Subthreshold Low-Transconductance M-CDTA based Low Frequency Current Mode Universal Filter

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Abstract *— In this research work, a low transconductance Modified Current Differencing Trans-Conductance Amplifier (M-CDTA) block customized to operate in the sub-threshold region of operation is presented. It is able to achieve a low transconductance value, with the minimum value being 68.8nA/V. As an application, a low frequency current mode universal filter is presented in this manuscript which is used in biomedical signal processing. The structure is composed of two M-CDTA blocks along with two grounded capacitors. The grounded capacitors make the circuit feasible from a fabrication point of view. The circuit has low input as well as high output impedances, which is as desired in a current mode (CM) circuit. The filter also possesses benefits such as electronically tunability of the pole frequencies using bias currents and orthogonal tunability of the pole frequency and the quality factor of the filter. Both the block and the filterare developed on CMOS 180nm technology node. The functionality of the circuit is simulated and verified on Cadence Virtuoso software. The simulation results reveal a good performance of the implemented block as well as the filter.*

Keywords *— CDTA, Low-Transconductance, Subthreshold Regime, Universal Filter.*

I. INTRODUCTION

Recently, in the domain of integrated circuits, a lot of attention has been devoted to various analog building blocks (ABB) due to their enormous implementation in various VLSI applications. Among the existing ABBs, current mode ABB have been more positively acknowledged due to their wider bandwidth, reduced power consumption and increased dynamic range, especially in the area of analog signal processing. CDTA [1] is a current processing ABB and can be advantageously employed in CM circuits as it has all the properties required in a CM block like proper input and output impedances and electronic tunability feature with the help of the bias currents present in the block. The output current in the CDTA block can be controlled using a transconductance value, which is also a really important characteristic of the block. Moreover, filters are an essential part in the field of analog signal processing due to their tremendous applications and it is desired to obtain all the possible filtered outputs simultaneously from any filter, i.e. universal filters. Thus, a lot of attention has been devoted in the recent past towards obtaining CDTA based universal CM filters. Furthermore, there is also a progressing demand to develop universal filters useful in the domain of biomedical signal processing [2]. Therefore, there is a developing need for filters having extremely low frequencies in the present.

A comprehensive literature survey reveals that many CDTA based universal CM filters [3-19] have been reported previously. To obtain a filter having pole frequency in the sub-hertz range, the previously reported filters [3-19] need to employ capacitors having extremely large values, which is practically not possible from fabrication point of view. Thus, it can be inferred that a universal CM filter having low pole frequencies is not available in the literature and due to the motivation to fulfil this gap, the same has been presented in this manuscript.

This work presents a low-transconductance M-CDTA block operating in subthreshold regime, which is employed in a CM universal filter having low pole frequencies and is thus presented as an application of the presented block. The implemented filter has proper impedances employing grounded capacitances with possibility of electronic tunability of the pole frequency along with orthogonal tunability of the pole frequency and the quality factor.

The organization of the manuscript isin the following manner: Section 2 describes the subthreshold low-transconductance M-CDTA block. Section 3 presents the design, implementation as well as the simulation results of the low frequency CM universal filter employing the low-transconductance M-CDTA block. Conclusions drawn are concluded in Section 4.

II. THE SUBTHRESHOLD LOW-TRANSCONDUCTANCE M-CDTA

CDTA [1] is a current ABB involving a Current Differencing Unit (CDU) appended with a transconductance amplifier (TA). The M-CDTA i.e. Modified Current Differencing Transconductance

Amplifier is a modified version of the CDTA block, wherein, auxiliary terminals are appended for effective copying of the available output currents in the ABB. Here, additional X_+terminals are augmented in the block to facilitate copying of currents.

The symbolic representation of the M-CDTA block is depicted in Fig. 1.

