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Novel Minimum Component Dual Mode Biquadratic SIMO Filter with Electronic Tunability

***Abstract**. Two topologies of minimum component single input multiple output (SIMO) filters are designed by employing a versatile active building block (ABB), the current conveyor transconductance amplifier (CCTA). The proposed filters work in current mode (CM) and trans-admittance mode (TAM). The CM SIMO filter is designed using two CCTA and two grounded capacitors. The CM filter can be converted to TAM filter just by adding a grounded resistor without any change in the topology. There is no need of passive component matching, and the filters provide all the five responses namely, 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). The active and passive sensitivities of the filter parameters are low. In CM mode the filter offers low input impedances and high output impedances and in TAM mode the filter offers high input impedance and hight output impedance that support the cascadeability. The CM and TAM filters are designed for a frequency 16.23MHz and the simulation results employing 0.18 µm CMOS technology parameters at a supply voltage of ±1.25 V are obtained using Cadence software to validate the proposed design. Also, the proposed CM SIMO universal filter has been implemented in hardware to confirm its practicality. The commercially available integrated circuits (ICs), the current feedback operational amplifier (AD844) and operational transconductance amplifier (CA3080) and employed for the experimental validation.*

***Streszczenie.** Zaprojektowano dwie topologie filtrów z pojedynczym wejściem i wieloma wyjściami (SIMO) o minimalnej składowej, wykorzystując wszechstronny aktywny blok konstrukcyjny (ABB), wzmacniacz transkonduktancji przenośnika prądu (CCTA). Zaproponowane filtry pracują w trybie prądowym (CM) oraz transadmitancyjnym (TAM). Filtr CM SIMO został zaprojektowany z wykorzystaniem dwóch kondensatorów CCTA i dwóch uziemionych kondensatorów. Filtr CM można przekształcić w filtr TAM po prostu dodając uziemiony rezystor bez żadnych zmian w topologii. Nie ma potrzeby dopasowywania komponentów pasywnych i zapewnia wszystkie pięć odpowiedzi: górnoprzepustowy (HP), środkowoprzepustowy (BP), dolnoprzepustowy (LP), all-pass (AP) i band-stop (BS)) odpowiedzi jednocześnie. Ponadto zapewnia niezależną elektroniczną regulację częstotliwości kątowej (ω) i współczynnika jakości (Q). Aktywna i pasywna czułość parametrów filtra jest niska. W trybie CM filtr oferuje niską impedancję wejściową i wysoką impedancję wyjściową, aw trybie TAM filtr oferuje wysoką impedancję wejściową i wysoką impedancję wyjściową, które wspierają kaskadowość. Filtry CM i TAM zaprojektowano dla częstotliwości 16,23 MHz, a wyniki symulacji wykorzystujące parametry technologii CMOS 0,18 µm przy napięciu zasilania ±1,25 V uzyskano za pomocą oprogramowania Cadence w celu walidacji proponowanego projektu. Również proponowany filtr uniwersalny CM SIMO został zaimplementowany sprzętowo w celu potwierdzenia jego praktyczności. Dostępne na rynku układy scalone (IC), wzmacniacz operacyjny ze sprzężeniem zwrotnym prądu (AD844) i operacyjny wzmacniacz transkonduktancyjny (CA3080) zostały wykorzystane do walidacji eksperymentalnej. (**Nowatorski, dwumodowy, dwukwadratowy filtr SIMO z minimalną składową i możliwością elektronicznego dostrajania**)*

Keywords: current mode, filter, current conveyor, universal filter, analog.
Słowa kluczowe: tryb prądowy, filtr, przenośnik prądowy, filtr uniwersalny, analogowy.

Introduction

From the last few decades, the designing of current mode (CM) analog filters have 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 the 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], extra x current conveyor transconductance amplifier [27], and voltage differencing current conveyor (VDCC) etc. A comparative study of some exemplary designs of CM SIMO filters is done based on the following points (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. The Table 1 presents the comparative analysis. It can be inferred from the literature survey that most of the designs suffer from one or more limitations as mentioned below.

