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FULLY INTEGRATED MULTIFUNCTION TRANS-IMPEDANCE MODE BIQUAD FILTER

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Abstract

This paper presents a new trans-impedance-mode biquad filter which simultaneously, realizes the multifunction filtering outputs such as low pass (LP), band pass (BP), high pass (HP) and band reject (BR). The presented filter topology consists of only single active element as voltage differencing trans-conductance amplifier (VDTA) along with two grounded capacitors and two MOS implemented grounded resistors. So, the proposed TIM filter structure is fully integrable and canonical in nature. Apart from these, the proposed filter also enjoys the 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 μm CMOS process.

Keywords: VDTA, Trans-impedance, Biquad, Filter, Tunable.

1. Introduction

In last several decades, active elements based on current-mode (CM) approach to study and synthesis of high performance continuous-time (CT) filters which form an important part of analogue signal processing systems such as radios, televisions, stereo systems, graphic equalizers and phase locked loop etc., have attracted significant research attention due to having its inherent advantages such as wider signal bandwidth, low power consumption, larger dynamic range, better linearity, simple circuitry and requirement of lesser on chip area with respect to voltage-mode counterpart [1].

Nomenclatures

C_{ox}	gate oxide capacitance per unit area
G_i	Admittance
g_i	Trans-conductance
I_{Bi}	Bias current
Q_0	Quality Factor
V_{ci}	biased voltage
V_T	Threshold voltage

Greek Symbols

β	Tracking error
ω_0	Angular Pole Frequency, rad.
μ_n	Mobility of electron

Abbreviations

BP	Band Pass
BR	Band Reject
BW	Band Width
CM	Current-Mode
HP	High Pass
LP	Low Pass
TIM	Trans-impedance mode
VDTA	Voltage Differencing Trans-Conductance Amplifier
VM	Voltage-Mode

Therefore, numbers of such type of CM active elements in which information is processed in term of currents are proposed in the literature. Current conveyors (CCII, CCI, and CCIII) and their variants such as DDCCII, DVCCII, FDCCII and DXCCII etc., are firstly proposed [2-8]. Later on other active elements having the property of inbuilt electronic tuning which may require in the adjustable applications such as music and speech synthesis are also proposed. Few names of them are OTA, CCCII, CCTA, CCCCTA, DDCCTA, CDTA, CCCDTA, CFTA, DVCCTA and VDTA, etc. [9-18]. The detailed properties and reviews of these CM active elements are well described in review published paper [19].

VDTA, a relatively new CM active element, was first introduced in 2011 by Yesil et al. [17]. After its inception, various applications of VDTA in analog filters design have also been reported in literature [20-26]. However, the VDTA based filter circuits proposed in the literature are either voltage-mode (VM) type [20, 21, 23, 27] or CM type [24, 25, 28] or trans-admittance (TAM) type [21, 22, 26, 27]. Unfortunately, the trans-impedance (TIM) type filter(s) using VDTA, which is the current input voltage output circuit and can be used as interface circuit connecting CM to VM in number of applications such as receiver block, TIM amplifier, analog-to-digital converter (ADC) [16], are being missed in the available literature.

Although, quite a few number of TIM biquad filters based on the active elements other than VDTA are found in the literature [16, 29-37]. Out of these, TIM biquads presented in [29, 30, 32-36] use only a single current input and provide the simultaneous realization of filtering functions in contrast to those presented in [16, 31, 37] which requires multiple current inputs and realize one output at a time but realization of multiple current inputs which may further require additional hardware. Furthermore, the paper presented in [29, 30] proposed TIM circuits each having three active elements (CDBA or DVCFAs), two capacitors with both being grounded, three resistors and also realize three filtering responses. Another paper presented in [32] proposed two different topologies each having four CCIIs, four resistors, two capacitors and realizing same number of filtering functions. Two more TIM filter circuits presented in [33, 34] still realizes three filtering functions. In one case [34], the circuit requires only three OTAs in contrast to other case which require 4 OTAs. In addition, each of these circuits uses two op-amps too. Detail comparative study of all these TIM filters requiring only single current input are also discussed in Table 1 which reveals the following points.

(i) None of the above proposed TIM filters can be implemented using only single active element. Use of single element is beneficial for cost reduction, low power consumption, space saving, simplicity of the circuit point of view [38].

(ii) All the circuits realize at most three filtering functions [29, 30, 32-34].

(iii) Few of the circuits use floating passive components too which are not favourable for IC integration point of view [29, 30, 32].

