Cascadable Low Voltage Operated Current-Mode Universal Biquad Filter

RAVINDRA SINGH TOMAR[1], SAJAI VIR SINGH[2], DURG SINGH CHAUHAN[3]
[1]Dept. of Electronics and Communication Engineering
Anand Engineering College, Agra, 282007
INDIA
r_tomar15@rediffmail.com
[2]Dept. of Electronics and Communication Engineering
Jaypee Institute of Information Technology, Noida, 201304
INDIA
sajaivir75@gmail.com
[3]Department of Electrical Engineering, Indian Institute of Technology
Banaras Hindu University, Varanasi, 221005
INDIA
pdschauhan@gmail.com

Abstract: **-** A new current-mode universal biquad filter structure using two Z-Copy Current Follower Trans-conductance Amplifiers (ZC-CFTAs), and two grounded capacitors is proposed in this paper. The proposed structure can be configured into either multiple inputs multiple outputs (MIMO) or multiple inputs single output (MISO) configurations. In each configuration, the proposed circuit can realize all the standard filtering responses such as low pass (LP), band pass (BP), high pass (HP), band reject (BR), and all pass (AP), by choosing the current input/output terminals appropriately. The circuit operates at lower supply voltage rails, and for response realization it does not require inverted current input signal(s) and component matching constraints. The proposed circuit offers an advantage of electronic tunability of pole-frequency independent to the quality factor. The effort is further extended to originate an N^{th}- order LP filter, through direct cascading of proposed circuit blocks. Performances of the proposed circuits were examined through P-SPICE programs on cadence tools using standard CMOS technology.

Key- Words: **-** Biquad, CFTA, Current-mode, Universal, Filter

1 Introduction

In recent past, a generous emphasis has been paid on the study and design of current-mode (CM) continuous-time (CT) filter structures, capable to realize all the standard filtering responses, such as LP, BP, HP, BR and AP. These filter structures are termed as universal filters. Since initiation, the design of such filters primarily focused to the simple architecture operable at low voltages, so that they can be employable for low power portable electronic gadgets/applications. Further, efforts have been made to reduce the number of passive components, specially floating capacitors or resistors which mislaid suitability of the designed circuit for its integrability [1-2]. Another issue pertinent to the integrability and high performance applications of any universal filter structure is the fine adjustment (electronic-tuning) of the filter parameters to compensate for undesired variations caused by different manufacturing tolerances, imperfections, thermal drift, malfunctions, etc [3]. In the process a good number of papers on current-mode filter circuit design, are available in the literature [5-30] employing different active elements such as current conveyor (CCII) [18-21,26], current controlled current conveyor (CCCII) [5-6,14-15,24,27-29], operational trans-conductance amplifier (OTA) [17], current differencing trans-conductance amplifier (CDTA) [7,9,12,16,25,31], current follower trans-conductance amplifier (CFTA) [10-11,23], current controlled current conveyor trans-conductance amplifier (CCCCTA) [8,13,22,30] etc. However, all of these structures belong to either single-input multiple-output (SIMO) or multiple-input multiple-output (MIMO) or multiple-input single output (MISO) configuration. SIMO filter structures [5-10] simultaneously realize different filtering functions (usually three or more) at different output terminals, without any alteration in the status of input signal.

However, MIMO [11-16] and MISO filter structures [17-30] can perform multifunction filtering by altering the status of applied input signals. MISO filter structure realizes only one function at a time across the single output terminal, whereas MIMO filter structure has at least two output terminals and realizes more than one function at a time. Moreover, the MISO and MIMO configuration may require a reduced number of active elements in comparison to the SIMO configuration and hence, seems to be more appropriate than that of the single input configuration for standard filtering response realization.

In the literature, two input three output MIMO current-mode filter [11] consists of four CDTAs, four grounded passive elements (two resistors and two capacitors), but it realizes only four filtering functions (LP, BP, HP and BR). The MIMO current-mode filters reported in Refs. [12-16] employing two grounded capacitors as passive elements and can realize all the standard filter functions i.e. LP, BP, HP, BR and AP. The structures in [12-13] realize two-input two output biquad current-mode filter by employing two MO-CCCCTAs [12] and four dual output CCCIIs (DO-CCCIIs) [13] as active elements. Whereas, structures in [14-15] realize two-input three-output biquad filter consisting of respectively three DO-CCCIIs [14] and three MO-CDTAs [15]. Moreover, filter structures in [13-15] require inverted current input signal for AP response realization therefore, additional active element(s) are required to obtain inverted current input signal(s). Another, novel work of three input three output current-mode filter design [16], employing three MO-OTAs and two grounded capacitors, can also realize all the standard filtering responses. However, it requires component matching condition for the AP response realization. On the other hand MISO current-mode filters [17-30] can realize standard filtering responses by choosing current input signals appropriately. However, none of these reported MISO circuits has satisfied all the enviable features of current-mode filter, and suffer from one or more of the following drawbacks:

(i). Excessive use of active and/or passive elements [17-20, 23-26, 28].
(ii). Lack of electronic tunability [17-20].
(iii). Use of floating capacitors [17-18] or floating resistors [27] which is not viable for IC fabrication viewpoint.
(iv). Require inverted current input signal(s) to realize at least one filtering response [21-23, 25-28, 30].
(v). Requirement of component matching condition [17-18, 23, 27, 29] to realize at least one filtering response.

Aside the above drawbacks, it may also be noticed that current-mode filter structures [11-30] are either belong to MIMO or MISO category. Subsequently, the objective of this study is to propose a current-mode biquad universal filter structure, which can be configurable into either MIMO (two inputs two outputs) or MISO (three inputs single output) from the same structure and can realize all the standard filtering responses in both of the categories. The proposed current-mode biquad filter consists of two ZC-CFTAs, two grounded capacitors as active and passive elements. The proposed filter structure is a resistor-less topology and requires neither inverted current input nor matching conditions for the realization of all filter responses and operated at lower voltage supply rails. Moreover, all the filter responses are obtained across explicit high-impedance output terminal(s) which convince the cause of concern for circuit cascading. Consequently, by using proposed circuit an Nth -order LP filter is realized through direct cascading as shown in Fig. 8. Moreover, the proposed circuit do possesses low active and passive sensitivity. With all these attributes, the proposed circuit is suitable for integrated circuit implementation. The performance of the proposed circuit is verified through P-SPICE programs using 0.25µm TSMC CMOS parameters [32], and various responses are included to verify the theory.

2 Basics of ZC-CFTA

Since after its inception as current-mode active element and its impedance suitability for current-mode analog signal processing applications [4], CFTA and its modified variants such as Z-copy CFTA has received considerable favour from circuit designers. The ZC-CFTA is a modified version of CFTA [10] and mainly consists of a current-follower (CF) followed by a balanced output trans-conductance amplifier (BOTA) [4]. The use of CF at the input stage sets a low impedance input terminal ‘f’ of CFTA. When an input current I_f applied to the input terminal, it is transferred to the high impedance auxiliary Z-terminal as ($I_Z = I_f$). A copy of I_Z current may also be conveyed to the Z-copy terminal (ZC). Mostly in the circuits, synthesized using CFTA, terminal Z is loaded with the grounded impedance. The voltage drop (V_Z) across grounded impedance is further transformed into current I_{X+} and/or I_{X-} by the BOTA. The trans-conductance (g_m)

of BOTA can be controlled by an external biasing current (I_S). Because of this feature ZC-CFTA can be extended for various electronically tunable current-mode applications [4, 10]. The schematic of ZC-CFTA is shown in Fig. 1. An ideal ZC-CFTA can be described mathematically by the following set of equations.

$$V_{fi}=0,\ i_Z=i_f,\ i_{ZC}=i_f,\ i_{\pm X}=\pm g_m V_Z \quad (1)$$

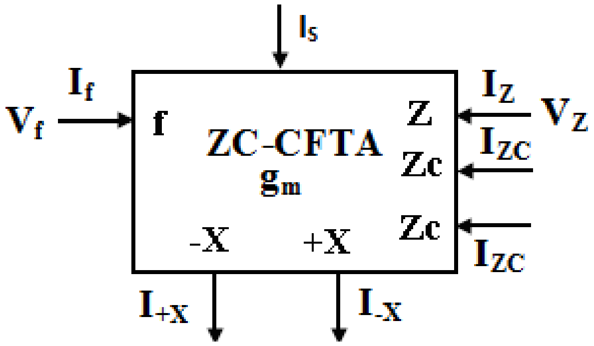


Fig. 1 Schematic symbol of ZC-CFTA

For CMOS implementation of ZC-CFTA [10], g_m relates with the biasing current as follows,

$$g_m=\sqrt{\beta_n I_S} \quad (2)$$

Where $\beta_n=\mu_n C_{OX}\left(W/L\right)$ with μ_n, C_{OX} and W/L are mobility of free electrons within the channel, gate-oxide capacitance per unit area and the aspect ratio of the NMOS transistors M_{13}-M_{14} forming a differential pair in the trans-conductance stage of employed ZC-CFTA.