- Low output impedance due to which cascading is not possible [9, 10, 26, 27].
- High output 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 use of floating passive elements [10, 12].
- 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 two SIMO filters devised utilizing two CCTAs. The CM filter requires only two grounded capacitors, and it can be converted to TAM filter just by adding a grounded resistor. The filters provide all five responses concurrently and they feature independent control of angular frequency(ω) and quality factor (Q) via transconductance of the CCTA. Another important advantage of the filters is that the outputs are available explicitly from high impedance terminals which is essential for cascading point of view. Additionally, there is no constraint of component matching in proposed SIMO filters and the filter gain of the SIMO filter can be adjusted independently. The design is validated using Cadence design software and the simulations results are found to be closely following the expected theoretical results. Also, experimental validation is done.

Current Conveyor Transconductance Amplifier (CCTA)

The current conveyor transconductance amplifier (CCTA) is functionally an improved and more versatile version of current conveyor (CCII). The CCTA [9] 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 CCTA are given in Equations (1-4) and the block diagram is presented in Figure 1.

(1) $V_X = V_Y$

(2) $I_X = I_{Z+} = I_{ZC}$

(3) $I_{O+} = -I_{O-} = g_m(V_{Z+})$

The expression for transconductance (g_m) is given in Equation 4.

(4) $g_m = \sqrt{\mu_n C_{OX} \left(\frac{W}{L}\right)_2 I_{Bias}}$

where C_{OX} 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_{Bias} and $\frac{W}{L}$ is the aspect ratio of the transistors.

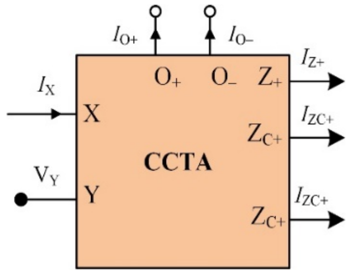

Fig. 1. Block Diagram of CCTA

The CMOS implementation of the CCTA is presented in Figure 2. The Y terminal is high impedance voltage input node and X is low impedance voltage output/current input node. The O_+, Z_+ & Z_{C+} terminals are high impedance current output nodes. The number of current output terminals (I_{ZC+}, O_+, O_-) can be increased by simply adding two MOS transistors.

Table 2: Comparative study of the CM SIMO universal filters

References	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
[8]	DVCC (3)	4R+2C	Yes	No	Yes	All five	No	No
[9]	CCTA (1)	2R+2C	Yes	No	No	All five	Yes	No
[10]	CCIII (1)	2R+2C	No	No	No	LP, BP	No	No
[11]	CFTA (4)	2C	Yes	Yes	Yes	All five	Yes	Yes
[12]	MOCCII (3)	5R+2C	No	No	Yes	All five	No	No
[13]	CCII (3)	3R+2C	Yes	Yes	Yes	All five	No	Yes
[15]	ZC-CFTA (4)	2C	Yes	Yes	Yes	All five	Yes	Yes
[16]	ZC-CITA (2)	2C	Yes	Yes	Yes	All five	Yes	No
[17]	MOCCII (3)	2R+2C	Yes	Yes	Yes	All five	No	No
[18]	VDCC (2)	2R+2C	Yes	No	Yes	All five	Yes	Yes
[19]	MOCCII (3)	2R+2C	Yes	Yes	Yes	All five	No	No
[24]	MO-OFC (2)	2R+2C	Yes	No	Yes	All five	No	No
[25]	DXMOCCII (2)	2R+2C	Yes	No	Yes	All five	Yes	Yes
[25]	DXMOCCII (2)	1R+2C	Yes	No	Yes	All five	Yes	Yes
[26]	VDCC (1)	2R+2C	Yes	No	No	All five	Yes	No
[27]	EXCCTA (1)	1R+2C	Yes	Yes	No	All five	Yes	No
[28]	CFTA (3)	2C	Yes	Yes	Yes	All five	Yes	No
[29]	DXMOCCII (2)	3R+2C	Yes	Yes	Yes	All five	No	Yes
[30]	MOCCII (3)	3R+2C	Yes	No	Yes	All five	No	Yes
Proposed CM	CCTA (2)	2C	Yes	Yes	Yes	All five	Yes	Yes
Proposed TAM	CCTA (2)	1R+2C	Yes	Yes	Yes	All five	Yes	Yes