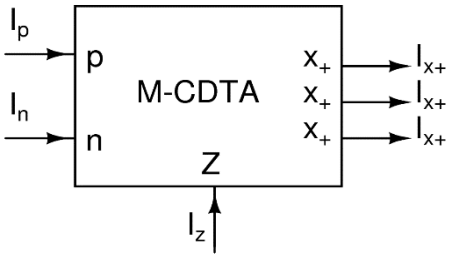


Fig. 1 M-CDTA Symbolic Representation

The functionality of the M-CDTA block is described as follows: the input currents applied at the p and n terminals are subtracted and the subtracted current is then available through the Z terminal. Further, the output current accessible through the X terminals is equal to the voltage produced at the Z terminal multiplied by the transconductance (g_m) of the M-CDTA. The functionality of the M-CDTA block can be described using the port relationships provided in (1).

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_{X+} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & g_m & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_z \\ V_{X+} \end{bmatrix} \quad (1)$$

The CMOS implementation of the M-CDTA block is described in Fig. 2. The CMOS implementation of the MCDTA block present in [10] is adapted and redesigned to incorporate the required additional terminals. Also, the M-CDTA block is customized to operate in the subthreshold region of operation by employing low power supply (V_{DD} and V_{SS}) near the threshold voltage of the transistors and also employing low bias currents (I_1, I_2 and I_3).

On routine analysis, the relation between the output current (I_{X+}) of the M-CDTA block with the voltage at the Z terminal (V_z) is expressed in (2) where I_{bias}=I3 and relation between gm of the block with the bias current can be expressed in (3). In (2) and (3), κ represents the exponential coefficient in the subthreshold region, V_t represents the thermal voltage and n represents the ideality factor of the semiconductor.

$$I_{X+} = I_{bias}\ tanh\frac{\kappa V_Z}{V_t} \quad (2)$$

$$g_m = \frac{I_{bias}}{2nV_t} \quad (3)$$

The relation between the g_m and bias current in case of saturation region of operation of transistors, is expressed in (4).

$$g_{m_{saturation}} = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right) I_{bias}} \quad (4)$$

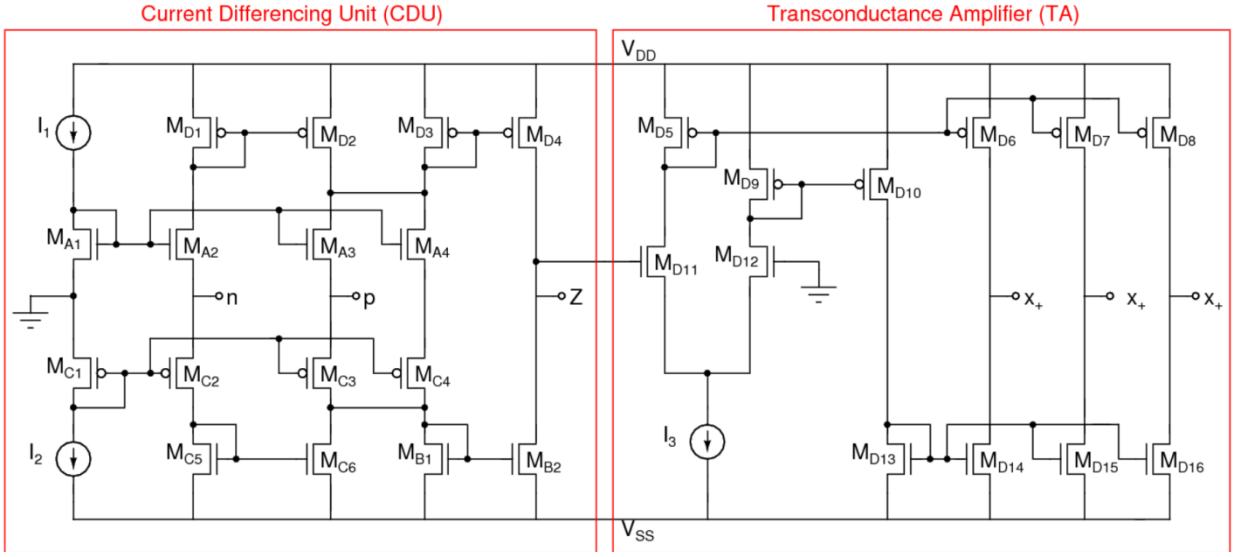


Fig. 2CMOS Implementation of the subthreshold low-transconductance M-CDTA block

From (3) and (4), it can be noted that with same bias currents (usually in the range of µA-nA), lower transconductance can be obtained using subthreshold region of operation due to direct relationship of the

