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CFDITA-Based Mixed-Mode Biquad Filter with Grounded Capacitors and Independent Q Control

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This work introduces a compact multi-mode biquad filter utilizing a Current Follower Differential Input Transconductance Amplifier (CFDITA). The suggested circuit design is resistor less and incorporates two CFDITAs along with two grounded capacitors exclusively. It functions in all four possible modes: voltage-mode (VM), current-mode (CM), transadmittance-mode (TAM), and transimpedance-mode (TIM). In CM, the proposed circuit achieves all filtering functions, including low-pass, high-pass, band-pass, band-reject and all-pass responses. Consequently, the suggested circuit serves as a universal filter in CM. The main characteristic of the proposed multi-mode filter includes the use of minimal, grounded passive components, which removes the requirement for input matching conditions. It sustains low input impedances for current inputs and high input impedances for voltage inputs, making it ideal for cascading. It operates effectively at higher frequencies (10.3 MHz), uses low supply voltages (±1.25 V), and consumes low power (1.32 mW). Additionally, it allows for independent and electronic control of the pole frequency and quality factor through the bias currents of the CFDITA. PSPICE simulation results utilizing 0.18 μm CMOS technology confirm the theoretical findings. Furthermore, the proposed circuit is experimentally verified for a voltage-mode low-pass filter response.

Keywords: Analog circuit, Active filter, Mixed-mode, CFDITA

1 Introduction

With the emergence of current-mode (CM) device i.e. current conveyor [1], extensive research has focused on developing the circuits of voltage-mode (VM) and CM filters [2-6]. In addition to these, the transimpedance-mode (TIM)[7] and transadmittance-mode (TAM)[8] filters have gained importance in practical applications, particularly when interfacing CM circuits with VM circuits or vice versa. In such cases, separate voltage-to-current or current-to-voltage converters are usually required at the interface. The overall efficiency and simplicity of the electronic system can be improved if both signal processing and voltage-to-current or current-to-voltage conversion are performed simultaneously. This is achieved by using TAM and TIM filters, which directly provide the required interfacing along with filtering in a single circuit, thus enhancing the versatility of mixed-mode (MM) analog systems[8-12]. MM filters have attracted significant attention in recent years due to their wide applicability in modern analog signal processing, optical communication, biomedical instrumentation and wireless communication systems. A MM universal filter provides low-pass (LP), high-pass (HP), band-pass (BP), band-reject (BR), and all-pass (AP), responses in all four modes[9]. The availability of all filtering responses makes the overall system simpler, more flexible, and suitable for modern mixed-signal applications. Therefore, MM universal filters capable of delivering all fundamental filtering responses across the four signal modes have emerged as a prominent focus of research.

Numerous MM filter circuits have been reported in the literature employing various high-performance active building blocks (ABBs) such as Fully Differential Second-Generation Current Conveyor (FDCCII)[9-11], Differential Difference Current Conveyor (DDCC)[11-12], Dual-X Current Conveyor Differential Input Transconductance Amplifier (DX-CCDITA)[13], Differential Difference Current Conveyor Transconductance Amplifier (DDCCTA)[14], Operational Transconductance Amplifiers (OTA)[15], Extra-X Current Controlled Second-Generation Current Conveyor (EXCCCII)[16], Voltage Differencing Gain Amplifier (VDGA)[17-18], Differential, Voltage Differencing Buffered Amplifier (VDBA)[19-20], Difference Gain Amplifier (DDGA)[21], Voltage Differencing Extra X Current Conveyor (VD-EXCCII)[22-23], Modified Current Conveyor Amplifier (MCCTA)[24], Multiple-input Operational Transconductance Amplifiers (MI-OTAs)[25], Current-Feedback Operational Amplifiers (CFOA)[26-27]. These

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filters are usually classified based on the number of inputs and outputs, such as single-input single-output (SISO), multiple-input single-output (MISO)[12-13, 16, 19-20, 22-23], multiple-input multiple-output (MIMO)[14] and single-input multiple-output (SIMO)[9-11, 15, 17, 19, 21, 24] structures. However, SISO and MISO filters have a limitation because only one type of filter response can be obtained at a time from a single output. In addition, MISO and MIMO filters often need strict input matching conditions to achieve the required filter functions, which makes the circuit design more complicated and less practical. In contrast, SIMO multi-mode filters offer greater flexibility since they are capable of generating all fundamental filter responses at the same time, without requiring specific input matching constraints.

The limitations observed from the study of the existing filters are given as follows;

i The work[11] requires different kinds of ABBs, leading to higher circuit complexity.

ii The passive components count in the work[9-14, 16-17, 19-24, 26-27] is high, resulting in high power consumption and increased circuit complexity.

iii All-grounded passive elements are not ensured in several reported works, resulting in more being affected by parasitic of the device[9,12,16-17, 20, 22-24].

iv A few of the reported filters do not provide independent control of the pole frequency and Q[12-13, 17].

v Many of the earlier reported works needs input matching conditions[10, 11-14, 18-19, 22, 24, 26].

vi Numerous circuits reported in the literature have lower operating frequency[9-15, 17-19, 21, 23, 25-27].