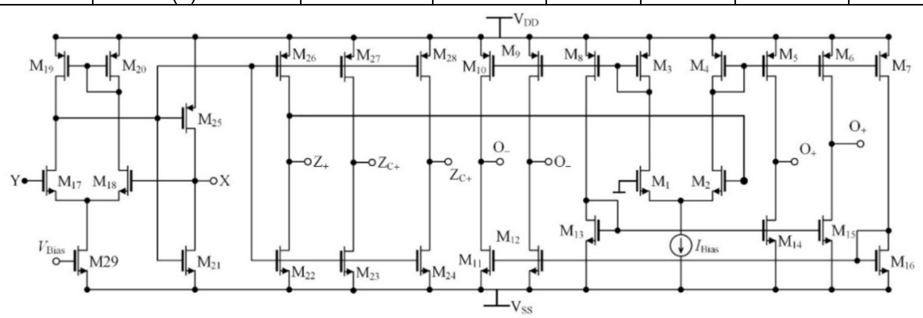

Fig. 2. CMOS implementation of CCTA

Proposed CCTA Based CM and TAM SIMO Filters

The proposed current mode SIMO filter is shown in figure 3. It employs two CCTA, 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 is the use of only positive current output terminals of the current conveyor stage as it avoids the use of additional MOS transistors for current reversal and improves accuracy.

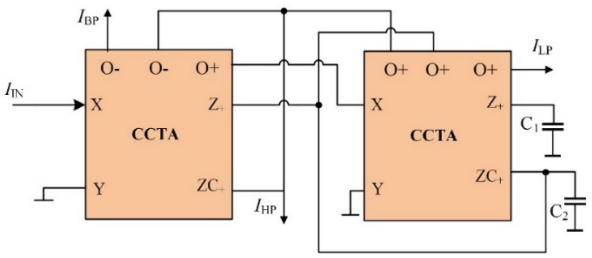

Figure 3: Proposed CM SIMO universal filter

The analysis of the filter circuit yields the transfer functions of all the five filter responses as given in Equations (5-9). The expressions of quality factor and pole frequency of the filter are presented in Equations (10-11). The AP and NP responses are obtained by adding HP, LP and BP currents as $\mathrm{I_{NP}} = \mathrm{I_{LP}} + \mathrm{I_{HP}}$ and $\mathrm{I_{AP}} = \mathrm{I_{HP}} + \mathrm{I_{LP}} + \mathrm{I_{BP}}$.

(5) $$\frac{I_{HP}}{I_{IN}} = -\frac{S^2C_1C_2}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}$$

(6) $$\frac{I_{LP}}{I_{IN}} = -\frac{-g_1g_2}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}$$

(7) $$\frac{I_{BP}}{I_{IN}} = +\frac{SC_1g_{m1}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}$$

(8) $$\frac{I_{NP}}{I_{IN}} = \frac{-S^2C_1C_2-g_{m1}g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}$$

(9) $$\frac{I_{AP}}{I_{IN}} = \frac{-S^2C_1C_2-g_{m1}g_{m2}+SC_1g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}$$

(10) $$f_o = \frac{1}{2\pi}\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$$

(11) $$Q = \sqrt{\frac{g_{m2}C_2}{g_{m1}C_1}}$$

From equation (10) to (11), 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.

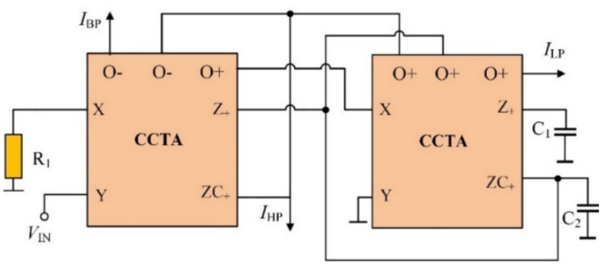

Figure 4: Proposed TAM SIMO universal filter

The TAM SIMO filter can be obtained from the above CM filter just by adding a grounded resistor at the X terminal of the CCTA. The TAM filter is also fully cascadable and offers high input impedance and high output impedance. Another advantage is that the gain of the filter can be tuned independently via resistor R_1.

The transfer functions of the filter are given in Equations (12-16). The expression of frequency and quality factor will be same as give above in Equations (10-11).

