

# Electronically tunable current mode biquad filter based on single VDTA and grounded passive elements

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**Abstract**— This paper presents a new filter structure based on only single voltage differencing trans-conductance amplifier (VDTA) and three grounded passive elements and has capability to low pass (LP), band pass (BP), high pass (HP), band reject (BR) and all pass (AP) biquad filtering functions at an explicit current output by the use of appropriate selection of three current input signals. Hence, it is fully integrable, canonical in nature and universal current-mode (CM) biquad. Besides it, the proposed filter also enjoys few more desirable features such as low active and passive sensitivities, low power consumption and orthogonal tunability of pole frequency and quality factor by electronic means. The presented filter is simulated using PSPICE in 0.18 $\mu$ m CMOS process.

**Keyword**- VDTA, Biquad, Tunable filter, Current-mode

## I. INTRODUCTION

In last several decades, analogue circuit designers have shown significant research attention on study and synthesis of CM biquad filters based on various high performances CM active elements and became one of the emerging topics in current research. Thus, applications, implementation and benefits of different CM active filters based on various active elements have been discussed and studied intensively in the literature [1-25]. However, with a view to being adaptable towards low cost, low power, simplicity and area saving of the circuits, it is beneficial to realize CM biquad filter using single active element. Thus, in recent years a number of CM biquad filter using single active elements are reported in the literature [9-24] employing CCII[18,23], FDCCII [11,24], DVCC[12], CCCII [20], CFTA [9,15,21], VDTA [10,13,22], CDTA[14,17] CCTA [16], CCCCTA [19], etc., whose features are compared and summarized in Table 1. After comparative study of the circuits endorsed in Table I, it has been concluded that these reported circuits unfortunately, suffer from at least one of the following disadvantages.

- i. Does not realize all the five filtering functions [9-19].
- ii. Need of inverted current input to realize AP function, which further required additional active elements to obtain inverted current signal [20-22].
- iii. Requires one or more floating passive element to realize filtering function in current-mode [9, 14, 15, 17-18, 20-21, 23].
- iv. Lack of electronic tunability [11, 12 15, 18, 21, 23-24].
- v. Excessive number of passive elements[11-12,14,16,18,23-24]

TABLE I. COMPARISON OF DIFFERENT SINGLE ACTIVE ELEMENT BASED CM FILTERS WITH PROPOSED CM FILTER CIRCUIT

Ref.	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	Proposed
Active Element used	MOTA	VDTA	FDCCI	DVCC	VDTA	DO-CDTA	CFTA	CCTA	CDTA	CCI	CCCCA	CCCII	CFTA	VDTA	CCII	FDCCII	VDTA
No. & type of Passive Elements employed	1R+2C	2C	2R+2C	2R+2C	1R+2C	2R+2C	1R+2C	2C+2R	1R+2C	2R+2C	2C	1R+2C	1R+2C	2C	2R+2C	2R+2C	1R+2C
Filtering Functions Realized	LP, BP, HP	LP, BP, HP	LP, BP or HP, BP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP	LP, BP, HP, BR, AP	LP, BP, HP, BR, AP	LP, BP, HP, BR, AP	LP, BP, HP, BR, AP	LP, BP, HP, BR, AP	LP, BP, HP, BR, AP
Floating Passive Elements used	1R	None	None	None	None	2R	1R	None	1R	1R	None	1R	1R	None	1C	None	None
Electronic Tunability of $\omega_0$ and Q	YES	YES	NO	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	YES	NO	NO	YES
Designed Pole Frequency	1.35 MHz	3.03 MHz	10 MHz	9.7 MHz	NA	NA	159 KHz	1 MHz	10 MHz	NA	572 KHz	1 MHz	1.12 MHz	3 MHz	NA	1.59 MHz	3.93 MHz
Inverted Input required	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO

Keeping above points in the mind, this study proposes a new current-mode filter by the use of only single active element and has number of attractive features which are (i) realizes all five standard filtering functions in CM without needing inverted current input signal(s), (ii) use of only grounded passive elements which is ideally suited for IC fabrication, (iii) high output impedance for current filtering response(s), (iv) providing low active and passive sensitivities, (v) orthogonal current control of the pole frequency and quality factor.