By the above observations, there is a strong need to develop a compact, low-power and fully integrated MM filter that can provide all standard filtering responses simultaneously in a single configuration without changing its circuitry, while utilizing a reduced number of active and passive elements, also avoiding input matching constraints. The proposed resistor less circuit of MM biquad filter uses two Current Follower Differential Input Transconductance Amplifiers (CFDITAs) and two grounded capacitors. It operates in VM, CM, TAM and TIM modes. The design uses grounded components, requires no input matching and is suitable for cascading due to proper input impedances. The pole frequency and quality factor can be independently and electronically adjusted through the CFDITA's bias currents. Table 1

Table 1 — Performance comparison of the suggested MM filter with earlier reported MM configurations

R Ref.	ABB/Count	No of R+C	Grounded passive elements	Independent tuning of Q	Need for input matching condition	Technology used (μm)	Operating Frequency	Power Supply (V)	Power Consumption (mW)	Experimental verification
[9]	FDCCII/2	4+2	NO	YES	NO	0.18	1.59 MHz	±0.9	1.32	NO
[10]	FDCCII/2	4+2	NO	YES	NO	0.18	1.59 MHz	±0.9	---	NO
[11]	FDCCII/1 DDCC/1	6+2	NO	YES	YES	0.18	1.59 MHz	±0.9	---	NO
[12]	DDCC/3	4+2	NO	NO	YES	0.25	3.97 MHz	±1.25	---	NO
[13]	DXCCDITA/1	2+2	YES	NO	YES	0.35	32 kHz	±1.5	---	YES
[14]	DDCCTA/3	3+2	YES	YES	YES	0.18	10 kHz	±0.5	0.374	NO
[15]	OTA/4	0+2	YES	YES	NO	0.18	3.39 MHz	±0.9	0.19	NO
[16]	EXCCCII/1	1+2	NO	YES	NO	0.18	22.9 MHz	±0.5	1.35	YES
[17]	VDGA/1	1+1	NO	NO	NO	0.18	1.59 MHz	±0.9	1.31	YES
[18]	VDGA/2	0+2	YES	YES	YES	0.18	1.59 MHz	±0.9	2.84	YES
[19]	VDBA/2	2+2	YES	YES	YES	0.18	1.52 MHz	±0.75	-	YES
[20]	VDBA/3	1+2	NO	YES	NO	0.18	16.34 MHz	±1.25	5.482	YES
[21]	DDGA/1	2+2	YES	YES	NO	0.18	1.59 MHz	±0.9	1.83	YES
[22]	VD-EXCCII/2	3+2	NO	YES	YES	0.18	16.42 MHz	±1.25	---	NO
[23]	VD-EXCCII/1	3+2	NO	YES	NO	0.18	8.08 MHz	±1.25	5.76	YES
[24]	MCCTA/1	2+2	NO	YES	YES	0.25 & 0.18	12.02 MHz	±1.25	---	NO
[25]	MI-OTA/3	0+2	YES	YES	NO	0.065	156 Hz	±0.5	.00045	YES
[26]	CFOA/2	3+2	YES	YES	YES	0.18	6.37 MHz	±2.8	3.36	YES
[27]	CFOA/5	6+2	YES	YES	---	0.18	159 kHz	±10	---	YES
This work	CFDITA/2	0+2	YES	YES	NO	0.18	10 MHz	±1.25	1.32	YES

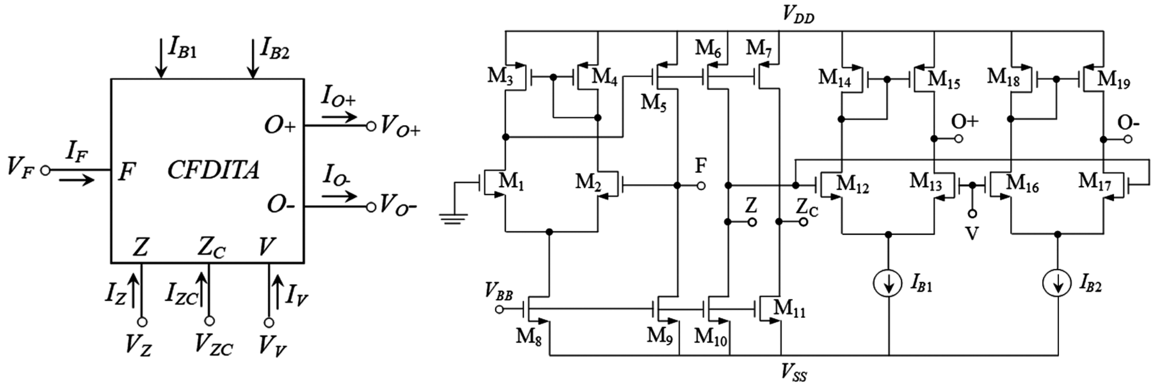

Fig. 1 — (a) Symbol; and (b) CMOS representation of the CFDITA

presents a comparative analysis highlighting the key benefits of the proposed MM filter in contrast to previously reported MM configurations.

2 CFDITA Description

CFDITA is formed by connecting a current follower stage in series with an operational trans conductance amplifier (OTA)[28]. It has been proven to be a versatile active element in the realization of different analog circuits[29-34]. The symbolic representation and CMOS structure of CFDITA are illustrated in Fig. 1 (a) and (b), respectively. The behavior of the CFDITA can be explained through a matrix equation, written in standard form which defines the relationships among its terminal voltages and currents.

$$\begin{bmatrix} I_V \\ I_Z \\ I_{ZC} \\ I_{O+} \\ I_{O-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ -g_{m1i} & g_{m1i} & 0 \\ g_{m2i} & -g_{m2i} & 0 \end{bmatrix} \begin{bmatrix} V_V \\ V_Z \\ I_F \end{bmatrix} \quad \ldots (1)$$

where g_{m1i} and g_{m2i} are the trans conductance gains of i^{th} CFDITA which are electronically controllable via bias currents I_{B1} and I_{B2}, respectively. The expression of trans conductance is given as $g_{mi} = \sqrt{\mu_n C_{ox}\left(W/_L\right) I_{Bi}}$. I_F, I_Z, I_{ZC}, I_{O+} and I_{O-} are the currents at terminal F, Z, Z_C, $O+$ and $O-$ respectively; V_F, V_Z, V_{ZC}, V_{O+} and V_{O-} are the voltages at terminal F, Z, Z_C, $O+$ and $O-$ respectively.

