3V_1 - s\alpha_{N1}\ \gamma_1 g_{m1}R_1R_2C_1V_3 + V_2\alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}{s^2C_1C_2R_2R_3 + \alpha'_{N2}\beta_{N2}\ \gamma_1 g_{m1}SC_1R_3R_1 + \alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}\right] \quad (4.2)$$

$$I'_{out(CM-Mode)} = \frac{\alpha_{N2}\beta_{N2}R_1}{R_2}\left[\frac{-s^2C_1C_2R_2R_3\alpha_{P2}I_1 + sC_1R_3\ \gamma_1 g_{m1}R_2I_3 - \alpha_{P1}\alpha_{N1}\beta_{N1}g_{m1}R_2I_2}{s^2C_1C_2R_2R_3 + \alpha'_{N2}\beta_{N2}\ \gamma_1 g_{m1}SC_1R_3R_1 + \alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}\right] \quad (4.3)$$

$$V'_{out(TIM-Mode)} = R_1\left[\frac{-s^2C_1C_2R_2R_3\alpha_{P2}I_1 + sC_1R_3\ \gamma_1 g_{m1}R_2I_3 - \alpha_{P1}\alpha_{N1}\beta_{N1}g_{m1}R_2I_2}{s^2C_1C_2R_2R_3 + \alpha'_{N2}\beta_{N2}\ \gamma_1 g_{m1}SC_1R_3R_1 + \alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1R_2}\right] \quad (4.4)$$

$$f'_0 = \frac{1}{2\pi}\sqrt{\frac{\alpha_{N1}\beta_{N1}\ \gamma_1\ \gamma_2 g_{m1}g_{m2}R_1}{C_1C_2R_3}} \quad (4.5)$$

$$Q' = \frac{R_2}{\alpha'_{N2}\beta_{N2}}\sqrt{\frac{\alpha_{N1}\beta_{N1}\ \gamma_2 C_2 g_{m2}}{\gamma_1 C_1 g_{m1}R_1R_3}} \quad (4.6)$$

The sensitivities of ω'_0 and Q' with respect to the non-ideal gains and passive components are given below in Equations (4.7) to (4.9).

$$S_{g_{m1}}^{\omega_o'} = S_{g_{m2}}^{\omega_o'} = S_{R_1}^{\omega_o'} = S_{\alpha_{N1}}^{\omega_o'} = S_{\beta_{N1}}^{\omega_o'} = S_{\gamma_2}^{\omega_o'} = S_{\gamma_1}^{\omega_o'} = -S_{C_1}^{\omega_o'} = -S_{C_2}^{\omega_o'} = -S_{R_3}^{\omega_o'} = \frac{1}{2} \tag{4.7}$$

$$S_{\alpha_{N1}}^{Q'} = S_{\beta_{NI}}^{Q'} = -S_{C_1}^{Q'} = S_{\gamma_2}^{Q'} = S_{g_{m2}}^{Q'} = S_{C_2}^{Q'} = -S_{g_{m1}}^{Q'} = -S_{R_1}^{Q'} = -S_{R_3}^{Q'} = -S_{\gamma_1}^{Q'} = \frac{1}{2}, \tag{4.8}$$

$$S_{R_2}^{Q'} = -S_{\alpha_{N2}'}^{Q'} = -S_{\beta_{N2}}^{Q'} = 1 \tag{4.9}$$

The sensitivities are low and have absolute values not higher than unity.

5 Simulation and validation

To verify the proposed mixed-mode filter, it is designed and simulated in Cadence virtuoso design software. The newly proposed VD-EXCCII is designed in 0.18 µm Silterra Malaysia technology at ±1.25V supply voltage. The widths and lengths of the transistors are given in Table 4. The bias current of the OTA is fixed at 120 µA resulting in a transconductance of 1.0321 µS. The layout of the VD-EXCCII Fig. 4 is drawn using the nhp and php high-performance MOS transistors from the Silterra library. The layout occupies a total area of 54.28*22.80µm^2.