## II. VDTA DESCRIPTION

The VDTA is relatively new element and has been popularized and frequently used in designing of analog filters [10, 13, 22, 26-29] in last few years. The symbolic diagram of VDTA is shown in Fig.1. The characteristic equation defining the relationship between various terminals voltage current of VDTA can be described as.

$$\begin{bmatrix} I_{Z+} \\ I_{Z-} \\ I_{X\pm} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ -g_{m1} & g_{m1} & 0 \\ 0 & 0 & \pm g_{m2} \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \end{bmatrix} \quad (1)$$

Here,  $g_{m1}$  and  $g_{m2}$  are trans-conductance parameters of VDTA which depending on the biasing current  $I_{B1}$  and  $I_{B2}$  of VDTA, respectively. The CMOS implemented model of VDTA as per Fig.1 is depicted in Fig.2. The expression of  $g_{m1}$  and  $g_{m2}$  in term of  $I_{B1}$  and  $I_{B2}$ , respectively, for CMOS implemented model of VDTA [27] shown in Fig.2 can be formulated as.

$$g_{m1} = \sqrt{I_{B1} \mu_n C_{ox} \left(\frac{W}{L}\right)_{M1,M2}} \quad (2)$$

$$g_{m2} = \sqrt{I_{B2} \mu_n C_{ox} \left(\frac{W}{L}\right)_{M17,M18}} \quad (3)$$

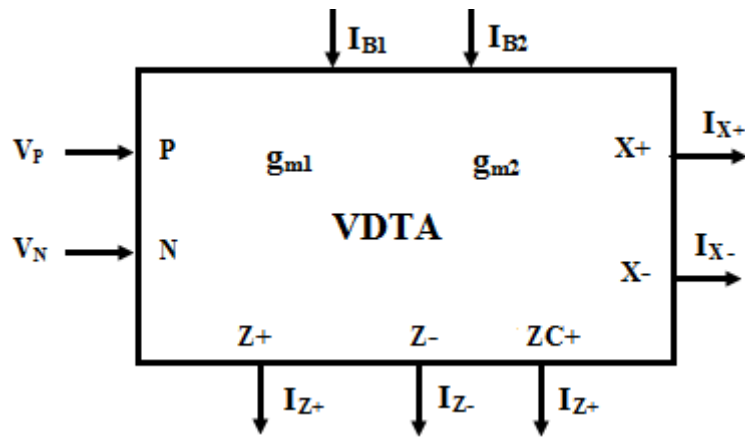


Fig.1.:Symbolic diagram of VDTA

Where  $\mu_n$  is the mobility of the electron and  $C_{ox}$  is the gate- capacitance per unit area of oxide layer used in NMOS.  $(W/L)_{M_1, M_2}$  and  $(W/L)_{M_{17}, M_{18}}$  are the aspect ratio of  $M_1, M_2$  and  $M_{17}, M_{18}$  NMOS transistor pairs, respectively.

