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A Novel Mixed-Mode Second-Generation Voltage Conveyor Based First-Order All-Pass Filter

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Abstract: A new plus-type second-generation voltage conveyor (VCII+) based first-order mixed-mode (MM) all-pass (AP) filter is proposed in this study. The proposed MM AP filter employs two VCII+s, three resistors and one grounded capacitor. It has low input and high output impedances for the current-mode selection while it has low input and low output impedances for the transimpedance-mode selection. The AP filter gain is unity for the current output while it is adjustable for the voltage output via a grounded resistor. However, a single passive component matching condition is needed for the proposed MM AP filter. Complete non-ideal analysis by taking into account all the parasitic resistors and non-ideal gains of the VCII+ is performed. The presented theory is verified through SPICE simulations by using supply voltage of ± 0.9 V and 0.18 μm Taiwan Semiconductor Manufacturing Company complementary metal oxide semiconductor technology parameters.

Nomenclature

VDD	positive supply voltage
VSS	negative supply voltage
VB	bias voltage
β	non-ideal current gain
η	non-ideal current gain
α	non-ideal voltage gain
$rx1$	parallel parasitic resistor at the X_1 terminal
$rx2$	parallel parasitic resistor at the X_2 terminal
ry	series parasitic resistor at the Y terminal
rz	series parasitic resistor at the Z terminal
fo	pole frequency
ω_o	angular pole frequency
φ	phase angle
R	resistor
C	capacitor

1 Introduction

Wide application areas in instrumentation and communication systems as quadrature oscillators, phase equalisers and delay equalisers have made the first-order all-pass (AP) filter design an important research topic [1–32]. The AP filters implemented by operational amplifiers (Op-Amps) suffer from low gain-bandwidth product of these active building blocks (ABBs). In the recent literature, as a result of numerous advantageous offered by the current-mode (CM) signal processing like simple circuitry, improved frequency performance, low voltage operation and so on, the realisations of a number of first-order AP filters using various CM ABBs [1–23, 26, 32] have been published.

Literature survey shows that first-order AP filters using secondgeneration current conveyors (CCIIs) [1–9], current followers (CFs) [10], inverting CCIIs (ICCIIs) [11], differential voltage current conveyors (DVCCs) [12–14], dual-X CCIIs (DX-CCIIs) [15–20], extra-X current controlled conveyors (EX-CCCIIs) [21, 22], third-generation current conveyors (CCIIIs) [23], dual-X current conveyor transconductance amplifiers (DXCCTAs) [24, 25], current operational amplifiers (COAs) [26], MOS transistors [27], bipolar junction transistors (BJTs) [28, 29], operational transresistance amplifiers (OTRAs) [30], current differencing transconductance amplifiers (CDTAs) [31], voltage gain-controlled modified current feedback operational amplifiers (VGC-MCFOAs) [32] and so on have been reported so far.

Some of the AP filters [1–29] can provide only CM operation while several AP filter topologies [30, 31] can realise only transimpedance-mode (TM) operation. Only one of [32] is mixedmode (MM). Also, some AP filters [7, 8, 11, 13, 23, 25–28, 30, 31] include a floating capacitor that is not suitable for integrated circuit (IC) fabrication. Several AP filter configurations [9, 13, 15, 24, 27] use more than one capacitor; accordingly, they occupy large chip area in IC process. Several AP filter circuits [8, 9, 28, 29, 31, 32] contain BJTs that are temperature dependent. Some of the AP filters [14, 32] need two input currents; thus, they need an extra circuitry. Some of the AP filters [12, 24, 32] do not use standard ABB. Several CM AP filter circuits [3, 7–9, 11, 13–17, 23, 26–28] do not provide both low input and high output impedances. Some TR AP filters [30, 31] do not realise both low input and low output impedances. Several AP filters [3, 15, 17, 24, 25, 31] have restrictions at high frequencies due to the use of operational transconductance amplifier [33] or a capacitor connection in series to the X terminal of the ABB [34]. Apart from these, some AP filters [35, 36] have been reported recently.