(iv) Few of the circuits is lacking electronic tunability feature of filter parameters [29, 30, 32-34] too.

(v) Few of the circuits use more number of passive elements [29, 30, 32] too.

Table. 1. A comparative study of various reported single input multiple output TIM biquad filters.

S. No.	**References**	**[29]**	**[30]**	**[32]**	**[33]**	**[34]**	**Proposed**
	Features						
1	**No. & types of active elements**	3 CDBA	3 DVCFA	4 CCII	6 (OP-Amp, OTA)	5 (OP-Amp, OTA)	1 VDTA
2	**No. & types of passive elements**	*3R+2C*	*3R+2C*	*4R+ 2C*	NO	NO	*2R+ 2C*
3	**Floating passive elements**	*2-R, 2-C*	*2-R*	*1-R*	NO	NO	NO
4	**Electronic control of filter parameter (ω_0 and Q_0)**	NO	NO	NO	NO	NO	YES
5	**Realization type**	LP,BP,HP	LP,BP,HP	LP,BP,HP	LP,BP,HP	LP,BP,HP	LP,BP, HP,BR
6	**Power supply**	±5V	±2.5V	-	±2.5V	±2.5V	±1.5V
7	**No. of transistors**	-	64	-	52	43	22
8	**Operating pole frequency**	912.01 KHz	1.25 MHz	-	435KHz-870KHz	435KHz-870KHz	5.02 MHz
9	**Technology used (Feature Sized)**	-	0.5μm	-	0.5μm	0.5μm	0.36 μm
10	**Sensitivity**	0.5	0.5	0.5	Less than 1	Less than 1	Less than 1

Keeping above points in the mind, a new circuit is proposed in this paper which simultaneously realizes four trans-impedance-mode filtering functions by the use of only single active element, namely, VDTA. Besides, it also employs two grounded capacitors and two grounded MOS resistors. Moreover, the proposed circuit offers low active and passive sensitivities, low power consumption and orthogonal electronic tunability of pole frequency and quality factor. The validity of proposed filter is also verified by simulating the circuit in PSPICE.

2. VDTA Description

The symbolic diagram of VDTA is shown in Fig. 1. Here (Fig. 1), *P* and *N* are the input ports and *Z*, Z_C, *X+* and *X-* are the output ports. The voltage and current relationship between various input and output ports of VDTA can be characterized by the following matrix equation [20].

$$\begin{bmatrix} I_Z \\ I_{Z_C} \\ I_{X\pm} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ g_{m1} & -g_{m1} & 0 \\ 0 & 0 & \pm g_{m2} \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \end{bmatrix} \tag{1}$$

where g_{m1} and g_{m2} are the trans-conductance parameters of first stage and second stage, respectively.

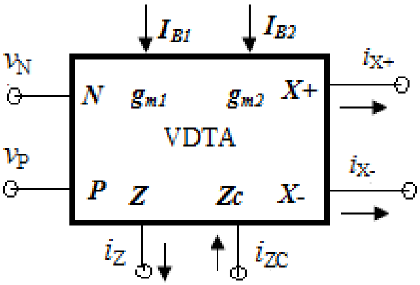


Fig. 1. Symbolic diagram of VDTA.

A CMOS model of above VDTA consisting of only eighteen transistors is also shown in Fig. 2. For the CMOS circuit of VDTA of Fig. 2, the expression of g_{m1}, g_{m2} can be derived as [20].

$$g_{m1} \cong \left(\frac{g_1 g_2}{g_1 + g_2}\right) + \left(\frac{g_3 g_4}{g_3 + g_4}\right), \quad g_{m2} \cong \left(\frac{g_5 g_6}{g_5 + g_6}\right) + \left(\frac{g_7 g_8}{g_7 + g_8}\right) \tag{2}$$

where $g_i = \sqrt{I_{Bi} \mu C_{ox} \left(\frac{W_i}{L_i}\right)}$ is the trans-conductance value of the i^{th} transistor (i=1, 2...8). Here I_{Bi} is the bias current of the i^{th} transistor, μ is the effective carrier mobility, C_{ox} is the gate oxide capacitance per unit area, and W_i & L_i are the effective channel width and length of the i^{th} MOS transistor, respectively.