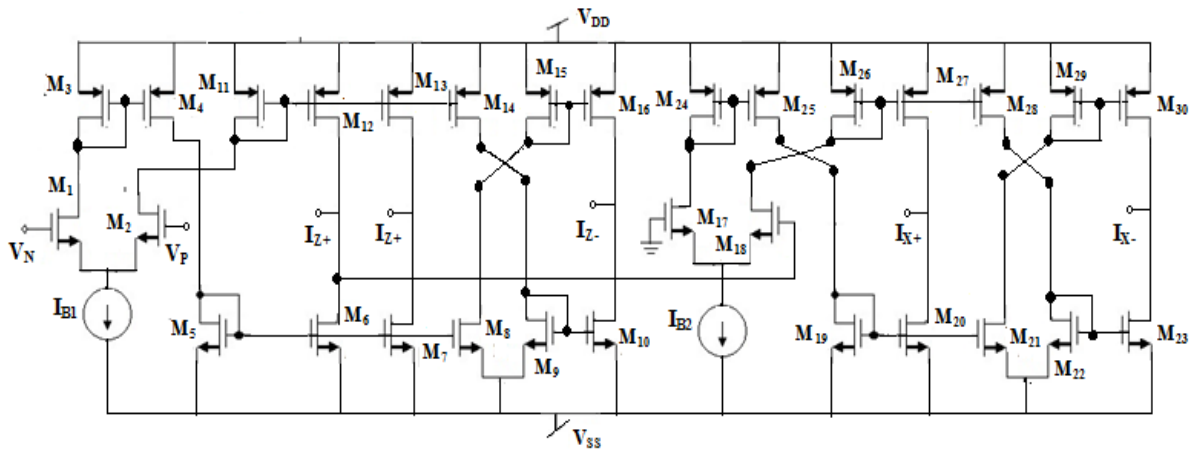


Fig.2. CMOS implemented model of VDTA

### III. PROPOSED CURRENT MODE BIQUAD FILTER

The proposed CM biquad with three current input signals ( $I_1, I_2$  and  $I_3$ ) and single current output signal ( $I_{out}$ ) is shown in Fig.3 which consists of single VDTA, one grounded resistor ( $R$ ) and two grounded capacitors ( $C_1$  and  $C_2$ ). On analysing the circuit in Fig.3, the current response at  $I_{out}$  can be derived, mathematically as given in the following equation.

$$I_{out} = \frac{s^2 g_{m1} R I_1 - \frac{s g_{m1} I_2}{C_2} + \frac{g_{m1} g_{m2} I_3}{C_1 C_2}}{s^2 + \frac{s g_{m1}}{C_2} + \frac{g_{m1} g_{m2}}{C_1 C_2}} \quad (4)$$

From the above equation, it can be found that the circuit of Fig. 3 is capable of realizing various CM filtering functions. But, each of the filtering functions can be synthesized by suitable selection of the current input signal(s) as discussed below.

- i. If  $I_1=I_2=0$  and  $I_3=I_{in}$ , a LP filter can be obtained.
- ii. If  $I_1=I_3=0$  and  $I_2=I_{in}$ , a BP filter can be obtained.
- iii. If  $I_2=I_3=0$  and  $I_1=I_{in}$ , a HP filter can be obtained.
- iv. If  $I_1=I_3= I_{in}, I_2=0, g_{m1}R= 1$ , a BR filter can be obtained.
- v. If  $I_1=I_2=I_3= I_{in}$ , and  $g_{m1}R= 1$ , an AP filter can be obtained.

Above discussion conclude that the filter structure shown in Fig.3 can realizes all five standard CM filtering functions without needing inverted/scaled- input signal(s). Moreover, the expression of filter parameters can be determined as:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad (5)$$

$$Q_0 = \sqrt{\frac{g_{m2}C_2}{g_{m1}C_1}} \quad (6)$$

Where  $\omega_0$ , and  $Q_0$  are angular pole frequency and quality factor. It is clear from Eq. (5)-(6) that  $Q_0$  can also be electronically tuned independent of  $\omega_0$  by simultaneous variation in both  $g_{m1}$  and  $g_{m2}$ . Similarly,  $\omega_0$  can also be electronically tuned independent of  $Q_0$  by varying  $g_{m1}$  or  $g_{m2}$  while keeping the product of  $g_{m1}$  and  $g_{m2}$  as constant. Thus, both filter parameters are orthogonal electronically tunable.

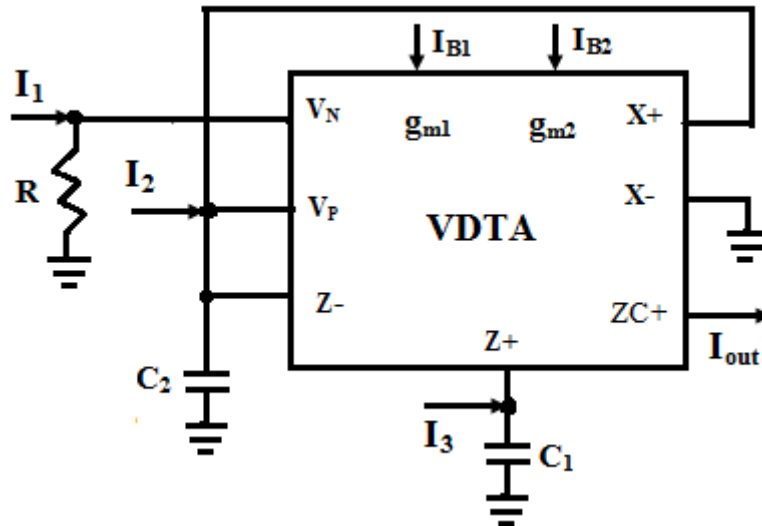


Fig.3. The proposed CM biquad filter

#### IV. NON IDEAL EFFECTS AND SENSITIVITY ANALYSIS

To see the effect of non ideal tracking errors of VDTA on the performance of the proposed CM structure, the current-voltage equations of VDTA can be rewritten as:

$$\begin{bmatrix} I_Z \\ I_{Z-} \\ I_{X\pm} \end{bmatrix} = \begin{bmatrix} \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ -\beta_1 g_{m1} & \beta_1 g_{m1} & 0 \\ 0 & 0 & \pm \beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \end{bmatrix} \quad (7)$$

Where  $\beta_1$  and  $\beta_2$  are the tracking errors of the VDTA and deviated from unit value. The proposed circuit of Fig.3 have been further reanalysed by taking the above non ideal errors into account. On re-analysing, the non-ideal filter transfer functions and its filter parameters can be derived as follow.

$$I_{out} = \frac{s^2 \beta_1 g_{m1} R_1 I_1 - \frac{s \beta_1 g_{m1} I_2}{C_2} + \frac{\beta_1 \beta_2 g_{m1} g_{m2} I_3}{C_1 C_2}}{s^2 + \frac{s \beta_1 g_{m1}}{C_2} + \frac{\beta_1 \beta_2 g_{m1} g_{m2}}{C_1 C_2}} \quad (8)$$

$$\omega_0 = \sqrt{\frac{\beta_1 \beta_2 g_{m1} g_{m2}}{C_1 C_2}} \quad (9)$$

$$Q_0 = \sqrt{\frac{\beta_2 g_{m2} C_2}{\beta_1 g_{m1} C_1}} \quad (10)$$

Above equations can conclude that the filter parameters such as pass band gain,  $\omega_0$  and  $Q_0$  may be slightly deviated from ideal ones due to effect of tracking errors of VDTA. Furthermore, the active and passive sensitivities of  $\omega_0$  and  $Q_0$  for the proposed filter in Fig.3 is determined as follow which results in low (with in unity in magnitude) active and passive sensitivities of  $\omega_0$  and  $Q_0$ .

$$S_{\beta_1, \beta_2, g_{m1}, g_{m2}}^{\omega_0} = \frac{1}{2}, S_{C_1, C_2}^{\omega_0} = -\frac{1}{2} \quad (11)$$

$$S_{\beta_2, g_{m2}, C_2}^{Q_0} = \frac{1}{2}, S_{\beta_1, g_{m1}, C_1}^{Q_0} = -\frac{1}{2} \quad (12)$$

## V. SIMULATION RESULTS

In order to check the performance, the presented filter shown in Fig. 3 was implemented using CMOS realization of VDTA (as shown in Fig. 2) with transistors W/L ratio calculated as given in Table. II and simulations were made using PSPICE along with 0.18 $\mu$ m CMOS process parameters from TSMC. To design the proposed filter of pole frequency of 3.93 MHz at  $Q_0 = 1$ , the circuit was set with biasing voltage of  $V_{DD} = -V_{SS} = 1.5V$  and the biasing currents were chosen so that  $g_{m1} = g_{m2} \approx 496.2 \mu A/V$  ( $I_{B1} = I_{B2} = 53 \mu A$ ). The passive components value were calculated as  $R = 2K\Omega$ ,  $C_1 = C_2 = 20pF$ . Fig.4 shows the simulated versus ideal current gain responses of LP, HP, BP, and BR for the proposed biquad filter of Fig. 3. The simulated gain responses given in Fig. 4 show good agreement with ideal responses. The total power consumption of the filter was obtained as 1.41mW. With the same component value setting, the simulated gain and phase response of AP filters are also depicted in Fig.5.