In [37, 38], voltage conveyors as a new family of ABBs were introduced. Recently, in [39–41], a type of voltage conveyor namely second-generation voltage conveyor (VCII) has been employed to realise voltage output filters. Having a low impedance voltage output terminal, a low impedance current input terminal and a high impedance current output terminal [42], the VCII provides flexibility in the design of various types of the filters.

In this paper, a new plus-type VCII (VCII+) based first-order MM AP filter is proposed. The proposed AP filter employs two VCII+s, three resistors and one grounded capacitor. By virtue of availability of low impedance current input, high impedance current output and low impedance voltage output terminals in the VCII+, a cascadable MM operation is possible without the use of any extra current and voltage buffers. Gain of the AP filter is unity for the current output while it is adjustable for the voltage output. Complete non-ideal analysis is performed by taking into account all the parasitic resistors and non-ideal gains of the VCII+. The presented theory is verified through SPICE simulations in which 0.18 µm supply voltage of ±0.9 V and Taiwan Semiconductor Manufacturing Company (TSMC) complementary metal oxide semiconductor (CMOS) technology parameters [43] are used.

The advantages of the proposed VCII + based AP filter structure over the previously published works can be summarised as in the following:

(i) The proposed filter has low supply voltages, and dissipates lowpower.
(ii) The proposed filter uses a grounded capacitor; thus, it is verysuitable for IC fabrication. Realisation of a floating capacitor requires poly2 CMOS process explained in [44].
(iii) The proposed filter provides output signal in both forms ofcurrent and voltage signals at high output impedance and low output impedance terminals, respectively. Hence, there is no requirement to use buffer stages at the outputs of the proposed filter.
(iv) The proposed filter provides input current signal at low inputimpedance terminal. Thus, the input signal can be directly connected to the proposed filter without requiring a buffer.
(v) The proposed filter is compact and has a simple structure due tothe absence of extra voltage and current buffers at the outputs and input, respectively.
(vi) The proposed filter can be easily cascaded at input and outputterminals.
(vii) The proposed filter has the feature of MM operation.
(viii) Capacitor of the proposed AP filter is not connected in seriesto the *Z* and or *Y* terminals (low impedance terminals); therefore, the proposed filter can be operated at high frequencies [34].
(ix) The proposed filter is novel because an AP filter based on theVCII has not been published so far.

However, the proposed MM AP filter suffers from the following drawbacks:

(i) A single resistive matching condition is needed for the proposedAP filter.
(ii) The proposed AP filter employs three resistors (minimum tworesistors are required).

Organisation of this paper is as follows. After introduction given in Section 1, the VCII + is described in Section 2. In Section 3, the proposed AP filter topology is introduced. In Section 4, non-ideal analysis is presented. After simulation results are provided in Section 5, the paper is concluded in Section 6.

2 Description of the VCII+

Equation (1) shows the ideal relationships between terminal currents and voltages of the VCII+. Furthermore, symbolic representation of the VCII+ is demonstrated in Fig. 1

$$\begin{bmatrix} i \\ i \\ v \\ v \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} v \\ v \\ i \\ i \end{bmatrix}$$

0 0

0

1

(1)

0 0 0 0

1 0 0 0

3 Proposed all-pass filter

The proposed first-order MM AP filter topology is shown in Fig. 2. It is based on two VCII+s, three resistors and one grounded capacitor. The proposed AP filter circuit can be operated in MM. In other words, each of the AP outputs is available either a current signal at high impedance *X* terminal of the second VCII + (with ideal value of infinity) or a voltage signal at low impedance *Z* terminal of the second VCII + (with ideal value of zero). Therefore, there is no requirement of additional current and voltage buffers. The input is a current signal applied to *Y* terminal of the first VCII +. Its low impedance at *Y* terminal (with ideal value of zero) allows the direct application of a current signal to the *Y* terminal without