The filter is designed for centre frequency of 16.4263 MHz and a quality factor of one by selecting passive component as $R_1 = R_2 = R_3 = 1$ kΩ, $C_1 = C_2 = 10$pF and $g_m = 1.0321$ µS. All five filter responses in VM, CM, TAM, and TIM modes are presented in Figs. 5-12. The simulated frequency for VM-AP is found to be 15.977 MHz leading to a 2.73% error.

Table 4: Width and Length of the MOS transistors

Transistors	Width (µm)	Length (µm)
M1–M2, M5–M6	1.8	0.36
M3–M4, M7–M9	5.7	0.36
M10–M14	1.8	0.72
M15–M18	3.06	0.36
M19–M22	10	0.36
M23, M25, M27, M33, M42, M44	2.16	0.36
M24, M26, M28, M32, M34, M30, M38, M36, M41, M43	0.72	0.72
M21, M31, M35, M37	1.08	0.72

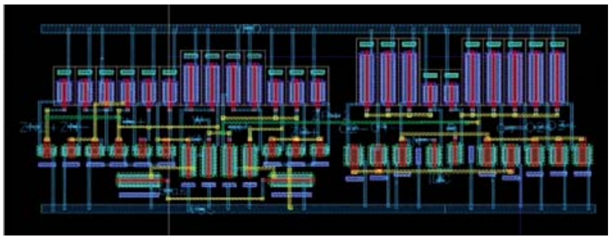

Figure 4: Layout of the VD-EXCCII

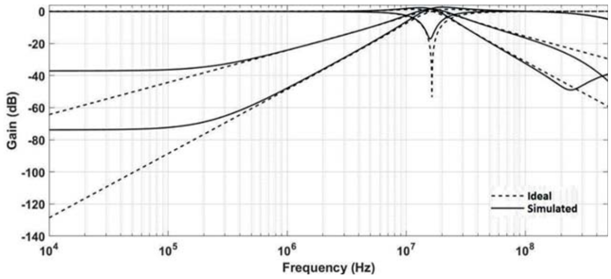

Figure 5: VM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

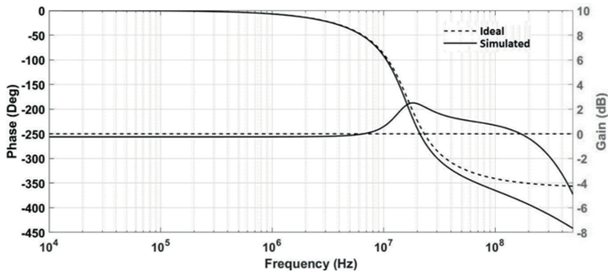

Figure 6: VM MISO configuration: Gain and phase responses of the AP filter

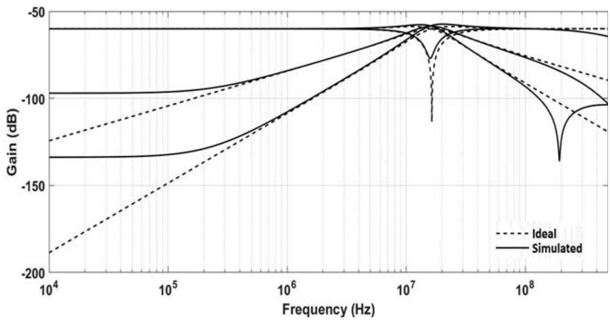

Figure 7: TAM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

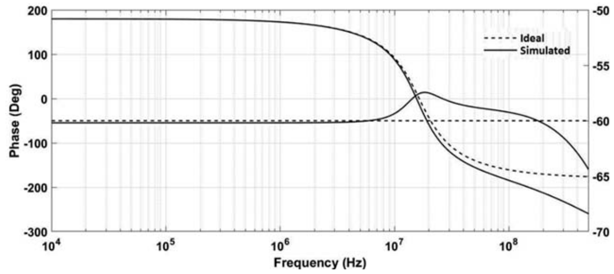

Figure 8: TAM MISO configuration: Gain and phase responses of the AP filter

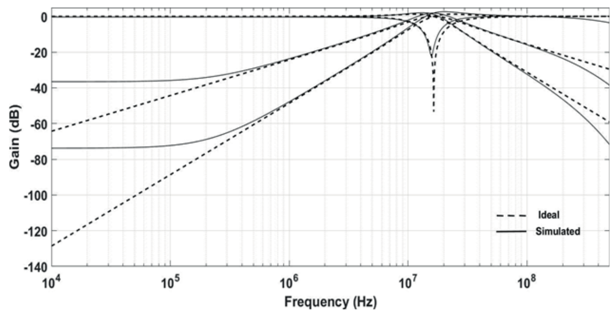

Figure 9: CM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

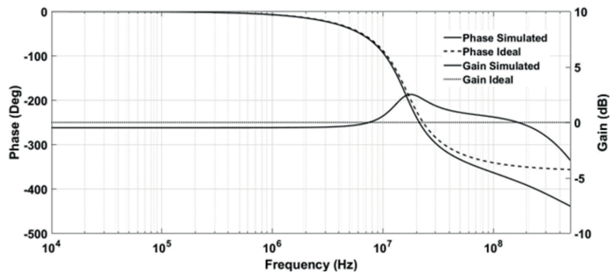

Figure 10: CM MISO configuration: Gain and phase responses of the AP filter