3 Proposed Multi-Mode Filter

The suggested MM biquad filter circuit is shown in Fig. 2. It uses two CFDITAs and two grounded capacitors only, making it a compact MM filter structure. In the circuit configuration, the voltage

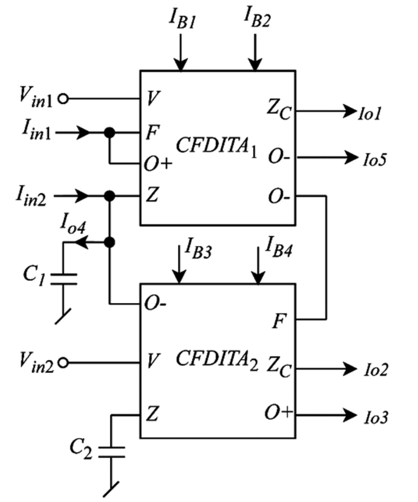

Fig. 2 — Proposed multi-mode biquad filter

input signals V_{in1} and V_{in2} are applied to the high-impedance terminals, whereas the current input signals I_{in1} and I_{in2} are fed into the low-impedance terminals of the CFDITA, which allows the ease of cascadability of the proposed filter. The output currents are obtained only from the high-impedance terminals, which assists the filter in easily driving the load for both CM and TAM. The proposed circuit works in VM, CM, TAM and TIM without any change in the topology. The functionality of the proposed multi-mode filter can be described using the following cases.

3.1 Operation in CM

In CM operation, the input signal is provided as a current. Hence, the input currents I_{in1} and I_{in2} are applied to the circuit, while the input voltages V_{in1} and V_{in2} are kept grounded. For CM operation, the output responses are obtained from the currents I_{o1}, I_{o2}, I_{o3}, I_{o4} and I_{o5}.

While applying $I_{in1} = I_{in}$, $I_{in2} = 0$, the transfer functions (TFs) obtained in CM operation are given as follows;

$$\frac{I_{o1}}{I_{in}} = \frac{-(s^2C_1C_2+g_{m21}g_{m22})}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (2)}$$

$$\frac{I_{o2}}{I_{in}} = \frac{-sC_2g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (3)}$$

$$\frac{I_{o3}}{I_{in}} = \frac{-g_{m12}g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (4)}$$

$$\frac{I_{o4}}{I_{in}} = \frac{-s^2C_1C_2}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (5)}$$

Based on Eqs. (2) - (5), the output currents I_{o1}, I_{o2}, I_{o3} and I_{o4} exhibit BR, BP, LP and HP responses, respectively. The output current obtained from I_{o5} exhibits the same response as I_{o2}, except that it is inverted in polarity. By combining the currents I_{o1} and I_{o5}, an AP filtering response can be obtained as outlined below;

$$\frac{I_{o1}+I_{o5}}{I_{in}} = \frac{-(s^2C_1C_2-sC_2g_{m21}+g_{m21}g_{m22})}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (6)}$$

Under the condition that $I_{B1} = I_{B2}$, which results in $g_{m21} = g_{m11}$, the above expression realize an inverting AP filter response.

while applying the $I_{in2} = I_{in}$, $I_{in1} = 0$, the TFs obtained in CM operations are given as follows;

$$\frac{I_{o1}}{I_{in}} = \frac{-sC_2g_{m11}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (7)}$$

$$\frac{I_{o2}}{I_{in}} = \frac{sC_2g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (8)}$$

$$\frac{I_{o3}}{I_{in}} = \frac{g_{m12}g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (9)}$$

$$\frac{I_{o4}}{I_{in}} = \frac{s^2C_1C_2}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (10)}$$

It is evident from Eqs. (7) - (10) that the output currents I_{o1} and I_{o2} realize BP, I_{o3} exhibits LP response and I_{o4} realizes HP response, respectively.

3.2 Operation in TAM

In TAM operation, the input signal is supplied as a voltage. Hence, the input voltages V_{in1} and V_{in2} are applied to the circuit, while input currents I_{in1} and I_{in2} are kept grounded. The outputs are obtained from currents I_{o1}, I_{o2}, I_{o3} and I_{o4}. While applying $V_{in1} = V_{in}$, $V_{in2} = 0$, the TFs obtained in TAM operations are given as follows;

$$\frac{I_{o1}}{V_{in}} = \frac{s^2C_1C_2g_{m11}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (11)}$$

$$\frac{I_{o2}}{V_{in}} = \frac{-s^2C_1C_2g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (12)}$$

$$\frac{I_{o3}}{V_{in}} = \frac{-sC_1g_{m12}g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (13)}$$

From Eqs. (11) - (13), indicates that the currents I_{o1} and I_{o2} realize HP response, whereas I_{o3} exhibits BP response. When $V_{in1} = 0$, $V_{in2} = V_{in}$, the TFs obtained in TAM operations are given as follows;

$$\frac{I_{o1}}{V_{in}} = \frac{-sC_2g_{m11}g_{m22}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (14)}$$

$$\frac{I_{o2}}{V_{in}} = \frac{sC_2g_{m21}g_{m22}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (15)}$$

$$\frac{I_{o4}}{V_{in}} = \frac{s^2C_1C_2g_{m22}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (16)}$$

Based on Eqs. (14) - (16), the currents I_{o1} and I_{o2} exhibit BP response, I_{o4} realizes HP response.

3.3 Operation in VM

In VM operation, the input signal is applied in the form of a voltage. Hence, the input voltages V_{in1} and V_{in2} are applied to the circuit, while input currents I_{in1} and I_{in2} are kept grounded. The filter responses are taken from v_{c1} *and* v_{c2} voltages.

while applying $V_{in1} = V_{in}$, $V_{in2} = 0$, the TF obtained in VM operation is given as follows;

$$\frac{v_{c2}}{V_{in}} = \frac{-sC_1g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (17)}$$

From Eq. (17), indicates that the output voltage v_{c2} realizes BP response.

when $V_{in1} = 0$, $V_{in2} = V_{in}$, the TFs obtained in VM operations are given as follows;

$$\frac{v_{c1}}{V_{in}} = \frac{sC_2g_{m22}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (18)}$$

$$\frac{v_{c2}}{V_{in}} = \frac{g_{m21}g_{m22}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (19)}$$

From Eqs. (18) - (19), indicates that the responses BP, LP are obtained from v_{c1} and v_{c2}, respectively.