g_m with the bias current. Thus, the transconductance values of the CDTA block, usually operated in the saturation region of operation, are in the range of microsiemens (µS), whereas, when being operated in the subthreshold region of operation, the transconductance values of the CDTA block reduces drasticallyto the nanosiemens (nS) range. Therefore, as the pole frequencies in most filters are dependent on the transconductance values of the ABB, it is preferred to reduce the transconductance to obtain low pole frequencies, which, which is possible by operating the ABB in the subthreshold regime.

To verify the functionality of the subthreshold low-transconductance M-CDTA on block, characterization of the block is performed using Cadence Virtuoso simulations for 180nm technology. To ensure subthreshold operation, the aspect ratios of the transistors are selectedas shown in Table 1. The power supply voltages (V_{DD} and V_{SS}) are set to be 0.3V and -0.3V and the bias currents as $I_1=I_2=I_3=5nA$.

TABLE I. ASPECT RATIO OF THE TRANSISTORS

Transistors	Aspect Ratios (W/L)
M_{A1}-M_{A4}	600nm/500nm
M_{B1}-M_{B2}	2µm/1.5µm
M_{C1}-M_{C6}	2µm/500nm
M_{D1}-M_{D16}	700nm/500nm

Current transfer from p to Z and n to Z; p to X_+ and n to X_+ terminals is depicted in the form of current transfer characteristics with respect to frequency in Figures 3 and 4 respectively. Fig. 5 illustrates the variation in gm with frequency with various values of bias current (I_3).

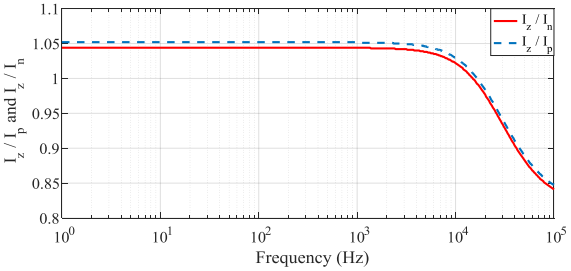


Fig. 3 Current transfer characteristics from p to Z and n to Z terminals

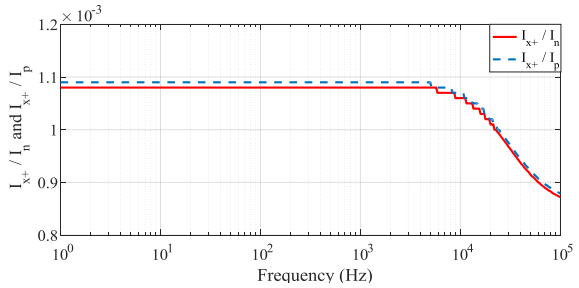


Fig. 4Current transfer characteristics from p to X_+ and n to X_+ terminals

Impedance seen from various terminals of the block is also calculated and the impedance seen from p & n, Z & X_+ terminals with frequency is shown in Fig. 6. As the M-CDTA block is a current processing block, impedances at the I/O terminals are expected to be low/high and the same has been obtained in the simulation analysis. Thus, the block has proper impedances.

The simulation results of the subthreshold low-transconductance M-CDTA block is provided in Table 2.