Further simulations to prove the electronic tuning capability of  $\omega_0$  independent of  $Q_0$  for the proposed circuit were also done. For this purpose, various BP responses at different set of  $g_{m1} = g_{m2} = 304.82 \mu A/V$ ,  $496.2 \mu A/V$ ,  $681.6 \mu A/V$ ,  $963.9 \mu A/V$  (by simultaneously variations in  $g_{m1}$  and  $g_{m2}$ ) are plotted in Fig. 6 which result in pole frequency ( $f_0$ ) variations of the circuit as 2.30 MHz, 3.93MHz, 5.6MHz, and 8.10MHz without changing  $Q_0 (=1)$ . Similarly, the simulation results showing the tuning feature of  $Q_0$  independent of  $\omega_0$  for the circuit is also shown in Fig. 7 which were obtained by maintaining the product of  $g_{m1}$  and  $g_{m2}$  to be a constant as ( $I_{B1} = 93.3 \mu A$ ,  $I_{B2} = 30 \mu A$ ), ( $I_{B1} = 70 \mu A$ ,  $I_{B2} = 40 \mu A$ ), ( $I_{B1} = 53 \mu A$ ,  $I_{B2} = 53 \mu A$ ), and ( $I_{B1} = 40 \mu A$ ,  $I_{B2} = 70 \mu A$ ) resulting  $Q_0 = 0.72, 0.83, 1, \text{ and } 1.16$  respectively, at constant pole frequency of 3.93MHz.

The transient behavior of the proposed CM circuit is also investigated by applying an input sinusoidal current signal at  $f_0 = 500$  KHz with peak to peak amplitude of  $80 \mu A$  and measuring the output at LP filtering response (when  $I_1 = I_2 = 0$  and  $I_3 = I_{in}$ ). Fig.8 shows the corresponding transient behavior of the LP output signal. The percentage of total harmonic distortion of Fig. 8 is 1.67. The dependence of the output harmonic distortion of LP current output on varying frequency in the range of 500 KHz to 4500 KHz of sinusoidal current input signal at constant peak to peak amplitude of  $40 \mu A$  is illustrated in Figure 9 which results the THDs within 3% acceptable limits.

Further to observe the effect of passive component mismatching on the filter's performance, Monte-Carlo analysis has been performed. To measure the impact, the CM BP output was simulated with 10% Gaussian deviation in  $C_1 = C_2 = 20$  pF for 500 concurrently runs. Corresponding simulated results of BP response are shown in Fig.10. Fig. 10a, shows the magnitude response whereas Fig.10b shows the statistical results in the form of histogram where the simulated mean, median and standard deviation were obtained as 4.17MHz, 4.17MHz and 160.009KHz, respectively which conclude that with respect to the simulated pole frequency of 3.93 MHz, the proposed filter is less sensitive to the change in capacitive value and thus offers good passive sensitivity of the circuit.