3.4 Operation in TIM

In TIM operation, the input signal is applied in the form of a current. Hence, the input currents I_{in1} and I_{in2} are applied to the circuit, while input voltages V_{in1} and V_{in2} are kept grounded. The outputs are taken from v_{c1} and v_{c2} voltages.

while applying $I_{in1} = I_{in}$, $I_{in2} = 0$, the TFs obtained in TIM operations are given as follows;

$$\frac{v_{c1}}{I_{in}} = \frac{-sC_2}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (20)}$$

$$\frac{v_{c2}}{I_{in}} = \frac{-g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (21)}$$

Based on Eqs. (20) - (21), it is noted that the output response from v_{c1} is BP and v_{c2} exhibits LP response.

when $I_{in2} = I_{in}$, $I_{in1} = 0$, the TFs obtained in TIM operations are given as follows;

$$\frac{v_{c1}}{I_{in}} = \frac{sC_2}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (22)}$$

$$\frac{v_{c2}}{I_{in}} = \frac{g_{m21}}{s^2C_1C_2+sC_2g_{m11}+g_{m21}g_{m22}} \quad \text{... (23)}$$

From Eqs. (22) and (23) BP and LP responses are obtained at the voltage outputs v_{c1} and v_{c2}, respectively.

The pole frequency, f_0 , and quality factor, Q obtained in all four modes are given as follows;

$$f_o = \frac{1}{2\pi}\sqrt{\frac{g_{m21}g_{m22}}{C_1C_2}} \quad \text{... (24)}$$

$$Q = \frac{1}{g_{m11}}\sqrt{\frac{g_{m21}g_{m22}C_1}{C_2}} \quad \text{... (25)}$$

when the bias currents satisfy $I_{B2} = I_{B4,}$ resulting in $g_{m21} = g_{m22} = g_m$ and the capacitors are chosen to be equal ($C_1 = C_2 = C$), the expressions for the pole frequency in Eq. (24) and quality factor in Eq. (25) can be derived as follows.

$$f_o = \frac{g_m}{2\pi C} \quad \text{... (26)}$$

$$Q = \frac{g_m}{g_{m11}} = \sqrt{\frac{I_{B2}}{I_{B1}}} \quad \text{... (27)}$$

It is evident from Eqs. (26) and (27) that the quality factor, Q can be independently controlled via bias current I_{B1} without affecting the pole frequency. The pole frequency can be tuned via bias current $I_{B2,}$ and for a desired value of pole frequency, the quality factor can be adjusted by bias current I_{B1}.

4 Non-ideal and Parasitic Analysis

Taking into account the non-ideal characteristics of the CFDITA, its port relationships are revised and represented by the following matrix Eq. (28).

$$\begin{bmatrix} I_V \\ I_Z \\ I_{ZC} \\ I_{O+} \\ I_{O-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \alpha_{1i} \\ 0 & 0 & \alpha_{2i} \\ -\gamma_{1i}g_{m1i} & \gamma_{1i}g_{m1i} & 0 \\ \gamma_{2i}g_{m2i} & -\gamma_{2i}g_{m2i} & 0 \end{bmatrix} \begin{bmatrix} V_V \\ V_Z \\ I_F \end{bmatrix} \quad \text{... (28)}$$

where α_{1i} , α_{2i} are non-ideal current transfer gains of i^{th} CFDITA from terminal F to terminal Z and $Z_{C,}$ respectively; γ_{1i} and γ_{2i} are non-ideal inaccuracies in trans conductance of i^{th} CFDITA from terminal Z to $O+$ and $O-$, respectively. The CFDITA has some parasitic elements, such as a series resistance R_F at the F terminal and a parallel combination of resistor R_k with capacitor C_k at each terminal k, where $k = Z, Z_C, V, O+, O-$. By accounting for the non-ideal and parasitic effects, the suggested MM filter is re-evaluated and the corresponding TFs for the different operating modes are derived accordingly.

4.1 In CM

while applying $I_{in1} = I_{in}$, $I_{in2} = 0$, the TFs obtained in CM operations are given as follows;

$$\frac{I_{o1}}{I_{in}} = \frac{-\left(\alpha_{21}s^2C_1'C_2'+\alpha_{12}\alpha_{21}\gamma_{21}\gamma_{22}g_{m21}g_{m22}\right)}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (29)}$$

$$\frac{I_{o2}}{I_{in}} = \frac{-\alpha_{11}\alpha_{12}\alpha_{22}\gamma_{21}sC_2'g_{m21}}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (30)}$$

$$\frac{I_{o3}}{I_{in}} = \frac{-\alpha_{11}\alpha_{12}\gamma_{12}\gamma_{21}g_{m12}g_{m21}}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (31)}$$

$$\frac{I_{o4}}{I_{in}} = \frac{-\alpha_{11}s^2C_1'C_2'}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (32)}$$

where $C_1' = C_1 + C_Z + C_{O-}$ and $C_2' = C_2 + C_Z$. When $I_{in2} = I_{in}$, $I_{in1} = 0$, the TFs obtained in CM operations are given as follows:

$$\frac{I_{o1}}{I_{in}} = \frac{-\alpha_{21}\gamma_{11}sC_2'g_{m11}}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (33)}$$

$$\frac{I_{o2}}{I_{in}} = \frac{\alpha_{12}\alpha_{21}\gamma_{21}sC_2'g_{m21}}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (34)}$$

$$\frac{I_{o3}}{I_{in}} = \frac{\alpha_{12}\gamma_{12}\gamma_{21}g_{m11}g_{m21}}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (35)}$$

$$\frac{I_{o4}}{I_{in}} = \frac{s^2C_1'C_2'}{s^2C_1'C_2'+\alpha_{11}\gamma_{11}sC_2'g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \text{... (36)}$$