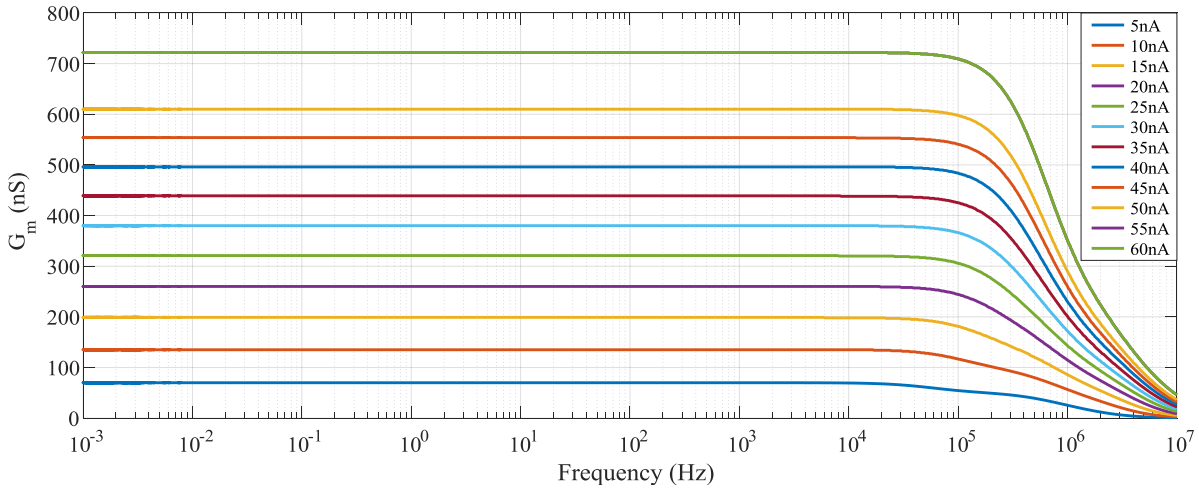
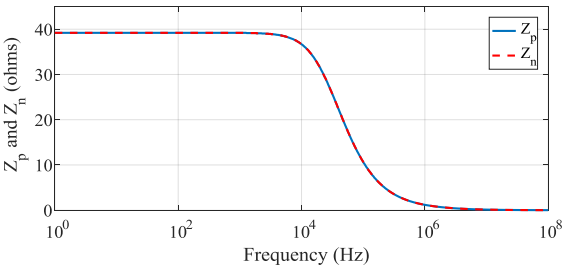
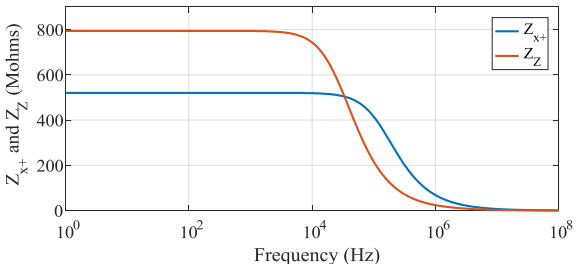


Fig. 5Variation in g_m with frequency for various bias currents



(a)



(b)

Fig. 6Impedance at (a) p, n (b) Z, X_+ terminals

III. APPLICATION

The functionality of the subthreshold low-transconductance M-CDTA block is verified using a low frequency universal filter [4] described in Fig. 7. The universal filter consists of two active M-CDTA blocks and two passive grounded capacitors. It is a Multiple Input Single Output (MISO) filter. The general transfer function of the filter can be presented as expressed in equation (5).

$$I_{out} = \frac{s\frac{g_m}{C_1}I_1 + \frac{g_m{}^2}{C_1C_2}I_2 + \left(s^2 + \frac{g_m}{C_1}s + \frac{g_m{}^2}{C_1C_2}\right)I_3}{s^2 + \frac{g_m}{C_1}s + \frac{g_m{}^2}{C_1C_2}} \quad (5)$$

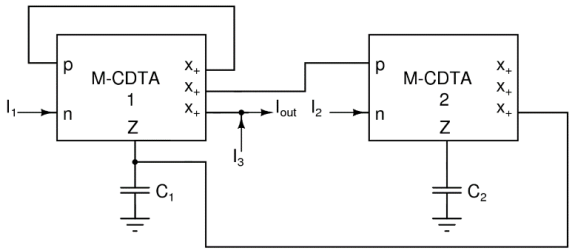


Fig. 7Low Frequency Filter [4]

An in-depth exploration of the general transfer function shows that the filter is capable of providing all Low pass (LP), High Pass (HP), Band Pass (BP), Band Reject (BR) and All pass (AP) responses. The different conditions which result in various filtered responses along with their transfer functions are described below:

1. For LP response, required input current combinations are: I_1=0, I_2=I_{in}, I_3=0 and its transfer function is expressed in (6).