3 Proposed Current Mode Filter Circuit

The proposed current-mode biquad filter with four input terminals (I_{in1}, I_{in2}, I_{in3} and I_{in4}) and three output terminals (I_{out1}, I_{out2} and I_{out3}) is shown in Fig. 2. It is based on two ZC-CFTAs and two grounded capacitors. The use of grounded capacitors is particularly attractive for integrability [31]. Through routine analysis of the proposed circuit we get the following current output expressions.

$$I_{out1}=\frac{-C_1C_2s^2I_{in1}-g_{m1}C_2sI_{in4}+g_{m1}g_{m2}(I_{in3}-I_{in2})}{D(s)} \quad (3)$$

$$I_{out2}=\frac{\begin{array}{c}C_1C_2s^2I_{in1}-(C_1C_2s^2+g_{m1}C_2s)I_{in2}\\+g_{m1}C_2sI_{in4}-g_{m1}g_{m2}I_{in3}\end{array}}{D(s)} \quad (4)$$

$$I_{out3}=\frac{\begin{array}{c}(g_{m1}C_2s+g_{m1}g_{m2})I_{in1}-g_{m1}C_2sI_{in4}\\+g_{m1}g_{m2}(I_{in3}-I_{in2})\end{array}}{D(s)} \quad (5)$$

$$\text{Where, } D(s)=s^2C_1C_2+g_{m1}C_2s+g_{m1}g_{m2} \quad (6)$$

Inspection of equations (3) - (5) suggest that various filtering responses can be obtained, by regulating the status of input currents I_{in1}, I_{in2}, I_{in3} and I_{in4}. Following two different cases are described below;

3.1 Two input two output current-mode filter

If $I_{in3}=I_{in4}=0$ and (I_{in1}, I_{in2}) are the only current input signals, then the specialization of numerators in equations (3) - (5) results into a current-mode filter with two inputs and two outputs as described in Table 1.

Table 1. Current-mode filter with two inputs and two outputs

Filter type	**Input (I_{in})**	**Output (I_{OUT})**
LP (Inv.)	$I_{in3}=I_{in4}=0$, $I_{in2}=I_{in}$, $I_{in1}=0$	I_{out1} & I_{out3}
BP (Non-inv.)	$I_{in3}=I_{in4}=0$, $I_{in1}=I_{in2}=I_{in}$	I_{out3}
HP (Inv.)	$I_{in3}=I_{in4}=0$, $I_{in1}=I_{in}$, $I_{in2}=0$	I_{out1}
BR (Inv.)	$I_{in3}=I_{in4}=0$, $I_{in1}=I_{in2}=I_{in}$	I_{out1}
AP (Inv.)	$I_{in3}=I_{in4}=0$, $I_{in1}=I_{in2}=I_{in}$	$I_{out1}+I_{out3}$

3.2 Three input single output current mode filter

If $I_{in1}=0$, and (I_{in2}, I_{in3}, I_{in4}) are considered as current input signals, then the specialization of the numerators in equations (3) - (5) results into a current-mode filter with three inputs and single output. And different filtering responses can be obtained across (I_{out2}) by selecting current inputs appropriately, as summarized;

(i). Inverted LP response in current form, with $I_{in3}=I_{in}$, and $I_{in2}=I_{in4}=0$.

(ii). Inverted HP response in current form, with $I_{in2}=I_{in4}=I_{in}$ and $I_{in3}=0$.

(iii). Non-inverted BP response in current form, with $I_{in4}=I_{in}$, and $I_{in2}=I_{in3}=0$.

(iv). Inverted BR response in current form, with $I_{in1}=I_{in2}=I_{in3}=I_{in}$.

(v). Inverted AP response in current form, with $I_{in4}=2I_{in}$, $I_{in2}=I_{in3}=I_{in}$.