4.2 In TAM

For the input selection taken as $V_{in1} = V_{in}$, $V_{in2} = 0$, the TAM TFs are obtained as follows;

$$\frac{I_{o1}}{V_{in}}=\frac{\alpha_{21}\gamma_{11}s^2C_1^{'}C_2^{'}g_{m11}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (37)$$

$$\frac{I_{o2}}{V_{in}}=\frac{-\alpha_{11}\alpha_{22}\gamma_{21}s^2C_1^{'}C_2^{'}g_{m21}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (38)$$

$$\frac{I_{o3}}{V_{in}}=\frac{-\alpha_{12}\gamma_{12}\gamma_{21}sC_1^{'}g_{m12}g_{m21}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (39)$$

when $V_{in1} = 0$, $V_{in2} = V_{in}$, the TFs obtained in TAM operations are given as follows;

$$\frac{I_{o1}}{V_{in}}=\frac{-\alpha_{21}\gamma_{11}\gamma_{22}sC_2^{'}g_{m11}g_{m22}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (40)$$

$$\frac{I_{o2}}{V_{in}}=\frac{\alpha_{11}\alpha_{22}\gamma_{21}\gamma_{22}sC_2^{'}g_{m21}g_{m22}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (41)$$

$$\frac{I_{o4}}{V_{in}}=\frac{\gamma_{22}s^2C_1^{'}C_2^{'}g_{m22}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (42)$$

4.3 In VM

when $V_{in1} = V_{in}$, $V_{in2} = 0$, the TFs obtained in VM operations are given as follows;

$$\frac{v_{c2}}{V_{in}}=\frac{-\alpha_{12}\gamma_{21}sC_1^{'}g_{m21}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (43)$$

when $V_{in1} = 0$, $V_{in2} = V_{in}$, the TFs obtained in VM operations are given as follows;

$$\frac{v_{c1}}{V_{in}}=\frac{\gamma_{22}sC_2^{'}g_{m22}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (44)$$

$$\frac{v_{c2}}{V_{in}}=\frac{\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (45)$$

4.4 In TIM

while applying $I_{in1} = I_{in}$, $I_{in2} = 0$, the TFs obtained in TIM operations are given as follows;

$$\frac{v_{c1}}{I_{in}}=\frac{-\alpha_{11}sC_2^{'}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (46)$$

$$\frac{v_{c2}}{I_{in}}=\frac{-\alpha_{11}\alpha_{12}\gamma_{21}g_{m21}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (47)$$

when $I_{in2} = I_{in}$, $I_{in1} = 0$, the TFs obtained in TIM operations are given as follows;

$$\frac{v_{c1}}{I_{in}}=\frac{sC_2^{'}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (48)$$

$$\frac{v_{c2}}{I_{in}}=\frac{\alpha_{11}\alpha_{12}\gamma_{21}g_{m21}}{s^2C_1^{'}C_2^{'}+\alpha_{11}\gamma_{11}sC_2^{'}g_{m11}+\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}} \quad \ldots (49)$$

The modified pole frequency, f_0, and quality factor, Q are now given as follows;

$$f_o=\frac{1}{2\pi}\sqrt{\frac{\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}}{C_1'C_2'}} \quad \ldots (50)$$

$$Q=\frac{1}{\alpha_{11}\gamma_{11}g_{m11}}\sqrt{\frac{\alpha_{12}\gamma_{21}\gamma_{22}g_{m21}g_{m22}C_1'}{C_2'}} \quad \ldots (51)$$

It is evident from Eqs. (50) and (51) that pole frequency and quality factor are affected by the non-ideal gains and parasitic of CFDITA. The effect of parasitic can be reduced by selecting the external capacitors such that $C_1 >> (C_Z, C_{O-})$ and $C_2 >> C_Z$.

5 Simulation Results

The performance of the suggested MM filter is verified through computer simulations using PSpice. The capacitors C_1 and C_2 are chosen as values of 15 pF. The circuit is powered by a supply voltage of ±1.25 V. Both CFDITA's trans conductance gains are set to 1 mS, by setting the bias currents to 125 µA. The designed pole frequency is 10.6 MHz and value of quality factor is 1. The aspect ratios of MOS transistors in µm are given as follows: M_1-M_2, M_5-M_7: W/L = 0.36/0.18, M_3-M_4: W/L = 1.44/0.18, M_8-M_{11}: W/L =16.2/0.18, M_{12}-M_{17}: W/L = 9/0.18, M_{18}-M_{19}: W/L = 1/0.18. Figure 3 illustrates the simulated frequency responses of the proposed filter in CM, when $I_{in1} = I_{in}$. The plot in Fig. 3 confirms the multifunction filtering capability of the proposed circuit, where filtering responses LP, HP, BP and BR are available simultaneously. Figure 4 illustrates the frequency responses obtained when $I_{in2} = I_{in}$, where LP, HP and BP responses are realized simultaneously.