$$\frac{I_{out}}{I_{in}} = \frac{\frac{g_m{}^2}{C_1C_2}}{D(s)} \quad (6)$$

2. For HP response, required input current combinations are: I_1=-I_{in}, I_2=-I_{in}, I_3=I_{in} and its transfer function is expressed in (7).

$$\frac{I_{out}}{I_{in}} = \frac{s^2}{D(s)} \quad (7)$$

3. For BP response, required input current combinations are: I_1=I_{in}, I_2=0, I_3=0 and its transfer function is expressed in (8).

$$\frac{I_{out}}{I_{in}} = \frac{\frac{g_m}{C_1}s}{D(s)} \quad (8)$$

TABLE II. SIMULATION RESULTS

Parameter		Value	Condition
Supply Voltage		±0.3V	-
Process Parameters		180nm	-
Bias Currents (I_1, I_2, I_3)		5nA, 5nA, 5nA	-
Parasitic Gains (α_p, α_n)		1.051, 1.043	-
3-dB Bandwidth	I_Z / I_p	592.30 kHz	Z terminal grounded
	Iz / I_n	546.744 kHz	Z terminal grounded
	I_{x+} / I_p	567.238 kHz	Z terminal grounded
	I_{x+} / I_n	527.481 kHz	R_z = 1kΩ for 59.24 dB gain
	I_{x+} / V_z	4.489 MHz	R_z = 1kΩ for 59.30 dB gain
Transconductance Gain (g_m)		68.9 nS	X_+ terminals grounded
Input impedance at p and n (Z_p and Z_n)		39.2 Ω	Z and X_+ terminals grounded
Output Impedance at Z (Z_z)		794.383 MΩ	p, n and X_+ terminals grounded
Output Impedance at X_+ (Z_{x+})		520.328 MΩ	p, n and Z terminals grounded

4. For BR response, required input current combinations are: I_1=-I_{in}, I_2=0, I_3=I_{in} and its transfer function is expressed in (9).

$$\frac{I_{out}}{I_{in}} = \frac{s^2+\frac{g_m}{C_1C_2}^2}{D(s)} \quad (9)$$

5. For AP response, required input current combinations are: I_1=-2I_{in}, I_2=0, I_3=I_{in} and its transfer function is expressed in (10).

$$\frac{I_{out}}{I_{in}} = \frac{s^2-\frac{g_m}{C_1}s+\frac{g_m}{C_1C_2}^2}{D(s)} \quad (10)$$

In equations (6)-(10),D(s) is described in (11).

$$D(s) = s^2 + \frac{g_m}{C_1}s + \frac{g_m}{C_1C_2}^2 \quad (11)$$

The pole frequency (ω_o), bandwidth (BW) and the quality factor (Q_o) of the filter are described in (12), (13) and (14) respectively.

$$\omega_o = \frac{g_m}{\sqrt{C_1C_2}} \quad (12)$$

$$BW = \frac{g_m}{C_1} \quad (13)$$

$$Q_o = \sqrt{\frac{C_1}{C_2}} \quad (14)$$

From (12), it can be concluded that to reduce the pole frequency we have to either reduce the transconductance of the TA stage of the M-CDTA block or to employ large-valued capacitances. Increasing the capacitance is not a preferred approach, due to the increase in the chip area during the fabrication process. Hence, this paper aims to reduce the transconductance of the TA stage. This reduction in g_m is achieved by biasing the M-CDTA block to obtain subthreshold region of operation for all the transistors, which reduces g_m drastically as explained in Section 2. The electronic tunability of the pole frequencies is possible by changing g_m, which can be accomplished by varying the bias currents in the M-CDTA block.

All the simulations are performed on Cadence Virtuoso 180nm Technology Node. Table 1 indicates the aspect ratios of the transistors of the M-CDTA block. The power supply voltage and the bias currents are selected as: V_{DD}=0.3V, V_{SS}=-0.3V and I_1=I_2=I_3=5nA respectively.

The frequency domain analysis of the filter is performed using the capacitance values as C_1=1nF, C_2=2nF, to obtain the value of Q_o as 0.707. The simulationresults of LP, HP and BP response is shown in Fig. 8. The simulationresult of the BR response is depicted in Fig. 9. The simulated magnitude and phase responses of the AP filter is shown in Fig. 10. The simulated stand close to the theoretical predictions proving the effectiveness of the block with the filter.