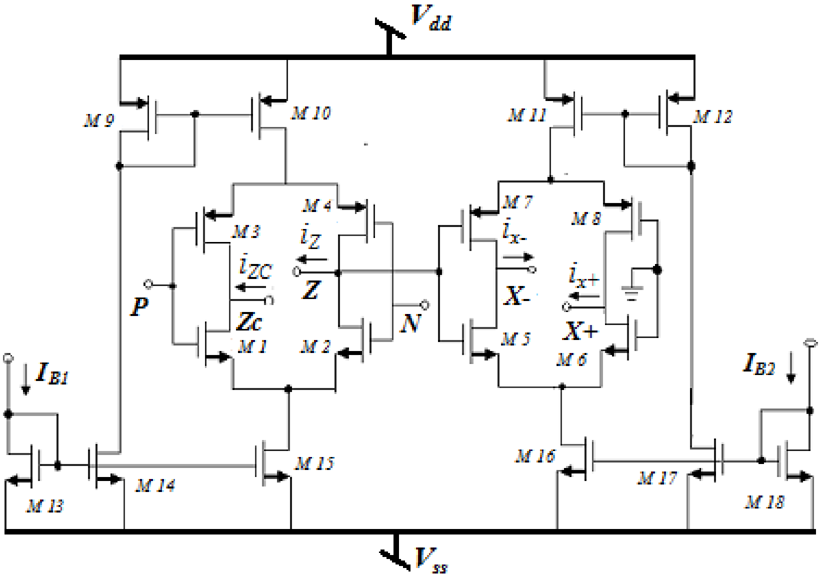


Fig. 2. Implementation of VDTA using CMOS transistors.

3. Proposed TIM Filter And Its Analysis

The proposed TIM filter topology is shown in Fig. 3 which employs single VDTA, two grounded resistors (R_1 and R_2) and two grounded capacitors (C_1 and C_2). In the proposed topology, each grounded resistor (R_i, where i= 1, 2) has been realized by using parallel connection of two NMOS transistors (M_{Ri} and M_{Ri}) [20]. Thus, the equivalent resistance can be calculated by

$$R_i = \frac{1}{2\mu_n C_{ox}\frac{W_{MRi}}{L_{MRi}}(V_{ci}-V_T)} \tag{3}$$

where V_T is the threshold voltage of the NMOS transistor. V_{ci} is the biased voltage and W_{MRi}/L_{MRi} stands for aspect ratio of NMOS transistor used in the resistance realization.

$$TIM_{BR}(s)=\frac{V_1}{I_{in}}=\frac{\left(s^2+{g_{m1}g_{m2}}/{C_1C_2}\right)R_1}{D(s)} \tag{4}$$

$$TIM_{LP}(s)=\frac{V_2}{I_{in}}=\frac{{g_{m1}g_{m2}R_1}/{C_1C_2}}{D(s)} \tag{5}$$

$$TIM_{BP}(s)=\frac{V_3}{I_{in}}=\frac{{sg_{m1}R_1}/{C_2}}{D(s)} \tag{6}$$

$$TIM_{HP}(s)=\frac{V_4}{I_{in}}=-\frac{s^2 g_{m1}R_1R_2}{D(s)} \tag{7}$$

On routine analysis of the circuit in Fig. 3, the transfer functions given in following equations can be derived.

where, $$D(s)=\left[s^2+\frac{sg_{m1}g_{m2}R_1}{C_2}+\frac{g_{m1}g_{m2}}{C_1C_2}\right] \tag{8}$$

It can be noted that from Eqs. (4)-(7) that the proposed topology is capable of realizing TIM LP, BP, HP and BR filtering responses and hence, the characterized parameters like pole frequency (ω_0) ,quality factor (Q_0) and bandwidth (BW) can be derived as

$$\omega_0=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \qquad Q_0=\frac{1}{R_1}\sqrt{\frac{C_2}{C_1g_{m1}g_{m2}}}, \quad BW=\frac{g_{m1}g_{m2}R_1}{C_2} \tag{9}$$

It can be concluded from Eq. (9) that by maintaining the condition of $g_{m1}=g_{m2}=1/R_1=g_m$, ω_0 can be varied electronically and without affecting the Q_0 by varying g_m. Similarly, Q_0 can also be varied independent of ω_0 by varying R_1 which can be further tuned electronically.