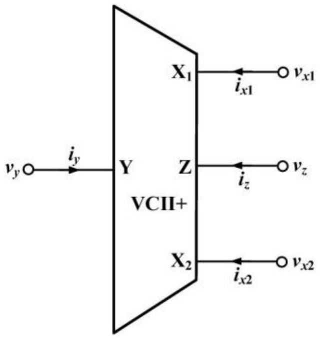

Fig. 1 *Symbolic representation of the VCII+*

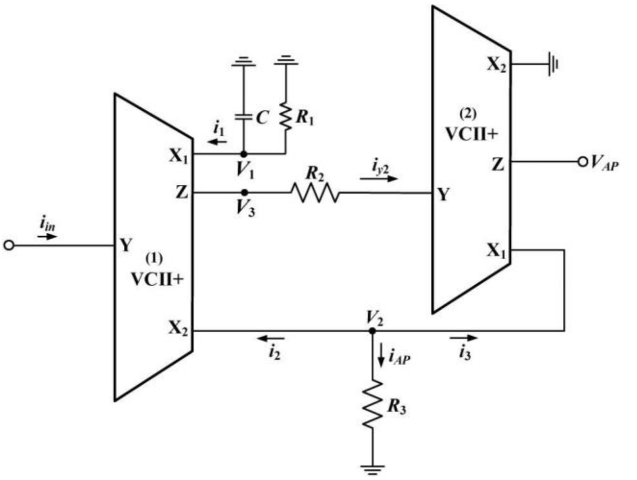

Fig. 2 *Proposed first-order MM all-pass filter topology*

needing an extra current buffer. In addition to these, R_3 can be chosen arbitrarily for the CM and TM operation.

The AP filter outputs of Fig. 2 can be found as follows: due to the current buffering action between Y and X terminals, we have

$$i_1 = i_2 = i_{in} \quad (2)$$

The voltage at X_1 terminal of the first VCII+, V_1 is evaluated as

$$V_1 = -\frac{R_1}{1 + sCR_1} i_{in} \quad (3)$$

Due to voltage buffering action between X and Z terminals of the first VCII+, V_3 is equal to V_1 and the voltage at Y terminal of the second VCII + is ideally zero; thus, i_{y2} is found as

$$i_{y2} = \frac{V_3}{R_2} = -\frac{R_1}{R_2(1 + sCR_1)} i_{in} \quad (4)$$

At the X terminals of the VCII+s, we have

$$i_{AP} = -(i_2 + i_3) \quad (5)$$

If it is considered that $i_3 = i_{y2}$ and using (2), (4) and (5), i_{AP} is calculated as

$$i_{AP} = -i_{in} - \frac{R_1}{R_2(1 + sCR_1)} i_{in} = \frac{(R_1/R_2) - 1 - sCR_1}{1 + sCR_1} i_{in} \quad (6)$$

If $R_1 = 2R_2$ is met, from (6), the output current is obtained as follows:

$$i_{AP} = \frac{1 - sCR_1}{1 + sCR_1} i_{in} \quad (7)$$

From (7), the following CM transfer function (TF) is obtained as

$$H(s) = \frac{i_{AP}}{i_{in}} = \frac{1 - sCR_1}{1 + sCR_1} \quad (8)$$

where pole frequency, $f_o = 1/(2\pi CR_1)$ is found. Also, phase response of the proposed AP filter is computed as

$$\varphi(\omega) = -2Arctan(\omega CR_1) \quad (9)$$

Fortunately, as X terminals of the VCII+s are high impedance terminals, an extra current buffer is not needed to obtain i_{AP}. The voltage produced at X terminal of the second VCII + is found as

$$V_2 = R_3 i_{AP} = R_3 \frac{1 - sCR_1}{1 + sCR_1} i_{in} \quad (10)$$

Due to the voltage buffering action between the X and Z terminals of the VCII+, V_2 is transferred to Z terminal of the second VCII+. As a result, a TM TF is obtained as follows:

$$\frac{V_{AP}}{i_{in}} = R_3 \frac{1 - sCR_1}{1 + sCR_1} \quad (11)$$

Voltage output AP is available at Z terminal of the VCII+; consequently, an extra voltage buffer is not needed. Further, the gain can be adjusted by R_3.