(12) $$\frac{I_{HP}}{V_{IN}} = \frac{1}{-R_1} * \left[\frac{S^2C_1C_2}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}\right]$$

(13) $$\frac{I_{LP}}{V_{IN}} = -\frac{1}{R_1} * \left[\frac{-g_{m1}g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}\right]$$

(14) $$\frac{I_{BP}}{V_{IN}} = +\frac{1}{R_1} * \left[\frac{SC_1g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}\right]$$

(15) $$\frac{I_{NP}}{V_{IN}} = \frac{1}{R_1} * \left[\frac{-S^2C_1C_2-g_{m1}g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}\right]$$

(16) $$\frac{I_{AP}}{V_{IN}} = \frac{1}{R_1} * \left[\frac{-S^2C_1C_2-g_{m1}g_{m2}+SC_1g_{m2}}{S^2C_1C_2+SC_1g_{m1}+g_{m1}g_{m2}}\right]$$

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 CCTA from the ideal one. This causes 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 CCTA will be modified to I_Y=0, $V_X = \beta(s)V_Y$, $I_{Z+} = I_{ZC+} = \alpha(s)\, I_X$, $I_{0+} = \gamma g_m V_{Z+}$ and $I_{0-} = \gamma' g_m V_{Z+}$. Where β is non-ideal voltage transfer gain, α is non-ideal current transfer gain and γ is non-ideal transconductance transfer gain. Ideally $\beta = \alpha = \gamma = 1$.

By considering the effect of CCTA non-idealities on the designed filter the expression of quality factor and angular frequency are modified as given in Equations 17-18.

(17) $$f_o = \frac{1}{2\pi}\sqrt{\frac{\alpha\gamma\gamma' g_{m1}g_{m2}}{C_1C_2}}$$

(18) $$Q = \sqrt{\frac{\gamma' g_{m2}C_2}{\alpha\gamma C_1 g_{m1}}}$$

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

(19) $$-S_{C_1}^{\omega} = -S_{C_2}^{\omega} = S_{g_{m2}}^{\omega} = S_{\gamma}^{\omega} = S_{\gamma'}^{\omega} = S_{\alpha_P}^{\omega} = S_{g_{m1}}^{\omega} = \frac{1}{2}$$

(20) $$S_{C_2}^{Q} = -S_{C_1}^{Q} = -S_{\gamma}^{Q} = -S_{\alpha_P}^{Q} = S_{\gamma'}^{Q} = S_{g_{m2}}^{Q} = -S_{g_{m1}}^{Q} = S_{\gamma'}^{Q} = \frac{1}{2}$$

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.

Simulation Results

To validate the proposed resistor less CM SIMO filter it is designed and simulated in Cadence virtuoso design software. The CCTA 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 selecting the bias current $I_{Bias} = 120$ µA.

Table 2: Width and Length of the MOS transistors

Transistors	Width (µm)	Length (µm)
M1-M4	1.8	0.36
M5-M10	5.4	0.36
M11-M16	1.8	0.72
M17-M18	3.06	0.36
M19-M20	10	0.36
M25-M28	2.16	0.36
M21-M24	0.72	0.72

The pole frequency of the filter is fixed at 16.23 MHz and quality factor to 1.2 by setting passive component values as $C_1 = C_2 = 10\mathrm{pF}$ and g_{m} =1.02 µS. The LP, HP, BP and NP responses of the CM SIMO filter are presented in Fig. 5. The AP gain and phase response is given in Fig. 6. The simulated frequency for CM-AP is found to be 16.38 MHz leading to 1% error.