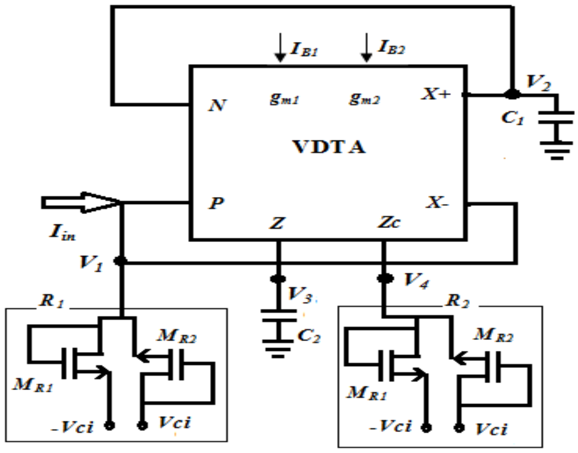


Fig. 3. Block diagram of proposed multifunction TIM biquad filter.

4. Non-Ideal Effects and Sensitivities Analysis

In the previous section, ideal VDTA is considered to derive the various transfer functions and filter parameters. However, the VDTA implemented using MOS transistors as shown in Fig. 2, will be chacterized by finite non ideal transconductance tracking errors occured due to the mismatching in the transistors. If we also consider these tracking errors, the current and voltage relationship between various ports of VDTA will be modified and can be rewritten as:

$$\begin{bmatrix} I_Z \\ I_{Z_C} \\ I_{X\pm} \end{bmatrix} = \begin{bmatrix} \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ 0 & 0 & \pm\beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \end{bmatrix} \tag{10}$$

where β_1 and β_2 are the transconductance tracking error for the first and second stages of the VDTA. Considering the effect of above non-ideal errors, we have further reanalyzed the proposed circuit of Fig. 3. On analyzing, the non-ideal filter transfer functions and its filter parameters can be further derived as follow.

$$TIM_{BR}(s)=\frac{V_1}{I_{in}}=\frac{\left(s^2+\beta_1\beta_2 g_{m1}g_{m2}\big/C_1C_2\right)R_1}{D(s)} \tag{11}$$

$$TIM_{LP}(s)=\frac{V_2}{I_{in}}=\frac{\beta_1\beta_2 g_{m1}g_{m2}R_1\big/C_1C_2}{D(s)} \tag{12}$$

$$TIM_{BP}(s)=\frac{V_3}{I_{in}}=\frac{s\beta_1 g_{m1}R_1\big/C_2}{D(s)} \tag{13}$$

$$TIM_{HP}(s)=\frac{V_4}{I_{in}}=\frac{s^2\beta_1 g_{m1}R_1R_2}{D(s)} \tag{14}$$

Where, $D(s)=\left[s^2+\frac{s\beta_1\beta_2 g_{m1}g_{m2}R_1}{C_2}+\frac{\beta_1\beta_2 g_{m1}g_{m2}}{C_1C_2}\right]$ (15)

$$\omega_0=\sqrt{\frac{\beta_1\beta_2 g_{m1}g_{m2}}{C_1C_2}},\ Q_0=\frac{1}{R_1}\sqrt{\frac{C_2}{C_1\beta_1\beta_2 g_{m1}g_{m2}}},\ BW=\frac{\beta_1\beta_2 g_{m1}g_{m2}R_1}{C_2} \tag{16}$$

It is evident from Eqs. (11) - (16) that the filter parameters such as pass band gain, ω_0, Q_0, and BW of various TIM filtering responses of the proposed circuit may be slightly changed due to effect of tracking errors of VDTA but these deviations can be minimized by adjusting the electronic controllable trans-conductance parameters.

The active and passive sensitivities of ω_0 and Q_0 for the proposed filter in Fig. 3 are also derived as follow.

$$S^{\omega_0}_{\beta 1}=S^{\omega_0}_{\beta 2}=S^{\omega_0}_{gm1}=S^{\omega_0}_{gm2}=\frac{1}{2},\ S^{\omega_0}_{C1}=S^{\omega_0}_{C2}=-\frac{1}{2} \tag{17}$$

$$S^{Q_0}_{\beta 1}=S^{Q_0}_{\beta 2}=S^{Q_0}_{gm1}=S^{Q_0}_{gm2}=S^{Q_0}_{C_1}=-\frac{1}{2},\quad S^{Q_0}_{C2}=\frac{1}{2},\ S^{Q_0}_{R_1}=-1 \tag{18}$$

From above equations, it can be observed that all the active and passive sensitivities of ω_0 and Q_0 are low and less than 1 in magnitude.