4 Non-ideal analysis

Equation (12) shows the general relationships between terminal currents and voltages. Here, β is the current gain between Y and X_1 terminals while η is the current gain between Y and X_2 terminals. Also, α is the voltage gain between X_1 and Z terminals. On the other hand, r_y, r_{x1}, r_{x2} and r_z are, respectively, parasitic resistors at the Y, X_1, X_2 and Z terminals of the VCII+. Fig. 3 shows the VCII + with its parasitic resistors

$$\begin{bmatrix} i \\ i \\ v \\ v \end{bmatrix} = \begin{bmatrix} 1/r_{x1} & 0 & \beta & 0 \\ 0 & 1/r_{x2} & \eta & 0 \\ 0 & 0 & r_y & 0 \\ \alpha & 0 & 0 & r_z \end{bmatrix} \begin{bmatrix} v \\ v \\ i \\ i \end{bmatrix} \quad (12)$$

In non-ideal case, the voltage and current gains are not unity. Owing to the fact that the used R_1, R_2 and R_3 resistors are in the range of a few kΩ while the value of parasitic resistors at the X terminals are in the range of tens of kΩ. For simplicity, the effects of r_{x1} and r_{x2} can be neglected due to their large values. By the assumptions given above, we have the following equations:

$$i_1=\beta_1 i_{in} \quad (13a) \quad i_2=\eta_1 i_{in} \quad (13b)$$

$$i_3=\beta_2 i_{y2} \quad (13c) \quad V_3=\alpha_1 V_1 \quad (13d)$$

$$V_{AP}=\alpha_2 V_2 \quad (13e)$$

V_1 can be easily calculated as

$$V_1=-\frac{R_1}{1+sCR_1}i_1 \quad (14)$$

Inserting (13a) into (14) results in the following equation:

$$V_1=-\frac{\beta_1 R_1}{1+sCR_1}i_{in} \quad (15)$$

Y terminal of the second VCII + is at virtual ground; therefore, i_{y2} is computed as

$$i_{y2}=-\frac{V_3}{R_2+r_{z1}+r_{y2}} \quad (16)$$

Inserting (13d) and (15) into (16) gives the following equation:

$$i_{y2}=-\frac{\quad 1\ 1}{(R_2+r_{z1}+r_{y2})(1+sCR_1)}i_{in} \quad (17)$$

From (6), the following AP filter current output is obtained:

$$\alpha\ \beta\ R$$

$$i_{AP}=-\eta_1-\frac{\alpha_1\beta_1\beta_2R_1}{(R_2+r_{z1}+r_{y2})(1+sCR_1)}i_{in} \quad (18)$$

From (18), CM AP filter TF is obtained as

$$\frac{i_{AP}}{i_{in}}=\frac{(\alpha_1\beta_1\beta_2R_1)/(R_2+r_{z1}+r_{y2})-\eta_1-sCR_1\eta_1}{1+sCR_1} \quad (19)$$

Using (13e) and (19), the TM AP filter TF is also found as

$$\frac{V_{AP}}{i_{in}}=\alpha_2R_3\frac{(\alpha_1\beta_1\beta_2R_1)/(R_2+r_{z1}+r_{y2})-\eta_1-sCR_1\eta_1}{1+sCR_1} \quad (20)$$

From (19) and (20), the pole frequency is calculated as $f_o=1/(2\pi CR_1)$. Also, phase response of the proposed AP filter due to non-idealities is computed as

$$\varphi_n(\omega)=-\mathrm{Arctan}\frac{\omega CR_1\eta_1}{(\alpha_1\beta_1\beta_2R_1)/(R_2+r_{z1}+r_{y2})-\eta_1}-\mathrm{Arctan}(\omega CR_1) \quad (21)$$