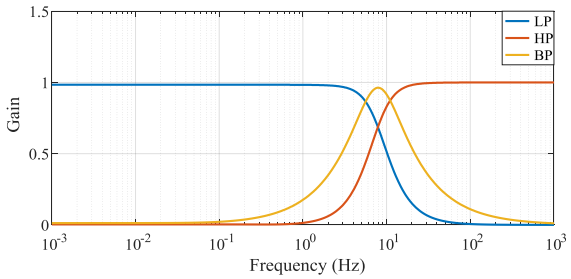


Fig. 8LP, HP and BP Response

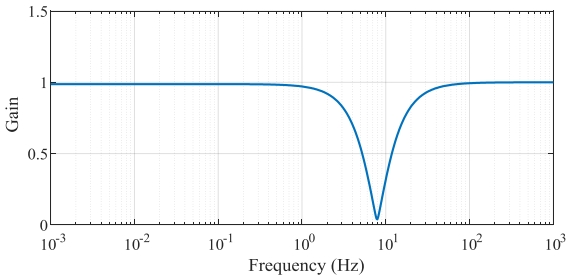


Fig. 9BR Response

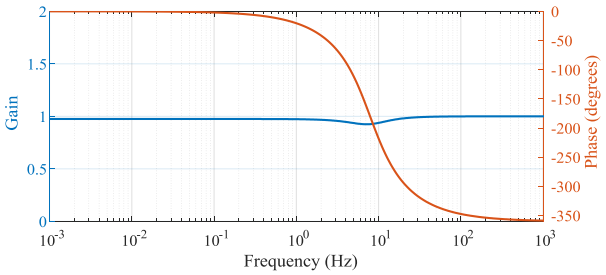


Fig. 10AP Response

To check the resilience of the filter against noise, noise analysis is performed. The input referred noise is depicted in Fig. 11. It can be seen from the simulation result, that the maximum noise is 248 nV/√Hz and thus, it can be inferred that the filter is insensitive towards noise.

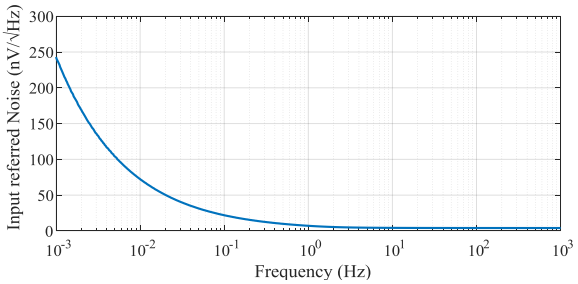


Fig. 11Noise Analysis

The electronic tunability of the filter is examined using the different values of the bias current I_3 ranging from 5nA to 60nA in steps of 5nA. BP is selected to illustrate this feature using capacitance values as C_1=1nF, C_2=2nF. The response is shown in Fig. 12. It is observed that different bias currents lead to different pole frequencies leading to electronic tunability of the pole frequencies in the circuit.

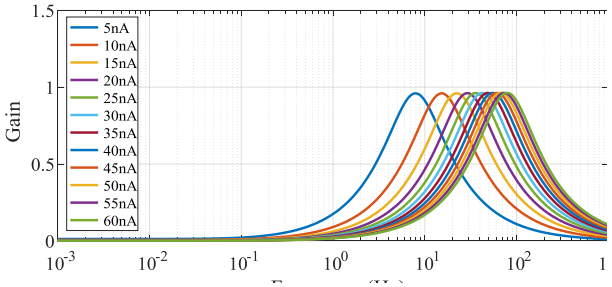


Fig. 12Electronic tunability usingbias current (I_3)