5. Non-Ideal Parasitics Analysis

In this section, the effect of VDTA parasitic on the performance of presented TIM filter is considered. In the presence of various ports parasitic in the form of parasitic capacitors and resistors, the circuit of Fig. 3 has been changed to Fig. 4. Here, $C_{P1}||R_{P1}$ at ports ($X+$, V_N) , $C_{P2}||R_{P2}$ at port Z , $C_{P3}||R_{P3}$ at ports ($X-$, V_P) and $C_{P4}||R_{P4}$ at port Z_C are combined parasitic impedance in the form of parallel combination of parasitic capacitances and resistances. The external resistance R_1, R_2 and parasitic resistances R_{Pi} (i=1, 2, 3, 4) can be represented in terms of admittances as G_1, G_2 and G_{Pi} (i=1, 2, 3, 4), respectively (where G_i=1/R_i, G_{Pi}=1/R_{Pi}). Practical value of parasitic capacitances C_{Pi} are in the range of fraction of picofarads and that of G_{pi} (i=1, 2) are less than 10 of micro mho. So, the external capacitances C_1 and C_2 can be chosen as much greater than the parasitic capacitances. Therefore, min (C_1, C_2)>> (C_{P1}, C_{P2}, C_{P3}, C_{P4}). Similarly, the external admittances can also be chosen much greater than the parasitic admittances. Therefore, min (G_1, G_2)>> (G_{P1}, G_{P2}, G_{P3}, G_{P4}). To see the effects of various parasitic impedances on the performance of the proposed TIM filter circuit, the circuit of Fig. 4 is again reanalyzed. On reanalyzing the circuit of Fig. 4, we get the following transfer functions for the TIM filtering functions.

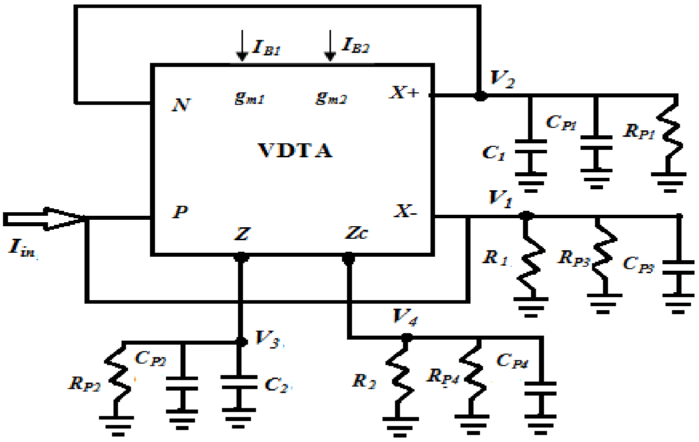


Fig. 4. Proposed TIM biquad filter in the presence of various ports parasitic.

$$TIM_{BR}(s)=\frac{V_1}{I_{in}}=\frac{\left[s^2\left(1+\frac{sC_{P3}}{G_1}\right)+\frac{g_{m1}g_{m2}}{C_1C_2}\right]}{G_1\left(1+\frac{sC_{P3}}{G_1}\right)^2 D''(s)} \tag{19}$$

$$TIM_{LP}(s)=\frac{V_2}{I_{in}}=\frac{\frac{g_{m1}g_{m2}}{C_1C_2G_1}}{\left(1+\frac{sC_{P3}}{G_1}\right)D''(s)} \tag{20}$$

$$TIM_{BP}(s)=\frac{V_3}{I_{in}}=\frac{\frac{g_{m1}}{C_2G_1}\left(s+\frac{G_{P1}}{C_1}\right)}{\left(1+\frac{sC_{P3}}{G_1}\right)D''(s)} \tag{21}$$

$$TIM_{HP}(s)=\frac{V_4}{I_{in}}=-\frac{s^2 g_{m1}/G_1G_2}{\left(1+\frac{sC_{P3}}{G_1}\right)\left(1+\frac{sC_{P4}}{G_2}\right)D''(s)} \tag{22}$$

where $$D''(s)=s^2+s\frac{g_{m1}g_{m2}}{C_1G_1\left(1+\frac{sC_{P3}}{G_1}\right)}+\frac{g_{m1}g_{m2}}{C_1C_2\left(1+\frac{sC_{P3}}{G_1}\right)} \tag{23}$$