All the sensitivities of the pole frequency are evaluated as in the following:

$$S^{f_o}_{R1}=-1 \quad (22a)$$

$$S^{f_o}_{R2}=-1 \quad (22b)$$

$$S^{f_o}_{C}=-1 \quad (22c)$$

$$S^{f_o}_{R3}=0 \quad (22d)$$

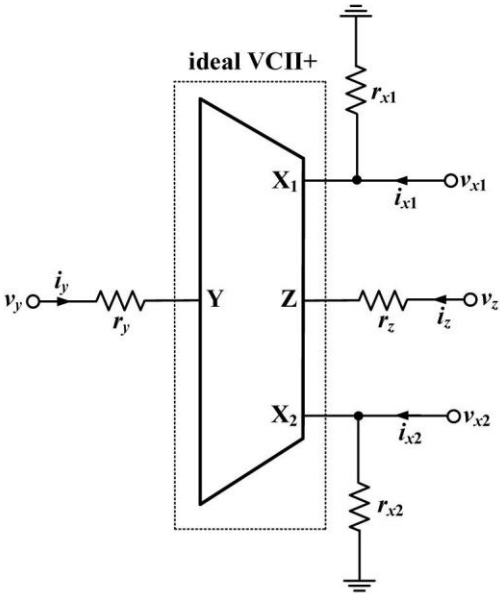

Fig. 3 *VCII + with its parasitic resistors*

Table 1 Aspect ratios of the MOS transistors

MOS transistors	Aspect ratios
M1–M10	40.5 µm/0.54 µm
M11, M12	81 µm/0.54 µm
M13–M20	13.5 µm/0.54 µm

Table 2 Performance parameters of the VCII + of Fig. 10

Parameters	Values
r_y	23.7 Ω
r_{x1}	68 kΩ
r_{x2}	68 kΩ
r_z	23.7 Ω
α	0.978

β	1.017
η	1.017
power consumption	458 µW

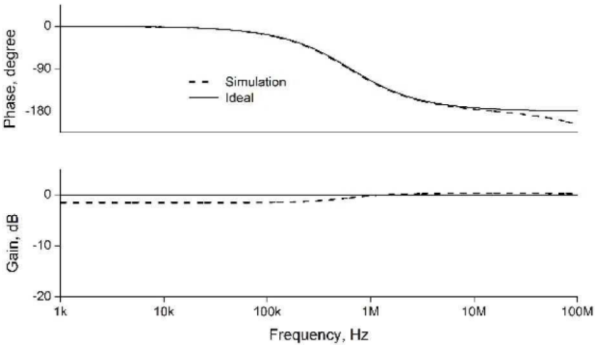

Fig. 4 *Phase and gain responses of the CM AP filter*

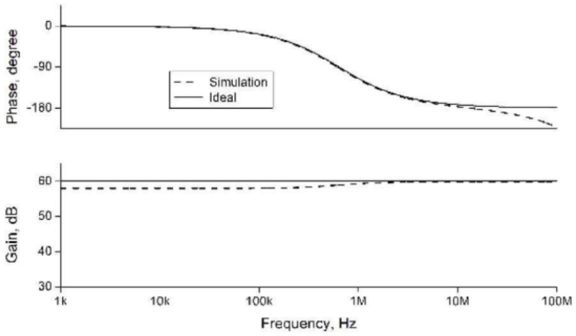

Fig. 5 *Phase and gain responses of the TM AP filter*

It is seen from (22) that sensitivities are no more than unity in magnitude. Also, all the active sensitivities are equal to zero.