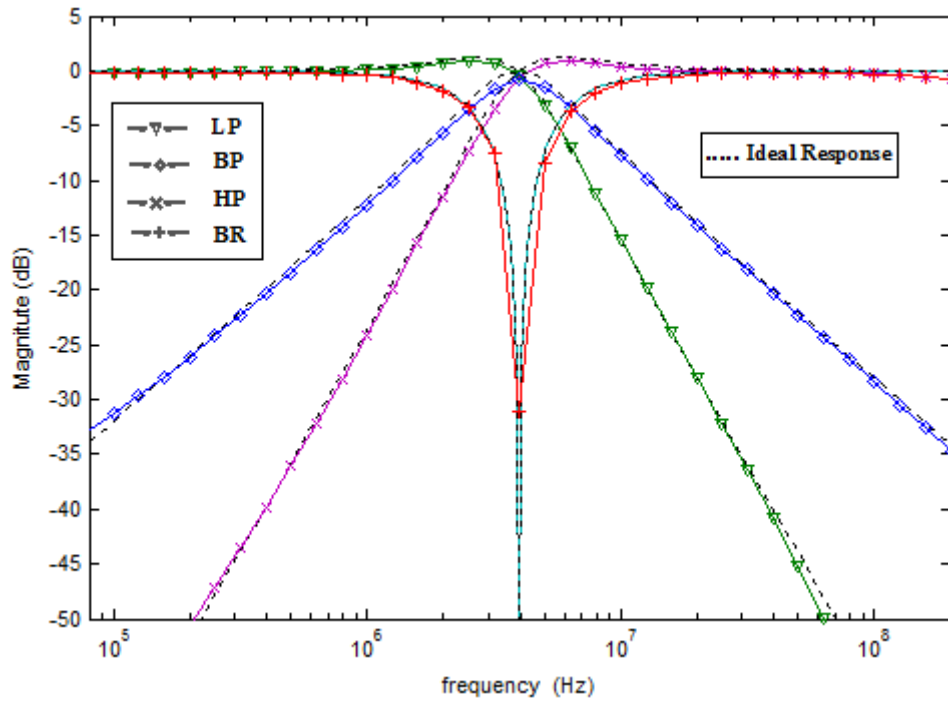


Fig.4. Ideal and PSPICE simulated response of LP, HP, BP, and BR CM Filter

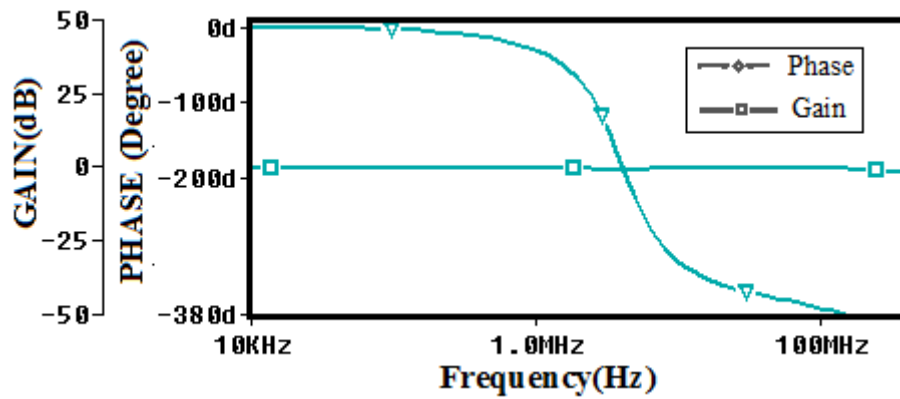


Fig.5. Gain and phase response of AP filter

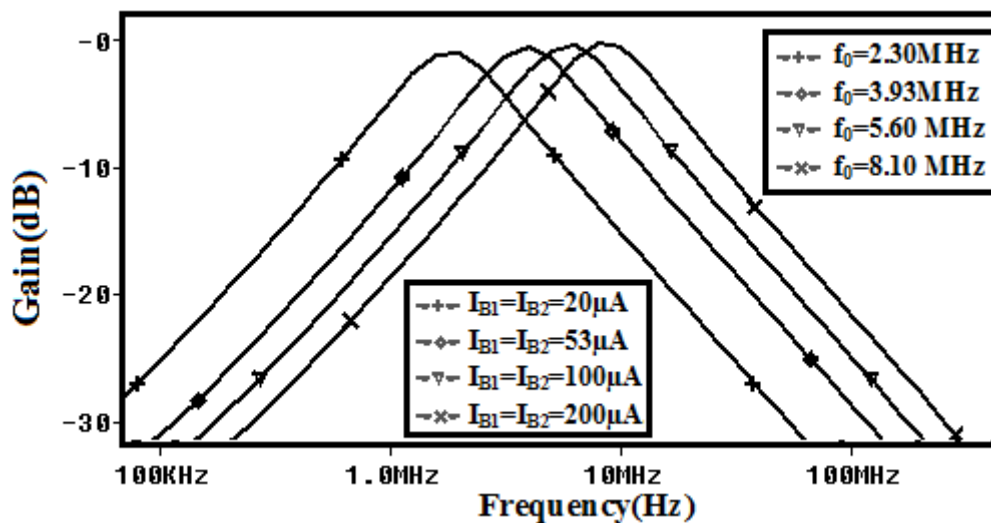


Fig. 6. Simulation results showing electronic tunability of  $f_0$  independent of  $Q_0$ .