As a result, the expressions of pole frequency and quality factor have been changed to

$$\omega_0' = \omega_0 \sqrt{\frac{1}{1+s\left(\frac{C_{P3}}{G_1}\right)}} \quad , \qquad Q_0' = Q_0\sqrt{1+s\left(\frac{C_{P3}}{G_1}\right)} \tag{24}$$

where, ω_0 and Q_0 are the pole frequency and quality factor of the TIM filter in ideal case. It can be clearly seen from Eqs. (19) - (24) that additional first order pole or zero are yielded in the expression of transfer functions and filter parameters due to various port parasitic of VDTA which may deviate undesirably the pass band gain, pole frequency and quality factor of the proposed filter. However, these undesirable factors can be eliminated or minimized and hence, the proposed filter may approach towards ideal response, if we choose the operating frequency (ω_0) in the design criterion as follows:

$$\frac{G_{P1}}{C_1} << \omega_0 << min\left(\frac{G_1}{C_{P3}}, \frac{G_2}{C_{P4}}\right) \tag{25}$$

6. Simulation Results

In order to check the performance, the presented filter circuit was designed using CMOS implementation of VDTA with aspect ratio of transistor as described in Table 2 and simulations were carried out using PSPICE in ORCAD 16.5 with model of 0.18μm CMOS process parameter from TSMC [21]. The circuit was biased with V_{DD}=-V_{SS}=1.5V DC power supply. To design the proposed filter of pole frequency 5.02 MHz and Q_0=1, the passive components value was set to R_1=R_2=2KΩ, C_1=C_2=15pF and biasing current were chosen so that g_{m1}=g_{m2}≈473.5μA/V (I_{B1}=I_{B2}=53μA). Figure 5 shows the simulated versus ideal (theoretical or analytical) gain responses of TIM LP, HP, BP, and BR for the proposed biquad filter. It is clear from Fig. 5 that simulated results are in good agreements with the ideal or theoretical results. Moreover, the simulated pole frequency was obtained 5.01 MHz which is closed to the theoretical value of 5.02 MHz. The total power consumption of the filter was obtained as 1.22 mW.

Table 2.Transistors aspect ratios of CMOS implementation of VDTA of Fig. 3.

Transistor	W(μm)/L(μm)
M1-M2,M5-M6	8.28/0.36
M3-M4,M7-M8	14.4/0.36
M9-M12	10.8/0.36
M13,M18	3.6/0.36
M14-M17	4.37/0.36

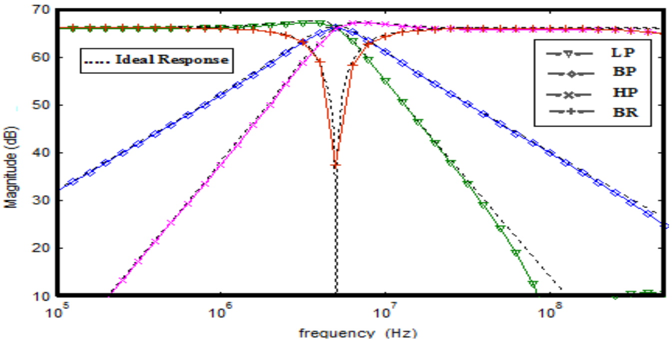
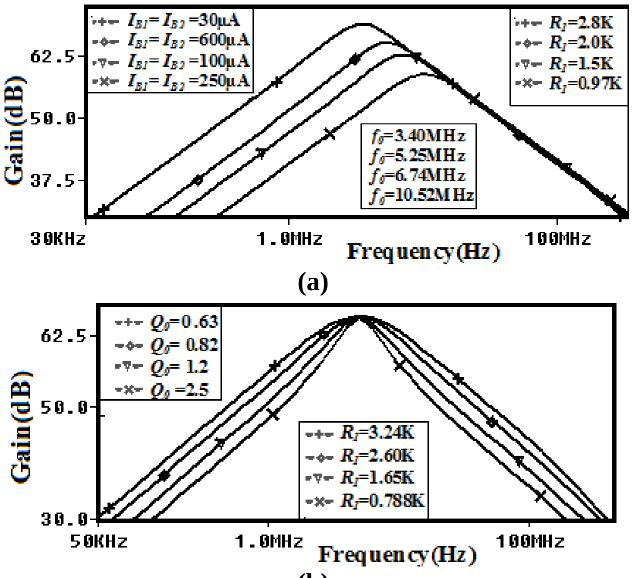


Fig. 5. Ideal and PSPICE simulated response of LP, HP, BP, and BR TIM Filter.