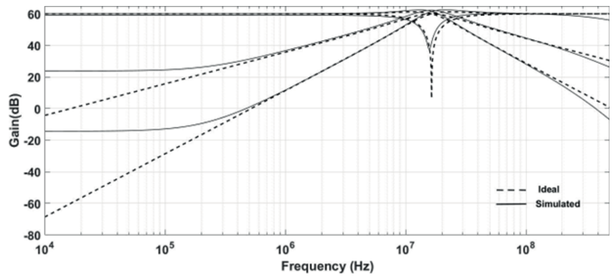

Figure 11: TIM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

To examine the signal processing capability of the proposed universal filter, the transient analysis is carried out in VM mode for HP, LP, BR, and BP responses. A VM sinusoidal signal of 100 mVp-p and 16.42 MHz frequency is applied at the input and the output is analyzed as presented in Fig. 13. Similarly, a CM sinusoidal signal of 50 µA p-p and 16.42 MHz frequency is applied at the input, and the BP output in CM is observed as shown in Fig. 14. In the presented filter, the quality factor can be set independently of the pole frequency of the filter. The tunability of the quality factor is verified by analysing BP response in VM for different values of resistor R_2 as shown in Fig. 15. It can be inferred from the figure that the quality factor of the filter can be tuned independently of the frequency. The frequency tuning is verified by varying the bias current of the OTAs and observing the CM-BP and VM-LP responses. It can be deduced that the frequency can be tuned without disturbing the Quality factor of the filter as presented in Fig. 16-17.

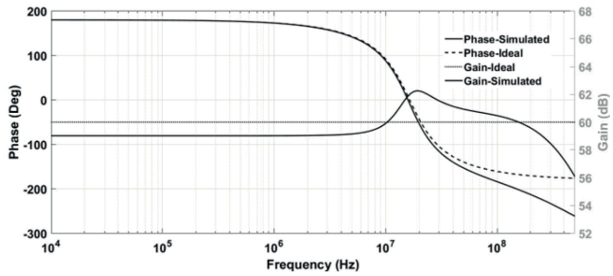

Figure 12: TIM MISO configuration: Gain and phase responses of the AP filter

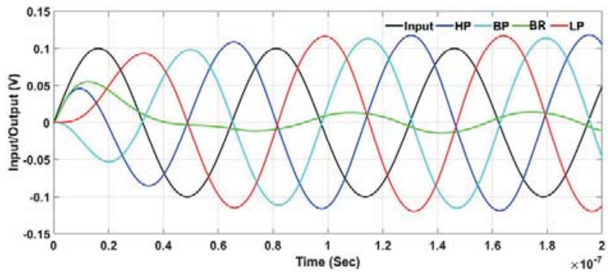

Figure 13: VM MISO configuration: Transient analysis results for BP, HP, LP, and BR filter configurations