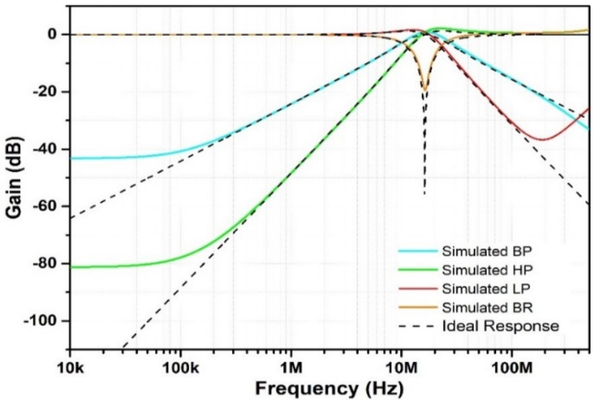

Fig. 5. The ideal and simulated results of the SIMO filter

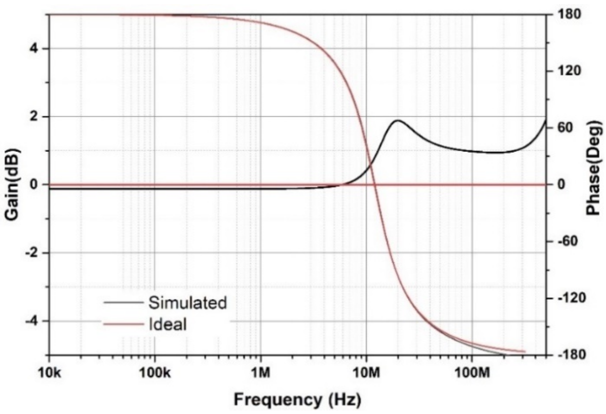

Fig. 6. The AP gain and phase response of the SIMO filter

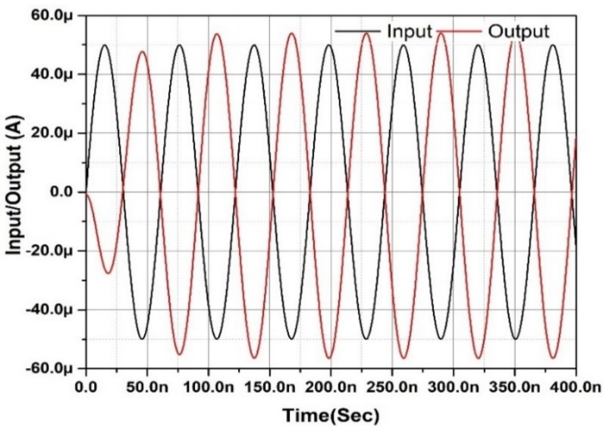

Fig. 7. Time domain results for BP configuration

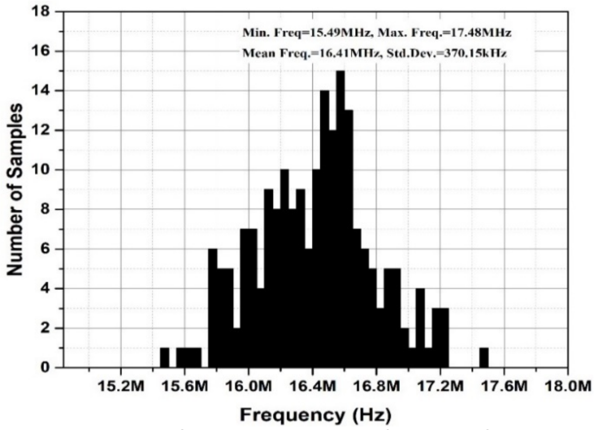

Fig. 8. The Monte Carlo analysis results for AP configuration

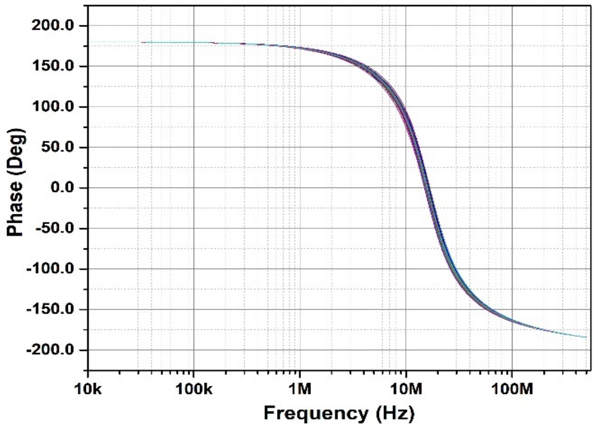

Fig. 9. The Monte Carlo analysis plot

To establish the signal processing capability of the proposed filter a sine wave of frequency 16.23MHz and 50µA(p-p) amplitude is applied, and the BP response of the filter is monitored as presented in Fig.7. It can be seen the filter output is accurate in terms of phase and magnitude. The Monte Carlo analysis is performed to examine the effect of process and passive component variations on the performance of the filter. It can be seen from the plot in Fig. 8 that minimum and the maximum frequency are 17.48MHz and 15.49MHz respectively. The mean frequency is found to be 16.41MHz which is close to the theoretical value. The phase plot of the all-pass response for the Monte Carlo analysis is presented in Fig. 9.