Further simulations of the proposed circuit were also done to show the electronic tuning capability of the circuit by plotting various BP filtering responses. Figure 6(a) shows the electronic tunability feature of ω_0 independent of Q_0 by getting the simulation results at different value of ω_0 as 3.40 MHz, 5.25 MHz, 6.74 MHz, and 10.52 MHz at constant Q_0=1, which were further obtained by varying g_{m1} and g_{m2} in such a way so that g_{m1}=g_{m2}=1/R_1 (for example, g_{m1} = g_{m2} = 356.3 µA/V, 503.9 µA/V, 650.3 µA/V, 1028.5 µA/V and R_1=2.80 KΩ (V_{ci}=.694), 1.98 KΩ (V_{ci}=.828), 1.53 KΩ (V_{ci}=.961) and 972 Ω (V_{ci}=1.303)). On the hand, Figure 6(b) shows the electronic tunability of Q_0 independent of ω_0 by changing R_1 which can be further varied by V_{ci} as mentioned in Fig. 6(b). The corresponding Q_0 value was obtained as 0.63, 0.82, 1.2 and 2.5 at various R_1 = 3.24 KΩ (V_{ci}=0.65), 2.6 KΩ (V_{ci}=0.72), 1.65 KΩ (V_{ci}=0.92) and 788 Ω (V_{ci}=1.52). The large signal behavior of the proposed TIM circuit is also investigated by applying an input sinusoidal current signal and measuring LP and HP voltage output.



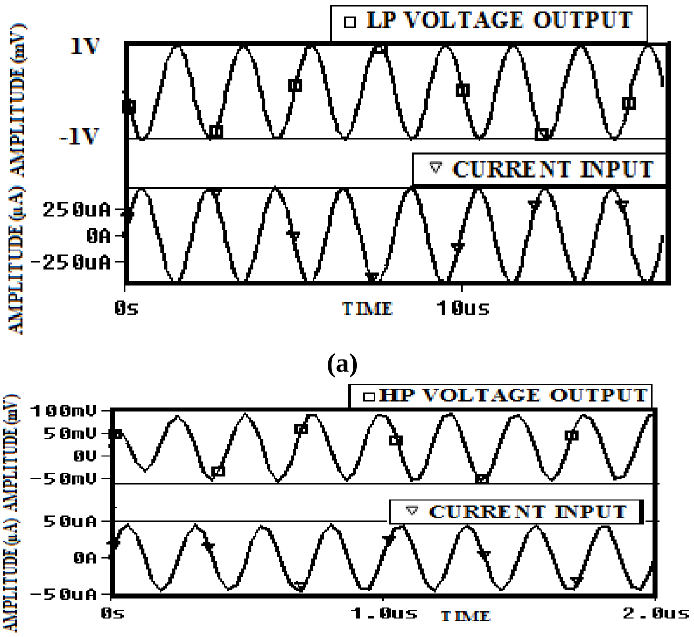
(a)

(b)

Fig. 6. Electronic tuning feature of (a) ω_0 independent of Q_0 (Q_0=1) (b) Q_0 independent of ω_0 (at ω_0=5.02MHz) for BP filter.

Figure 7(a) shows the time domain sinusoidal input current signal of frequency of 500 KHz having peak to peak amplitude of 900 μA and corresponding LP voltage output while Figure 7(b) shows the time domain sinusoidal input current signal of frequency of 4000 kHz having peak to peak amplitude of 90 μA and corresponding HP voltage output. Furthermore, the total harmonic distortions (THDs) results for LP voltage responses with respect to sinusoidal input current signal of constant peak to peak amplitude of 100 μA and having variable frequency in the range of 600 kHz to 2600 kHz are also shown in Fig. 8. The THDs results shown in Fig. 8 indicate that THDs value of the circuit are within acceptable limits of 4% which shows a fairly moderate THD performance of the circuit. To observe the effect of passive component mismatching on the filter's performance, Monte-Carlo analysis has been performed. For this, The TIM BP output was simulated with 10% Gaussian deviation in $C_1 = C_2 = 15$ pF for 500 concurrently runs where first run is done with nominal values of capacitor while the subsequent runs are done with values generated randomly by PSPICE.