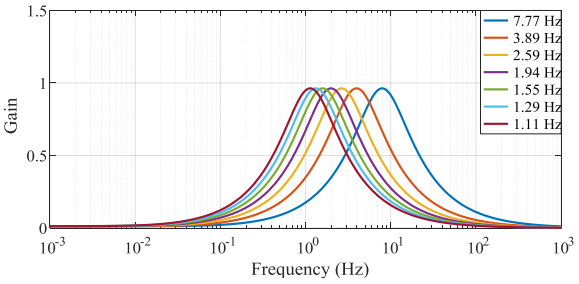
The ω_o and Q_o are capable of orthogonal tunability using the capacitances: C_1 and C_2. Variation in pole frequency with constant quality factor can be achieved by maintaining same C_1/C_2 when the product C_1C_2 changes. Whereas, variation in quality factor with constant pole frequency can be achieved by maintaining constant product C_1C_2 when the quotient C_1/C_2 changes. The simulation results for both of these cases using BP response is shown in Fig. 13 and the capacitance values required along with the obtained ω_o and Q_o of both of the cases are mentioned in Tables 3 and 4. It can be inferred from the simulation results that it is possible to orthogonally tune the pole frequency and the quality factor as per the requirement.

TABLE III. VARIABLE Q_o WITH CONSTANT ω_o: SIMULATION RESULTS

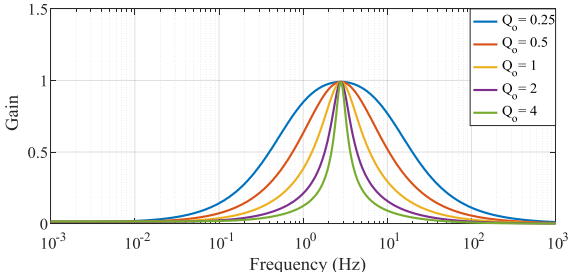
Capacitance		Quality Factor (Qo) (ω_o=7.7 Hz)
C_1	C_2	
16nF	1nF	4
8nF	2nF	2
4nF	4nF	1
8nF	2nF	0.5
16nF	1nF	0.25

TABLE IV. VARIABLE ω_o WITH CONSTANT Q_o: SIMULATION RESULTS

Capacitance		Pole Frequency (Qo=0.707)
C1	C2 (nF)	
1nF	2nF	7.7 Hz
2nF	4nF	3.89 Hz
3nF	6nF	2.59 Hz
4nF	8nF	1.94 Hz
5nF	10nF	1.55 Hz
6nF	12nF	1.29 Hz
7nF	14nF	1.11 Hz



(a)



(b)

Fig. 13Orthogonal Tunability of (a) ω_o with Q_o(b) Q_o with ω_o

The capacitors once fabricated, are susceptible to mismatches, leading to slight variations in their capacitance values from their ideal values. This mismatch is studied by Monte Carlo simulations. The histogram after 40 runs for ±5% gaussian variation in all capacitances is shown in Fig. 14. It is inferred from the histogram that the spread in the pole frequency is observed to be 9.96%.

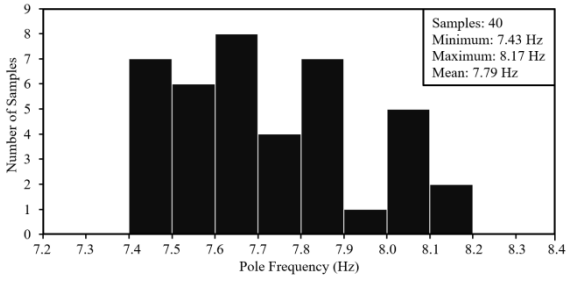


Fig. 14Monte Carlo Analysis

IV. CONCLUSION

This paper presents a low transconductance M-CDTA block customized to operate in the sub-threshold region of operation achieving a low transconductance value i.e. 68.9nA/V. It is further verified using a universal CM low frequency filter useful in many biomedical applications. The low frequency filter has a low pole frequency of 7.77Hz and also, has a number of advantages such as, all the passive components of the filter are grounded which makes it appropriate for fabrication along with proper input and output impedances. The pole frequency is electronically tunable with the bias currents. The mismatch in the passive components are verified using Monte Carlo simulations which gives a maximum 9.96% variation in the pole frequency. Also, using noise analysis, it can be inferred that the filter is insensitive towards noise. Further, it also has the feature of orthogonal tunability of ω_o and Q_o.

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