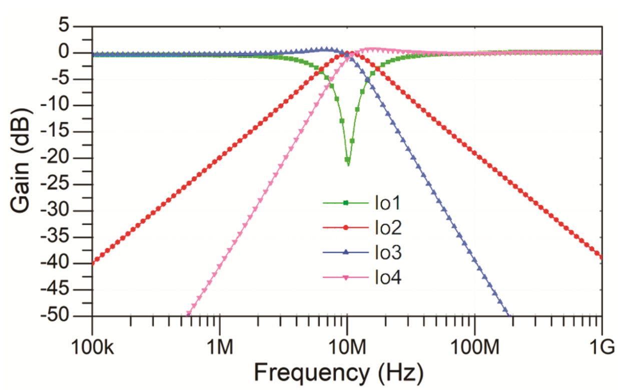

Fig. 3 — The frequency responses of CM filters when $I_{in1} = I_{in}$

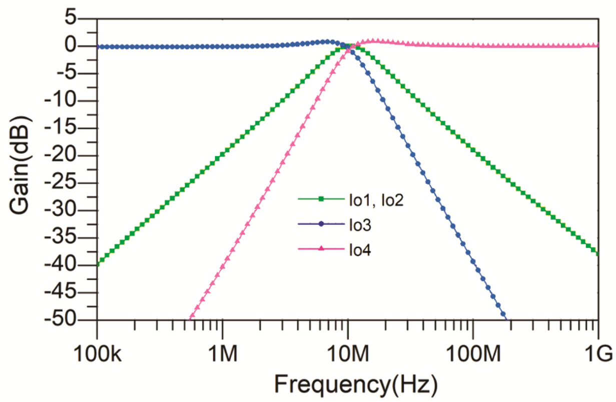

Fig. 4 — The frequency responses of CM filters when $I_{in2} = I_{in}$

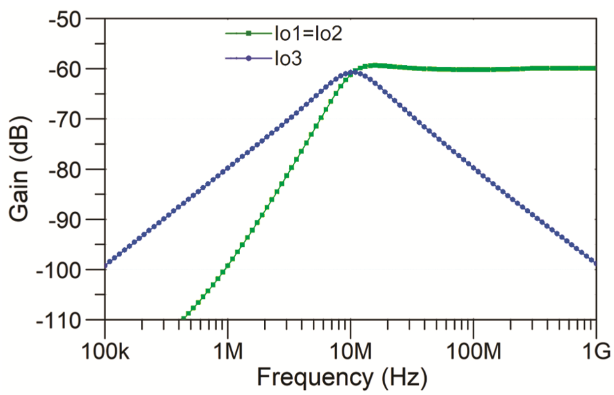

Fig. 5 — The frequency responses of TAM filters when $V_{in1} = V_{in}$

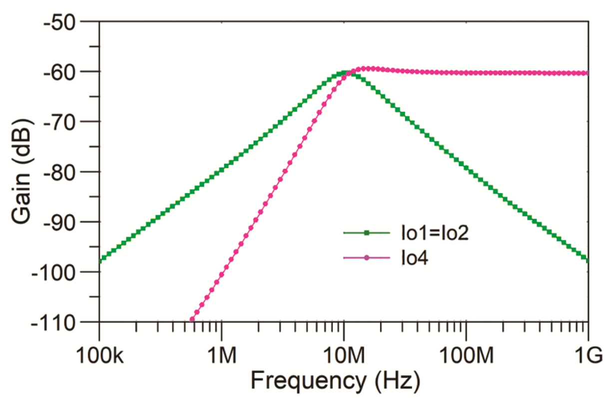

Fig. 6 — The frequency responses of TAM filters when $V_{in2} = V_{in}$

Figure 5 depicts the frequency responses of the proposed filter operating in TAM when the input voltage $V_{in1} = V_{in}$ is applied, yielding BP and HP output current responses. When $V_{in2} = V_{in}$, the corresponding TAM responses, namely BP and HP, are observed as shown in Fig. 6. Figure 7 depicts the simulated frequency responses in TIM for $I_{in1} = I_{in}$, where BP and LP responses are obtained. Finally, Fig. 8 shows the VM operation of the filter with

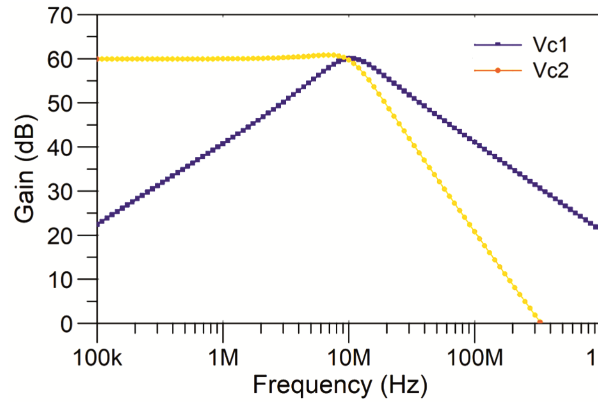

Fig. 7 — The frequency responses of TIM filers when $I_{in1} = I_{in}$

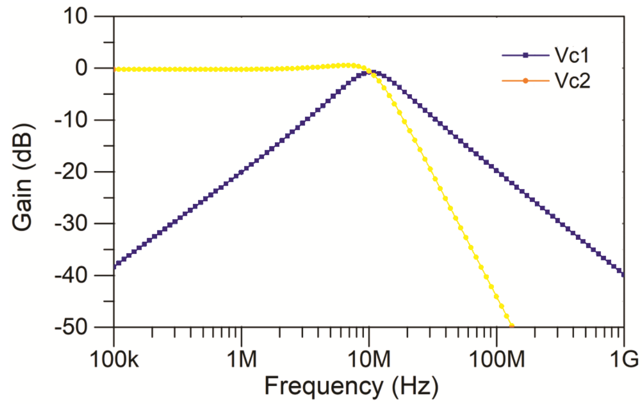

Fig. 8 — The frequency responses of VM filters when $V_{in2} = V_{in}$

$V_{in2} = V_{in}$, producing BP and LP responses. The time-domain input and output currents of the BP filter are shown in Fig. 9 at 10.3 MHz frequency. Figure 9 (a) shows the time-domain waveforms for $I_{in1} = I_{in}$ realizing a non-inverting BP filter and Fig. 9 (b) shows the time-domain waveforms for $I_{in2} = I_{in}$ realizing an inverting BP filter. Figure 10 shows the tunability of quality factor Q through the bias current, I_{B1}. The simulated quality factor is 1.38, 1.14 and 1 when I_{B1} is set to 65, 95 and 125 μA, respectively, while I_{B2} is set to 125 μA. From Fig. 10, it is clear that the filter allows independent electronic control of quality factor without affecting the pole frequency.