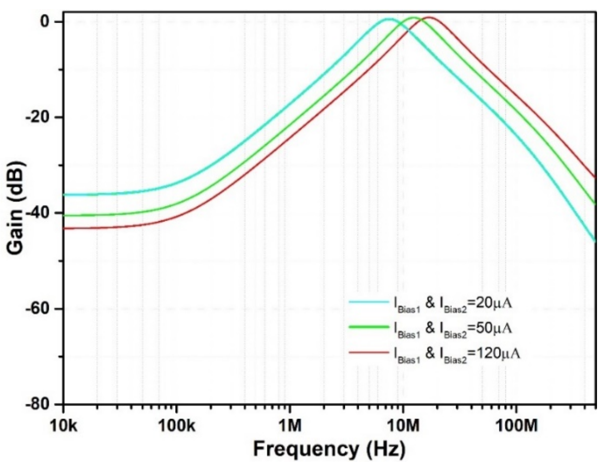

Fig. 10. BP pole frequency tuning

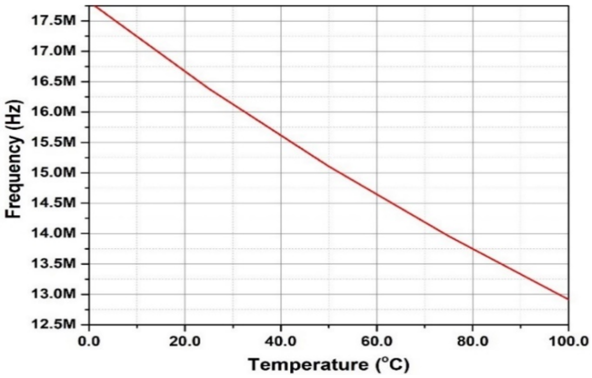

Fig. 11. Effect of temperature on the BP frequency

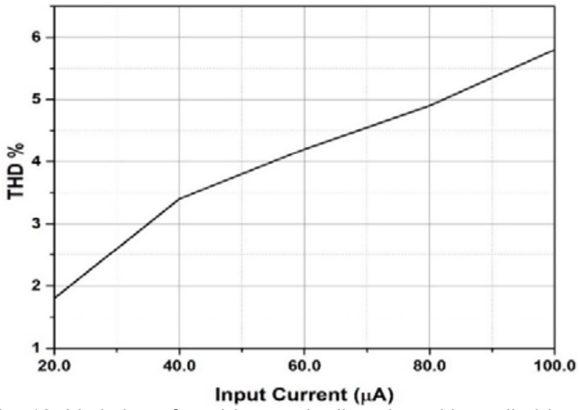

Fig. 12. Variation of total harmonic distortion with applied input current

The variation of the pole frequency independent of the quality factor is verified by varying the bias currents I_{Bias2} and I_{Bias1} from 20μA, 50μA and 120μA as presented in Fig. 10. The effect of temperature variation on the functioning of the filter is examined by analyzing the BP response under different temperature values ranging from 0^o to 100^0C. It can be inferred for the graph in Fig. 11 that although the filter frequency decreases with increase in temperature it is close to theoretical value within 20^o to 60^0C range. The total harmonic distortion (THD) of the filter is measured for different input current amplitudes as presented in Fig. 12. The THD remains within acceptable limit of 5% for significant input current range.

The TAM filer is validated by designing it for a frequency of 16.23MHz by setting passive component values as $C_1 = C_2 = 10\text{pF}, R_1 = 1\text{k}\Omega$ and g_m =1.02 μS. The LP, HP, BP and NP responses of the TAM SIMO filter are presented in Fig. 13 and the AP response is given in Fig.14.