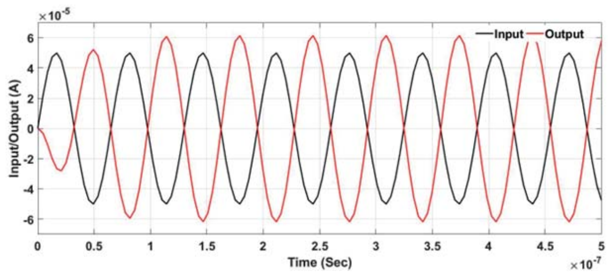

Figure 14: CM MISO configuration: Transient analysis results for BP filter configuration

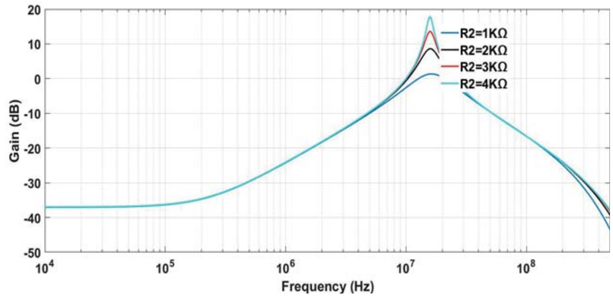

Figure 15: VM MISO configuration: Quality factor tuning for different resistor values in BP filter

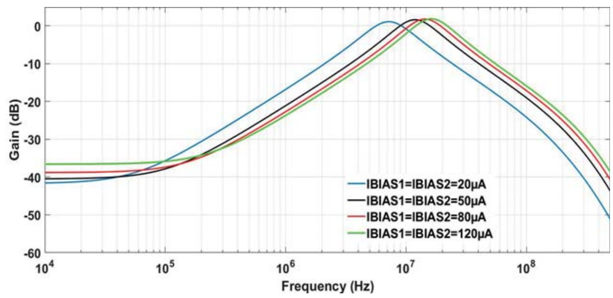

Figure 16: CM MISO configuration: Frequency tuning for different bias current (I_{Bias1} and I_{Bias2}) values in BP filter

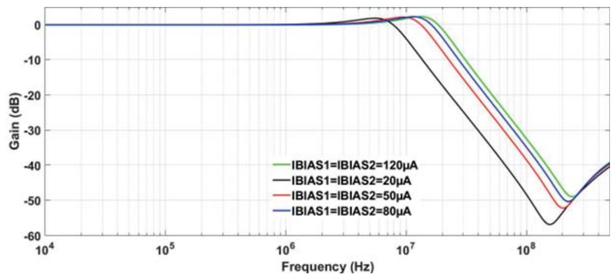

Figure 17: VM MISO configuration: Frequency tuning for different bias current (I_{Bias1} and I_{Bias2}) values in LP filter

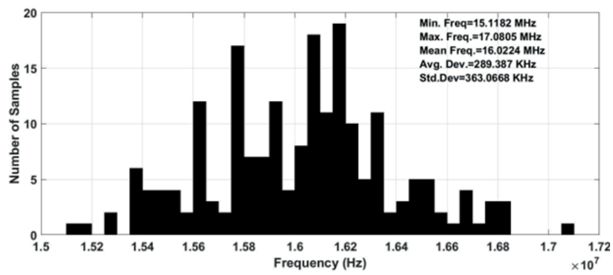

Figure 18: VM MISO configuration: The Monte Carlo analysis result for BP response

To study the effect of process spread on the performance of the designed filter, Monte Carlo analysis is carried out for 200 runs. The Monte Carlo analysis results for VM-BP response are given in Fig. 18 and 19. The results for CM-AP configuration is given in Fig. 20.

The total harmonic distortion (THD) of the filter for VM-BP response is plotted for different input signal values, as shown in Fig. 21. The THD plot for CM-BP and CM-LP is presented in Fig. 22. The THD remains within acceptable limits (≤5%) for the appreciable input range.

The input and output noise of the filter for VM-LP configuration is shown in Fig. 23. The input referred noise magnitude in the pass band of VM-LP is found in the range of 2.914E-08 $V/Hz^{1/2}$. The magnitude of output referred noise is in the range of 3.425E-08 $V/Hz^{1/2}$.