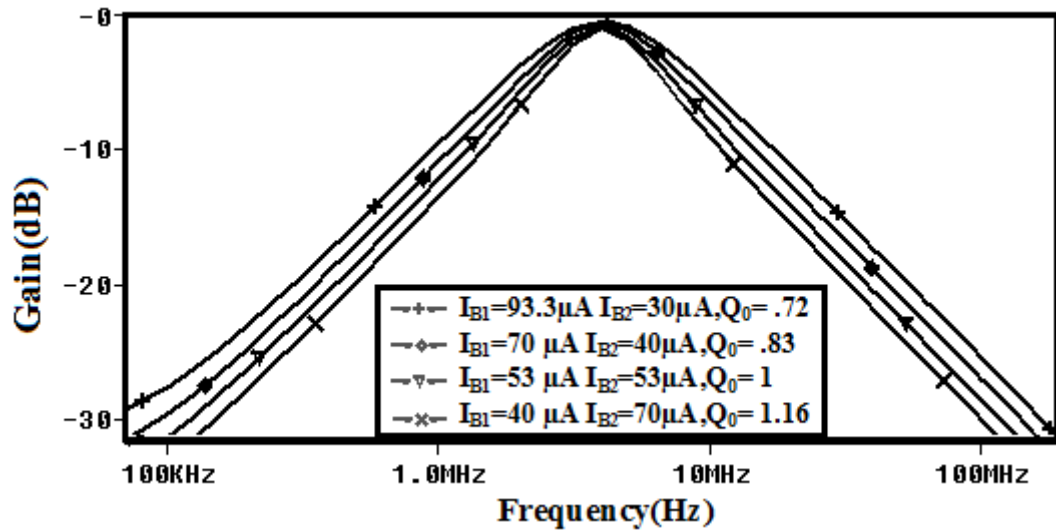


Fig. 7. Simulation results showing electronic tunability of  $Q_0$  independent of  $f_0$ .

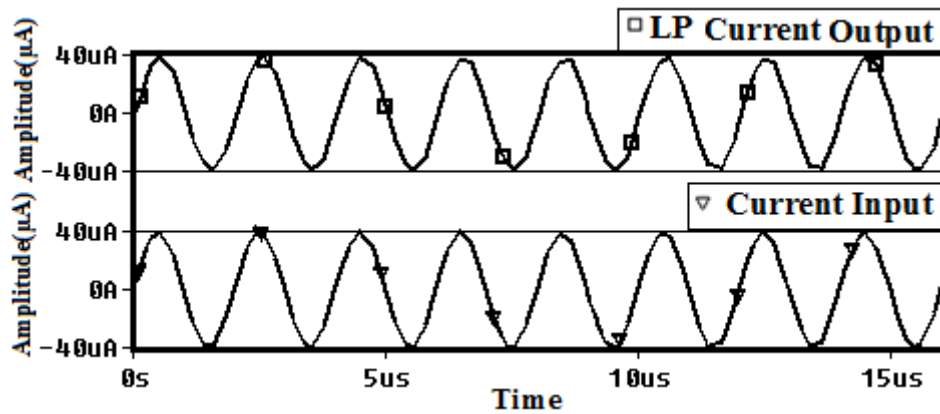


Fig. 8. Transient response of LP filter

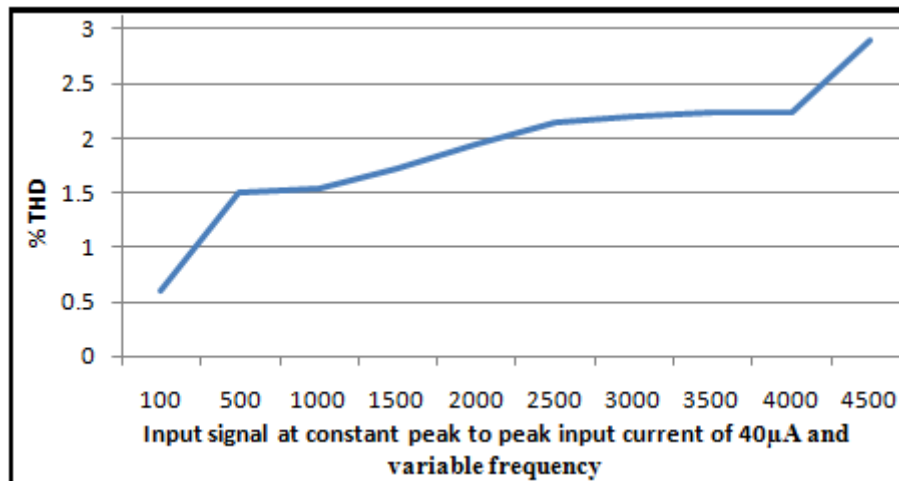


Fig. 9. % THDs of LP filter at constant peak to peak input current of  $40\mu\text{A}$  and variable frequency