5 Simulation results

To verify the presented theory, some SPICE simulations using 0.18 µm TSMC CMOS technology parameters, supply voltage of ±0.9 V and a bias voltage of 0.3 V are performed. Aspect ratios of the MOS transistors of the internal structure of the VCII + derived from one in [45] are listed in Table 1 while performance parameters of the VCII + are given in Table 2. The proposed MM AP filter given in Fig. 2 is designed with the passive element values of $R_1 = 5$ kΩ, $R_2 = 2.5$ kΩ and $C = 50$ pF to accomplish a first-order MM AP filter with a pole frequency of $f_o \cong 636.6$ kHz. R_3 is chosen as 1 kΩ to achieve a gain of 60 dB at the voltage output terminal. Phase and gain responses for the CM AP filter are shown in Fig. 4 while phase and gain responses for the TM AP filter are denoted in Fig. 5. To examine the time domain performance of the proposed AP filter, a sinusoidal input current with 40 µA peak and a frequency of 636.6 kHz is applied to the input of proposed AP filter configuration. The input and output current signals are shown in Fig. 6, which shows about −90° phase shift between input current and produced corresponding output currents. Similarly, the input current and corresponding output voltage signals are depicted in Fig. 7, which shows about −90° phase shift between input current and produced output voltages. The total harmonic distortion (THD) variations for the CM AP filter are shown in Fig. 8 where different sinusoidal input currents are applied. Likewise, THD

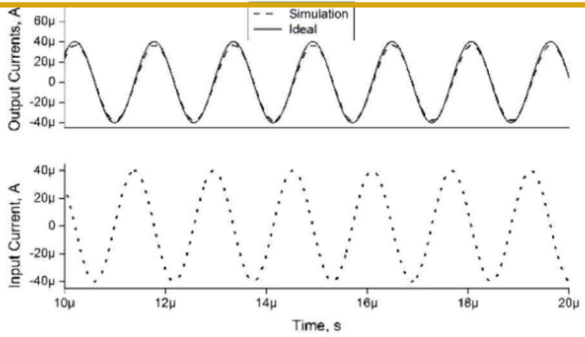

Fig. 6 *Input current with 40 µA peak and a pole frequency of 636.6 kHz and output current signals*

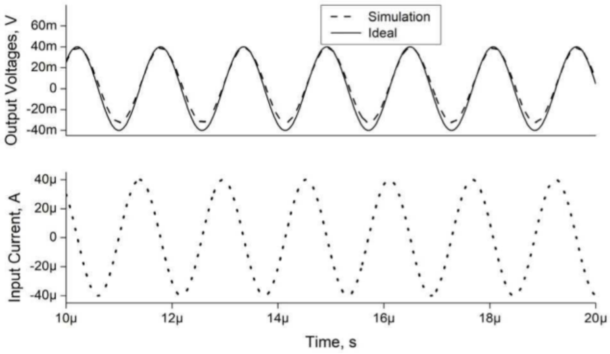

Fig. 7 *Input current with 40 µA peak and a pole frequency of 636.6 kHz and corresponding output voltage signals*

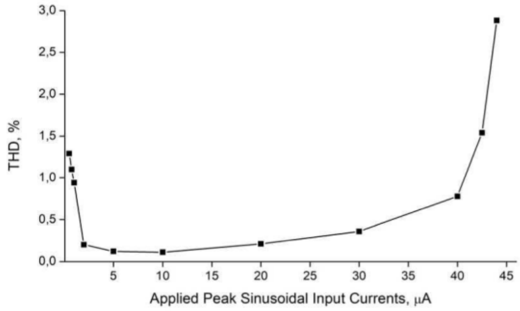

Fig. 8 *THD variations for the CM AP filter topology*

changes for the TM AP filter are demonstrated in Fig. 9. It is seen from Figs. 8 and 9 that THD remains below 3% for both current and voltage outputs. To investigate the effect of mismatches on the overall performance of the proposed CM AP filter, a Monte Carlo (MC) simulation for the CM AP filter is performed in 100 runs by considering 2% uniform change in transconductance parameters of all the MOS transistors given in Fig. 10. Likewise, an MC simulation for the TM AP filter is performed. The results, respectively, presented in Figs. 11 and 12 for the CM and TM AP filters show that mismatches affect the gain negligibly while the phase remains almost unchanged. Moreover, MC simulations for the CM and TM AP filters are performed in 100 runs by considering 2% uniform change in all the passive elements. The simulation results for the CM and TM AP filters are shown in Figs. 13 and 14, respectively. The parasitic resistors at the current output and voltage output terminals are 68 and 23.7 Ω, respectively. Also, the parasitic resistor at the current input terminal is evaluated as 23.7 Ω. Total power consumption of the proposed MM AP filter is found as 1.22 mW through SPICE program.