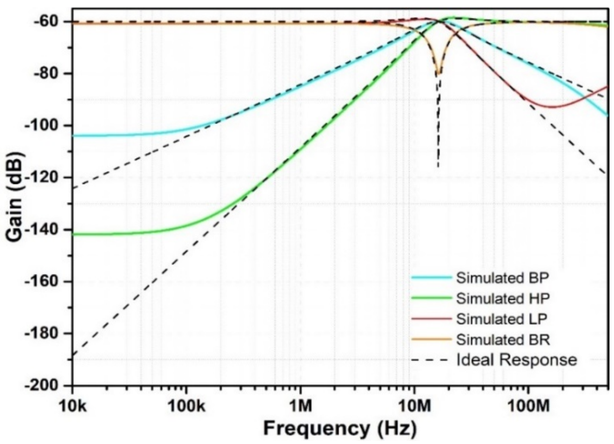

Fig. 13. The ideal and simulated results of the SIMO filter

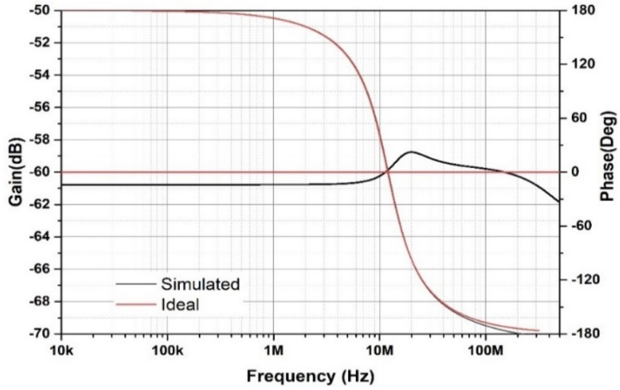

Fig. 14. The ideal and simulated results of the SIMO filter

The Monte Carlo analysis of the AP response as given in Fig. 15 suggest stable performance of the filter under process variations.

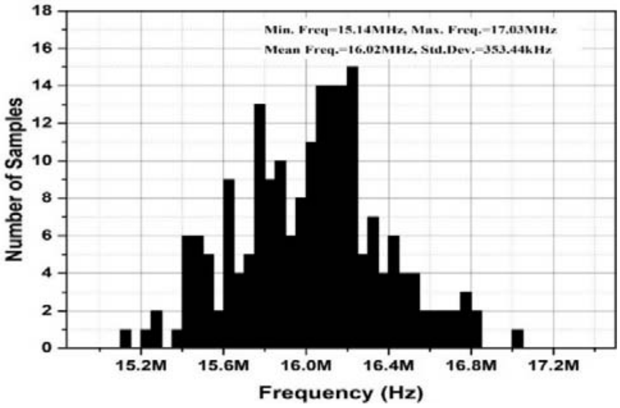

Fig. 15. The Monte Carlo analysis results for AP configuration

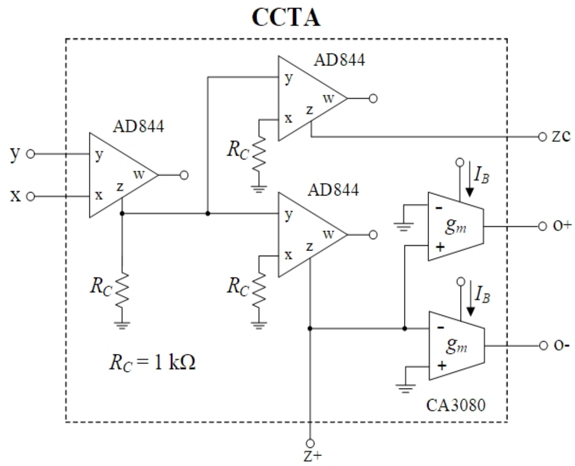

Fig. 16. Practical CCTA implementation for experimental measurements

Experimental Results

The suggested CM SIMO universal filter in Figure 3 has been implemented in hardware to confirm its practicality. As can be seen in Fig. 16, the experimental CCTA was constructed using commercially available IC AD844s and OTA CA3080s [32]. The supply voltages were considered to be ±5V symmetrically. In this instance, the g_m value of the CCTA was directly controlled by the amplifier bias current (I_B) of the OTA CA3080, according to the relation: $g_m = 20I_B$ [33]. Fig. 17 displays the experimental setup for the proposed CM SIMO universal filter in Figure 3. To measure current signal, additional AD844s and converting resistors (R_C) are used to convert voltage to current, and current to voltage at the input and output terminals, respectively.

For all the experiments, the components were set as: $g_{m1} = g_{m2} = 0.5$ mA/V ($I_{B1} = I_{B2} = 25$ µA), $C_1 = C_2 = 0.1$nF, which ideally results in $f_o = 79.58$ kHz, and $Q = 1$. Fig. 18 shows the theoretical and experimental results for current LP, BP and HP responses. The gain and phase plots of the AP response are also shown in Fig. 19. The findings clearly show that the experimental and theoretical responses are consistent.