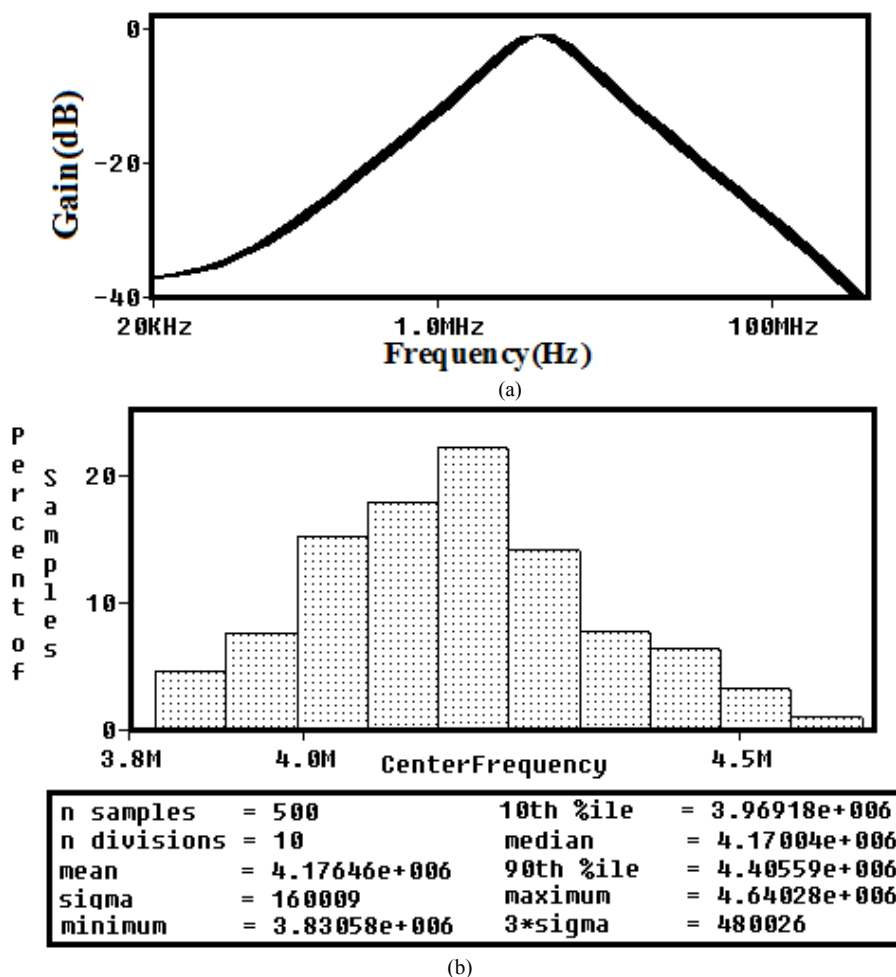


Fig.10.(a,b) Monte Carlo analysis of CM biquad filter

TABLE II. : TRANSISTORS ASPECT RATIOS OF CMOS IMPLEMENTATION OF VDTA OF FIG.3

Transistors	W(μm)/L(μm)
M1-M2,M17-M18	8.28/0.36
M3-M4, M11-M16, M24-M30	4.32/0.36
M5-M10,M19-23	3.6/0.36

## VI. CONCLUSION

A new three input single output CM biquad universal filter based on single active element has been proposed in this paper which also consists of only three grounded passive elements and can realizes all five filtering functions such as LP, BP, HP, BR and AP. To prove the workability of the proposed biquad filter in all aspect, extensive PSPICE simulation results are also made. In addition, the proposed circuit has also number of the benefits as discussed below.

- i. Requiring no inverted type and/or scaled type current input signal(s) to realize any filtering functions.
- ii. Using only grounded passive elements which make the circuit suitable for IC fabrication point of view.
- iii. Using only minimum number of active element.
- iv. Exhibiting low active and passive sensitivities.
- v. Consuming low power of 1.41mW.
- vi. Providing orthogonal current tuning capability tunability of filter parameters.
- vii. Providing the canonical structure as it requires only two grounded capacitors.

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