The statistical results in the form of histogram plots are shown in Fig. 9. From these plots, the simulated mean, median and standard deviation were obtained as 5.23 MHz; 5.23 MHz, 209.75 KHz, respectively which conclude that with respect to the simulated pole frequency of 5.02 MHz, the proposed filter is less sensitive to the change in capacitive value and thus offers good passive sensitivity. Further, to check the circuit immunity with respect to circuit noise, the noise analysis of LP filter has been performed and corresponding simulation results in term of input noise and LP output noise at different frequencies are shown in Fig. 10. The maximum output noise spectral density obtained from Fig. 10 is equal to 18.72nV/Hz$^{1/2}$ which is small and acceptable range [27].



(a)

(b)

Fig. 7. Transient response of (a) LP filter (b) HP filter.

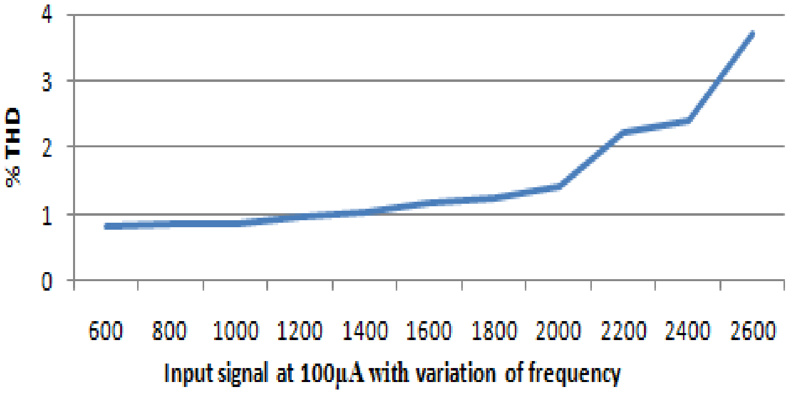
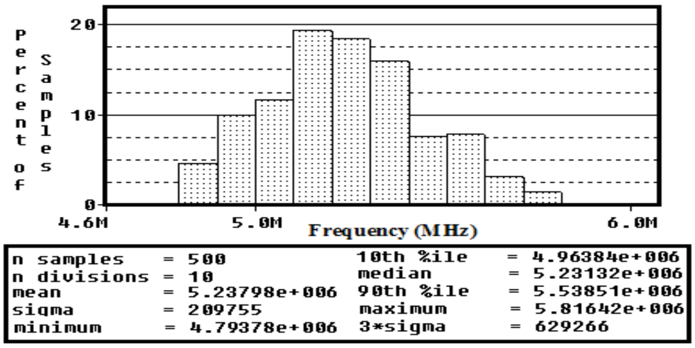


Fig. 8. % THDs of LP filter at constant peak to peak input current of 100μA and variable frequency.



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n samples    = 500             10th %ile    = 4.96384e+006
n divisions  = 10              median       = 5.23132e+006
mean         = 5.23798e+006    90th %ile    = 5.53851e+006
sigma        = 209755          maximum      = 5.81642e+006
minimum      = 4.79378e+006    3*sigma      = 629266
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Fig. 9. Monte Carlo analysis.

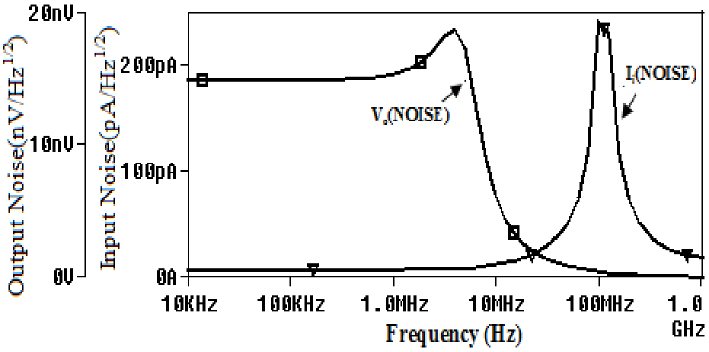

Fig. 10. Input-Output noise spectral density of LP filter.

7. Conclusion

In this paper a new VDTA based TIM biquad filter topology is presented which realizes four filtering functions such as the LP, BP, HP and BR, simultaneously using only single active element. In addition of using only single CMOS based active element, it also employs two grounded capacitors and two MOS implemented grounded resistors which can be easily realize using MOS technology [20] and hence, the presented circuit can be made fully integrable in CMOS technology and provide canonical structure. Moreover, the presented TIM filter enjoys the feature of simultaneously TIM outputs, all grounded passive elements, low active and passive sensitivities, low power consumption, independent electronic tuning of filter parameters. The above distinguished features of the circuit make hope that this work will add to the body of knowledge on classical filter design.

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