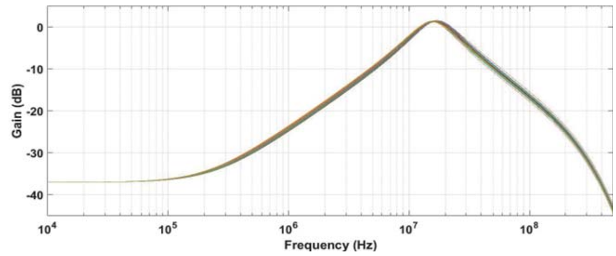

Figure 19: VM MISO configuration: The Monte Carlo analysis result for BP configuration

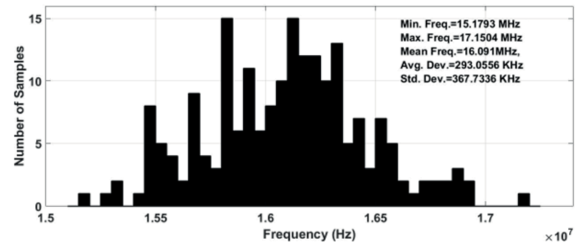

Figure 20: CM MISO configuration: The Monte Carlo analysis result for AP response

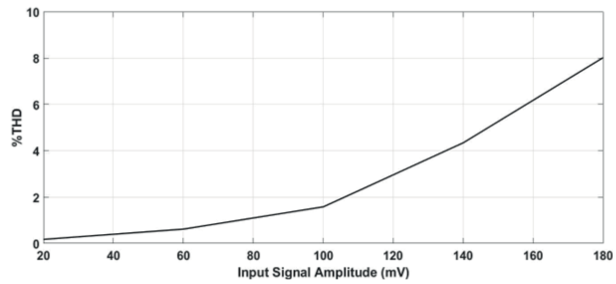

Figure 21: Total harmonic distortion for VM-BP

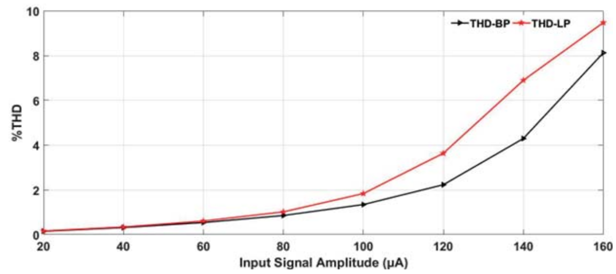

Figure 22: Total harmonic distortion for CM-BP & CM-LP

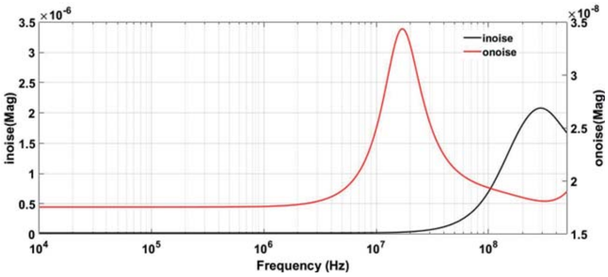

Figure 23: Input and Output referred noise

6. Conclusion

This paper presents a new VD-EXCCII based electronically tunable mixed-mode filter. The filter employs two VD-EXCCIIs, three resistors, and two grounded capacitors. The presented MISO filter has inbuilt tunability and can realize all five filter responses in all four modes of operation (VM, CM, TAM, and TIM). Detailed theoretical analysis and non-ideal gain analysis are done. The VD-EXCCII is designed in Cadence Virtuoso software and extensive simulations are carried out to examine and validate the proposed filter in all four modes of operation. The proposed filter has all the advantages mentioned in Table 2 (iv)-(x). The filter is designed for a frequency of 16.42 MHz at ±1.25 V power supply. The Monte Carlo analysis shows that the frequency deviation is within acceptable limits. Furthermore, the THD is within 5% for a considerable voltage/current input signal range. The simulation results are found consistent with the theoretical predictions.

7 Conflict of interest

Authors declare no conflict of interest

8 Acknowledgement

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