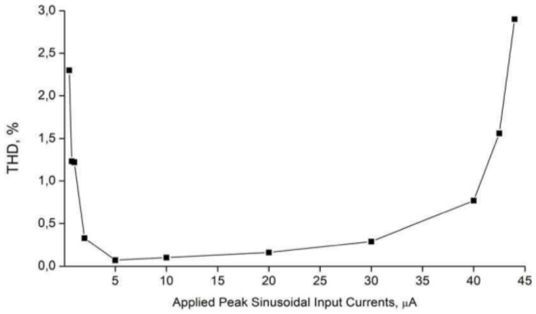

Fig. 9 *THD variations for the TM AP filter circuit*

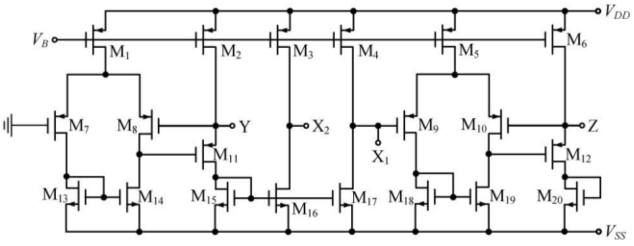

Fig. 10 *Internal structure of the VCII*

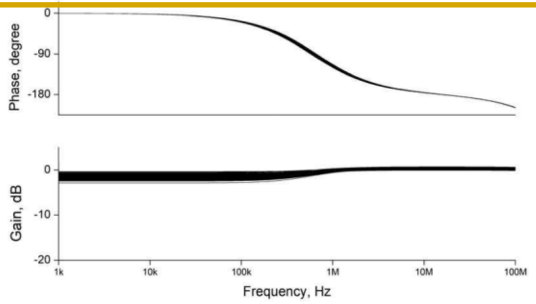

Fig. 11 *MC simulation results for the CM AP filter performed by considering 2% uniform change in transconductance parameters of all the MOS transistors*

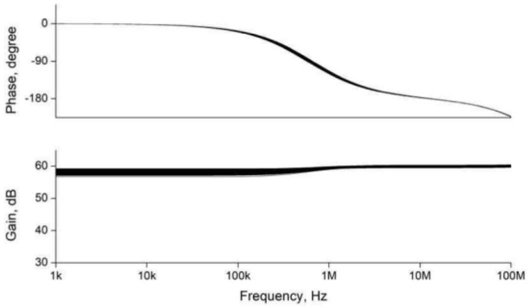

Fig. 12 *MC simulation results for the TM AP filter performed by considering 2% uniform change in transconductance parameters of all the MOS transistors*

One can observe from the simulation results demonstrated in Figs. 4–9, 11–14 that simulation results are close to ideal ones whereas an unimportant difference between them arises from nonidealities of the VCII + as discussed above. Moreover, the proposed MM AP filter can be operated properly up to 100 MHz.

It is observed from Figs. 8 and 9 that THD values of the proposed MM AP filter circuit for the input currents between 3 and 40 μA remain below 1%.

If power supplies and bias voltage of the VCII + in Fig. 10 are, respectively, chosen as ±1.25 and 0.55 V, THD values of the proposed MM AP filter for a wider range of the input current (3 and 100 μA) remain below 1% whereas power dissipation of the proposed MM AP filter topology becomes 4.6 mW. The