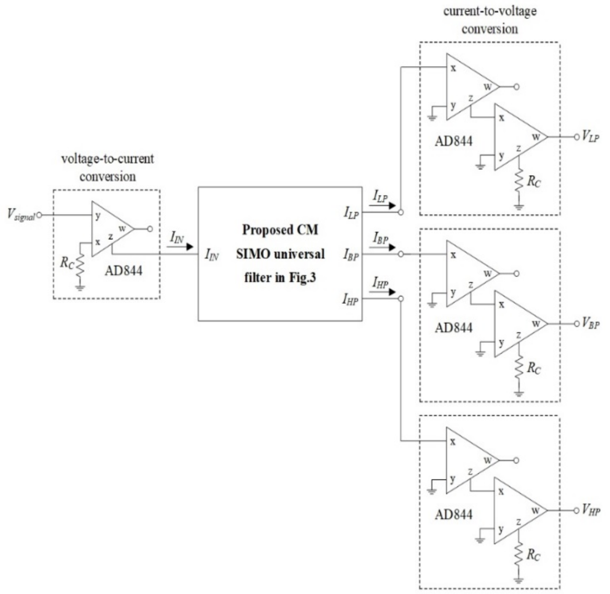

Fig.17. Experimental setup for the proposed CM SIMO universal filter in Figure 3

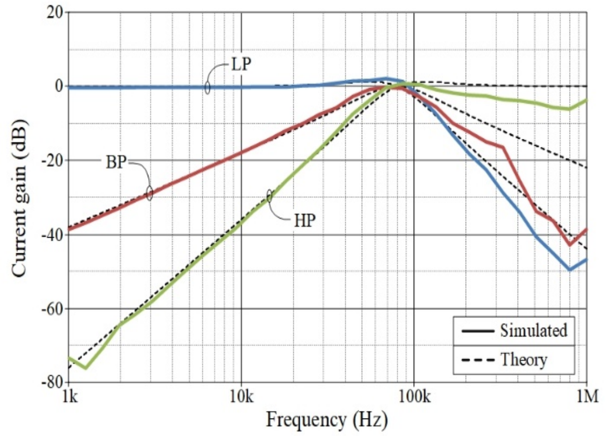

Fig. 18. Theoretical and experimental results for current LP, BP and HP responses of the proposed CM SIMO universal filter in Figure 3

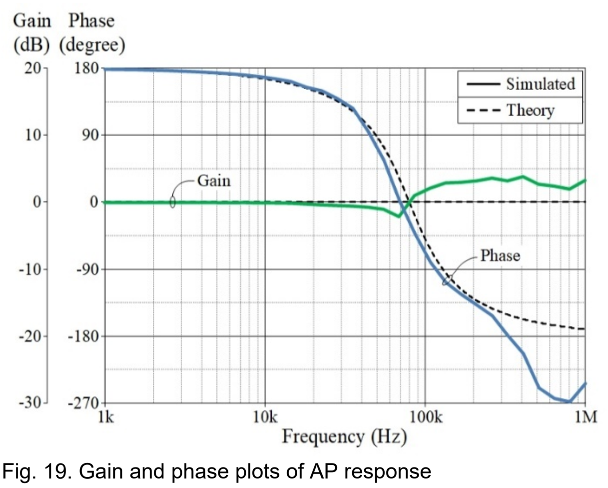

Fig. 19. Gain and phase plots of AP response

Conclusion

This paper presents two topologies of CCTA based electronically tunable SIMO filters. The designed filters work in CM and TAM modes. The CM filter employs two CCTA, and two grounded capacitors for implementation. It can be converted to TAM mode just by adding a grounded resistor. Presented SIMO filters have inbuilt tunability and can realize all five filter responses simultaneously. The CCTA is designed in Cadence Virtuoso software and extensive simulations are carried out to examine and validate the proposed filters. The proposed filters have all the advantages mentioned in Table 1. The filters are designed for a frequency of 16.38 MHz at ±1.25 V supply. The Monte Carlo analysis shows that the frequency deviation is within acceptable limits. Furthermore, the THD for CM mode is within 5% for considerable current input signal range. Also, the proposed CM SIMO universal filter is implemented in hardware to confirm its use for practical applications. The commercially available integrated circuits (ICs), the AD844 and CA3080 are employed for the experimental validation. The simulation and experimental results are found consistent with the theoretical predictions.

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