The tuning of pole frequency is illustrated in Fig. 11 where BP filter frequency responses are shown for different values of bias current I_{B2} while keeping the current ratio I_{B2}/I_{B1} constant. When I_{B2} is set to 65, 95 and 125 μA, the natural frequency is found to be 6.2, 8.4 and 10.3 MHz, respectively. The quality factor value in Fig. 11 is 1 and stays constant without affecting the tuning of the pole frequency. The suggested filter is now configured as an AP filter

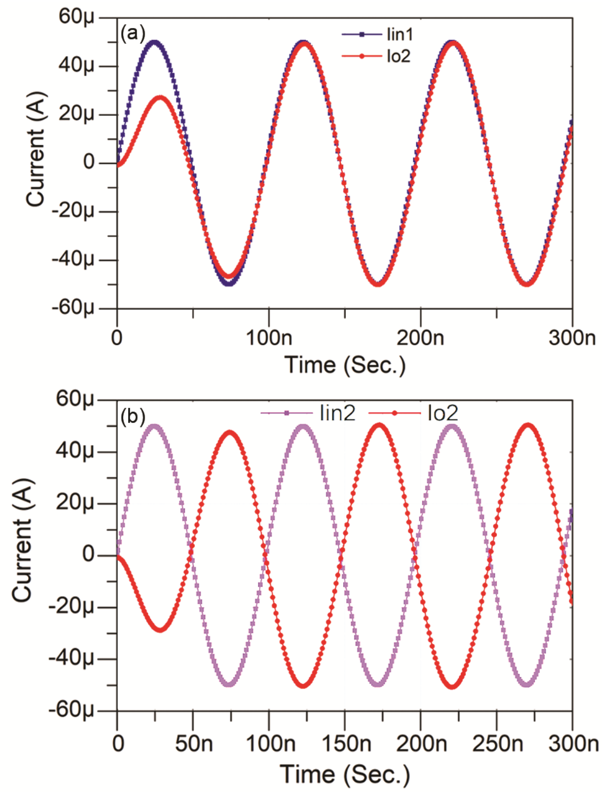

Fig. 9 — Transient responses of CM filter for the currents (a) I_{in1} and I_{O2} (b) I_{in2} and I_{O2}

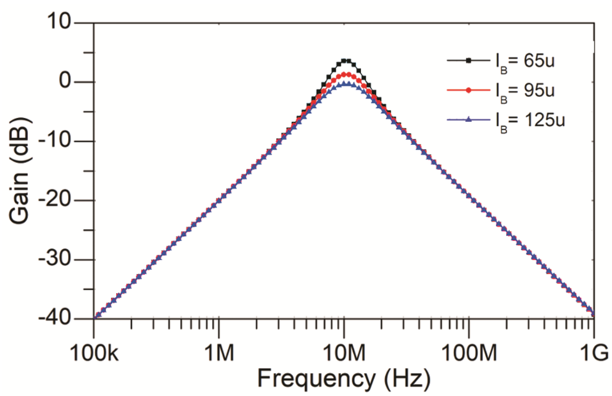

Fig. 10 — Independent tuning of quality factor via bias current I_{B1}

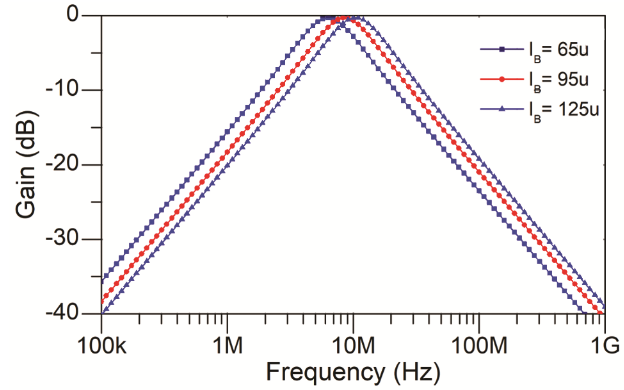

Fig. 11 — Independent tuning of pole frequency via bias current I_{B2} while maintaining I_{B2}/I_{B1} constant

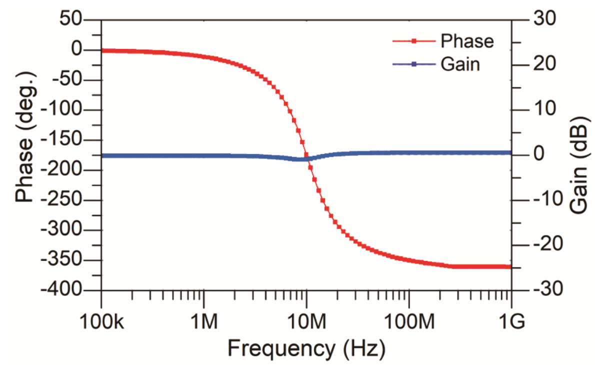

Fig. 12 — Frequency responses for gain and phase of AP filter

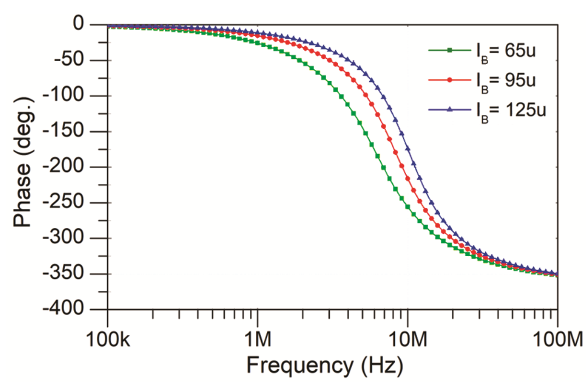

Fig. 13 — The tuning of phase of AP filter via bias current I_{B2}

in CM, and its gain and phase plots are depicted in Fig. 12. It is also discovered that the simulated pole frequency for all type of responses is 10.3 MHz, which is nearly identical to the intended value. Figure 13 illustrates the tuning of the pole frequency for the AP filter for different values of the bias current I_{B2}. When I_{B2} is set to 65, 95, and 125 µA, the corresponding natural frequencies are observed to be 6.2, 8.4 and 10.3 MHz, respectively. Figure 14 shows the transient responses of the AP filter for currents, I_{in} and I_{out} at pole frequency. A 180° phase shift is observed between currents, I_{in} and I_{out} at pole frequency. Figure 15 shows the Monte Carlo simulation results of the AC response of the frequency of output current of the suggested MM filter. The simulation is carried out for 100 runs, considering a 5 % variation in the threshold voltages, to examine the effect of process variation on the frequency of output signal.