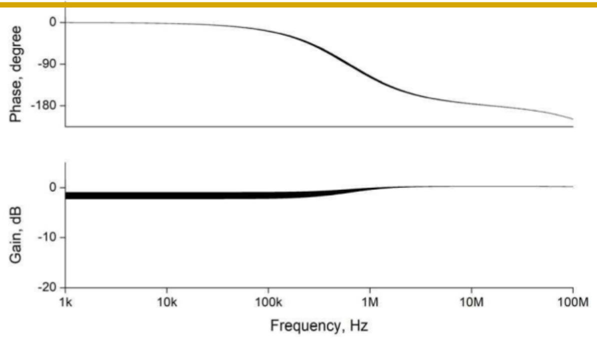

Fig. 13 *MC simulation results for the CM AP filter performed by considering 2% uniform change in all the passive elements*

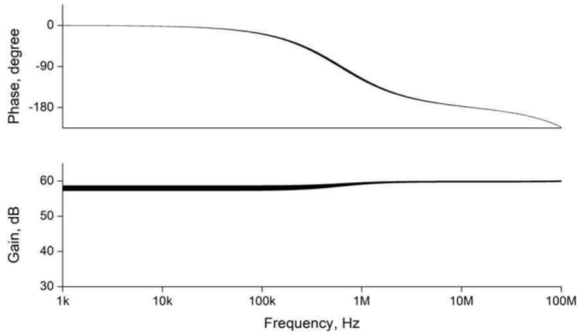

Fig. 14 *MC simulation results for the TM AP filter performed by considering 2% uniform change in all the passive components*

performance of the proposed MM AP filter is compared with previously published similar works in Table 3.

6 Conclusion

The proposed MM AP filter circuit in this paper uses two VCII+s, three resistors and a single grounded capacitor. It can produce outputs in both forms of current and voltage signals at high impedance and low impedance terminals, respectively. The gain for the current output is unity while it can be set to an arbitrary value by means of a grounded resistor for the voltage output. Due to the inherent low input impedance at the current input terminal, high impedance at the current output terminal and low impedance at the voltage output terminal, there is no need for extra current and voltage buffers. Hence, a compact and simple circuitry is obtained. Nonetheless, a single passive element matching condition is required for the proposed MM AP filter. Non-ideal analyses considering all the effects of the non-ideal gains and parasitic impedances of the VCII+s are performed. Simulation results via SPICE program verify the discussed theory well. It is expected that the proposed first-order MM AP filter configuration will be beneficial in a number of areas such as telecommunications, signal processing, control engineering and so on.

Table 3 Comparison table

References and related figures	No. of active building blocks	No. of R	No. of C	No. of transistors
[1] in Fig. 2	2 CCII			
[2] in Fig. 3	2 CCII			
[3] in Fig. 2	2 CCII			
[4] in Fig. 1	2 CCII			
[5] in Fig. 3	2 CCII			
[6] in Fig. 2	2 CCII			
[7] in Fig. 3	1 CCII			
[8] in Fig. 1	1 CCII			NA
[9] in Fig. 1*a*	2 CCII			NA
[10] in Fig. 2	2 CF			
[11] in Fig. 10	2 ICCII			
[12] in Fig. 4	2 DVCC			
[13] in Fig. 3-1	1 DVCC			
[14] in Fig. 3	1 DVCC			
[15] in Fig. 2	1 DX-CCII			
[16] in Fig. 3	1 DX-CCII			
[17] in Fig. 3	1 DX-CCII			
[18] in Fig. 2	1 DX-CCII			
[19] in Fig. 2	1 DX-CCII			
[20] in Fig. 2	1 DX-CCII			
[21] in Fig. 1	1 EX-CCCII			
[22] in Fig. 3	1 EX-CCCII			
[23] in Fig. 10	1 CCIII			NA
[24] in Fig. 1	1 DXCCTA			
[25] in Fig. 2	1 DXCCTA			
[26] in Fig. 2	1 COA			
[27] in Fig. 1	—			
[28] in Fig. 2	—			
[29] in Fig. 5	—			
[30] in Fig. 2	1 OTRA			
[31] in Fig. 2	1 CDTA			
[32] in Fig. 3	1 VGC-MCFOA			
proposed	2 VCII+			

NA: not available; —: ABB is not used.

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