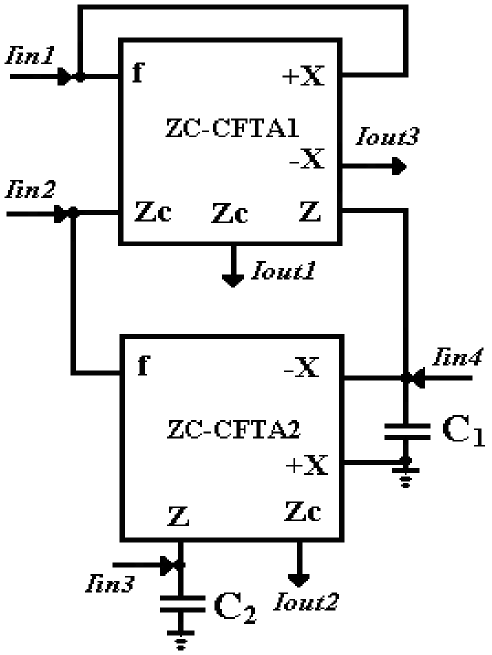


Fig. 2 Proposed current-mode biquad filter

From 3.1 and 3.2, it can be noticed that the proposed circuit can act as a universal current-mode filter either as two input two outputs (MIMO) or three input single output (MISO) configuration from same structure and can realize LP, BP, HP, BR and AP filtering functions in each case without component matching condition(s). Moreover, there is no requirement of inverting-type input current signal(s) to realize all the responses in the design.

The filter parameters such as pole frequency (ω_0), the quality factor (Q_0) and band-width (BW) can be expressed as;

$$\omega_0=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}},\ Q_0=\sqrt{\frac{C_1\,g_{m2}}{C_2\,g_{m1}}},\ BW=\frac{g_{m1}}{C_1} \tag{7}$$

Substituting trans-conductance parameter g_{m1} and g_{m2} in terms of CMOS process parameters and biasing currents I_{S1} and I_{S2} as depicted in equation (2), it yields

$$\omega_0=\sqrt{\frac{\beta_n(I_{S1}I_{S2})^{1/2}}{C_1C_2}},\ Q_0=\sqrt{\frac{C_1}{C_2}\left(\frac{I_{S2}}{I_{S1}}\right)^{1/2}} \tag{8}$$

From equation (8), it is evident that the pole frequency can be electronically tuned by I_{S2} and I_{S1}, without affecting quality factor by keeping the ratio between I_{S2} and I_{S1} to be constant. In addition, BW of the proposed filter circuit can be expressed as;

$$BW=\frac{(\beta_n I_{S1})^{1/2}}{C_1} \tag{9}$$

Equation (9) shows that the BW can solely be controlled by I_{S1} only. From equations (8) - (9), it is also clear that filter parameter ω_0 and Q_0 can be adjusted electronically by adjusting bias current I_{S2} without affecting BW.

4 Non-ideal Analysis

In this section, non-ideal aspects of the proposed biquad filter circuit are considered. For the non-ideal case, employed ZC-CFTA can be characterized by the following modified set of equations.

$$V_{fi}=0,\ i_{Zi}=\alpha_i i_{fi},\ i_{ZCi}=\beta_i i_{fi},\ i_{\pm Xi}=\pm\gamma_i g_{mi}V_{Zi} \tag{10}$$

Where, $\alpha_i=1-\varepsilon_i$ with ε_i ($|\ \varepsilon_i\ |$<<1) and $\beta_i=1-\delta_i$ with δ_i ($|\ \delta_i\ |$<< 1) represent the current tracking errors between f to Z terminal and f to Z-copy terminal of the employed ith ZC-CFTA (ith =1, 2), respectively. γ_i is the trans-conductance inaccuracy factor between Z to ± X terminal of the ith ZC-CFTA. On taking these non-ideal parameters of the ZC-CFTA into account and re-analyzing the proposed filter of Fig. 2, we receive the denominator of each current output expressions as;

$$D(s)=s^2C_1C_2+\alpha_1\gamma_1 g_{m1}C_2 s+\gamma_1\gamma_2\beta_1 g_{m1}g_{m2} \tag{11}$$

With involved non-idealities, the modified ω_0 and Q_0 are obtained from equation (11) as,

$$\omega_0=\sqrt{\frac{\gamma_1\gamma_2\beta_1 g_{m1}g_{m2}}{C_1C_2}},\ Q_0=\frac{1}{\alpha_1}\sqrt{\frac{\beta_1\gamma_2 C_1\,g_{m2}}{\gamma_1 C_2\,g_{m1}}} \tag{12}$$