6 Experimental Verification

For simplicity, the VM LP filter is experimentally validated by using the ICs AD844 and LM13700 to

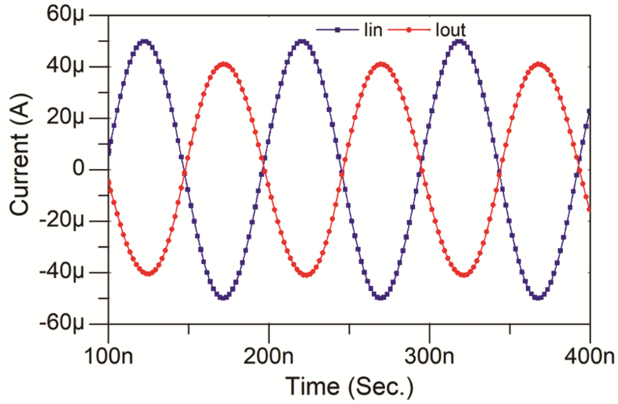

Fig. 14 — Transient responses of CM AP filter for I_{in} and I_{out}

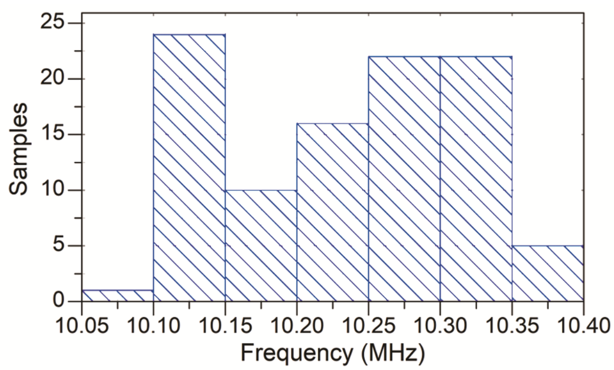

Fig. 15 — MCS results depicting a histogram of the frequency of output current for 5% variation in threshold voltage

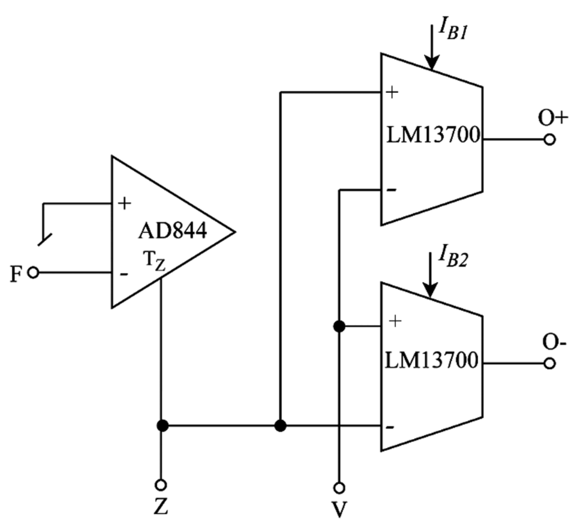

Fig. 16 — Practical realization of the CFDITA using commercially available ICs

implement the active block, CFDITA, as illustrated in Fig. 16. A sinusoidal signal of 1 V (p-p) is applied as the input voltage. An additional AD844, along with a 10 kΩ resistor are used to generate bias current. The bias currents I_{B1} and I_{B2} are adjusted to 90 μA, which

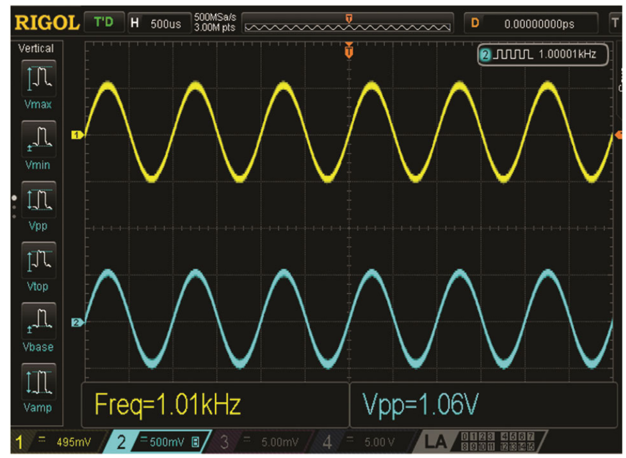

Fig. 17 — Transient waveform of VM LP filter at a frequency of 1 kHz

corresponds to a trans conductance (g_m) of 1 mS. Both capacitors are selected as C_1= C_2 = 10 nF. The designed pole frequency is 15.6 kHz. The transient response of the input voltage and the corresponding output voltage is observed at 1 kHz and its waveform is presented in Fig. 17.

7 Conclusion

A compact CFDITA-based MM biquad filter has been implemented using only two CFDITAs and two grounded capacitors. The circuit operates in VM, CM, TAM and TIM and it realizes all standard filtering responses in CM, thereby functioning as a universal filter in CM. Electronic tunability of the pole frequency and Q is achieved through the CFDITA's bias currents. The circuit functions well up to a frequency of 10.3 MHz. The proposed filter supports low-voltage (± 1.25 V) and low-power (1.32 mW) operation, good cascading capability and provides independent control of Q and pole frequency. It is validated through PSPICE simulations using 0.18 µm CMOS technology, confirming close agreement with theoretical predictions. Additionally, the proposed VM LP filter is also tested experimentally. Overall, the proposed MM filter offers electronic tunability and reliable performance, making it suitable for integrated analog signal-processing applications.

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