It can be noted from equation (12) that slight deviations are expected in ω_0 and Q_0 due to appearance of non-ideality terms. However, these deviations may be negligible, because non-ideal parameters α, β and γ can be found closed to unity at working frequency. To what an extent the filter parameters are affected for the corresponding changes in the values of active/passive elements can be determined by evaluating sensitivity coefficients, which are found to be as follows;

$$S^{\omega_0}_{\gamma_1,\gamma_2,\beta_1,g_{m1},g_{m2}}=\frac{1}{2},\ S^{\omega_0}_{C_1,C_2}=-\frac{1}{2},\ S^{\omega_0}_{\alpha_1,\alpha_2,\beta_2}=0 \tag{13}$$

$$S^{Q_0}_{\beta_1,\gamma_2,C_1,g_{m2}} = \frac{1}{2}, S^{Q_0}_{\gamma_1,C_2,g_{m1}} = -\frac{1}{2}, S^{Q_0}_{\alpha_1} = -1,$$

$$S^{Q_0}_{\alpha_2,\beta_2} = 0 \quad (14)$$

Above result implies a good sensitivity performance of the proposed circuit, since all the active and passive sensitivity coefficients are obtained within ‘unity’ in magnitude.

5 Application as Higher Order Filter

Proposed biquad filter circuit in Fig. 2, offers low-impedance input terminals and high-impedance output terminals, which is a prominent situation for synthesizing higher order current-mode filters through cascading. Consequently, a current-mode Nth - order low pass (LP) filter of Fig. 8 is derived through direct cascading of the biquad filter circuit of Fig. 2 without using any impedance matching elements/devices. In the design, for each biquad block (1, 2…..m) the component values were chosen as $I_{S1} = I_{S2} = 100$ µA and $C_1 = C_2 = 16$ pF. The voltage supply rails were used as $V_{DD} = -V_{SS} = 1.0$ V with bias $V_{BB} = -0.5$V. The resulting current output expression will be as follows;

$$I_{out} = \left(\frac{g_{m1}g_{m2}}{D(s)}\right)^m I_{in} \quad (15)$$

With, $D(s) = s^2C_1C_2 + g_{m1}C_2s + g_{m1}g_{m2}$

From (15), it is clear that the gain of resulting filter is unity. This Nth - order filter consists of ‘N’ number of ZC-CFTAs or m number of (m = N/2) proposed filter blocks of Fig. 2. The simulated frequency responses of the cascaded filter of Fig. 8 for N = 2, 4, 6 are illustrated in Fig. 9. From different simulation results it is evident that the higher order circuits realized through direct cascading are attractive choice and operable at low frequency as well as at high frequency efficiently.

6 Simulation Results

The proposed current-mode universal biquad filter in Fig. 2 was implemented using standard CMOS technology (TSMC 0.25µm) and examined using PSPICE simulation on cadence tools to verify the theoretical expectations. For this, ZC-CFTA was implemented using CMOS transistors as shown in Fig. 3. The dimensions of MOS transistors were taken as specified in Table 2. The proposed circuit was designed for $f_0 = \omega_0/2\pi = 11$ MHz at $Q_0 = 1$, by selecting $I_{S1} = I_{S2} = 100$ µA and $C_1 = C_2 = 16$ pF. The voltage supply rails were used as $V_{DD} = -V_{SS} = 1.0$ V with bias $V_{BB} = -0.5$V. For MIMO (two inputs two outputs) configuration of the proposed current-mode filter circuit, the simulated gain and phase responses of HP and LP output is shown in Fig. 4 (a) and Fig.4 (b) respectively. Whereas, the simulated gain response of BP, BR and AP filtering functions are illustrated in Fig. 5. Similarly, for the MISO (three inputs single output) configuration of proposed current-mode filter circuit the simulated gain response of the LP, BP, BR, HP and AP filtering functions is shown in Fig. 6 (a). The simulated gain and phase response of current-mode AP filtering function for MISO configuration of the proposed current-mode filter is illustrated in Fig. 6 (b). For filtering responses of both MIMO and MISO configurations, the simulated pole frequency is measured as 10.76 MHz, which is fairly close to the designed value. Next, the frequency tuning aspect of the circuit was demonstrated for a constant Q=1 through simulation of the BP responses as shown in Fig.7. The frequency was found to vary as 5.40MHz, 7.49MHz, 10MHz and 12.16MHz, for four different sets of $I_{S1} = I_{S2}$ as 20 µA, 40 µA, 80 µA, and 140 µA respectively. The gain and phase response of Nth -order LP filter circuit of Fig. 8 for N = 2, 4 & 6 is shown in Fig. 9. Further Nth - order filter in Fig. 8 was simulated for THD analysis at LP (N= 6) output, by applying sinusoidal input current I_{in} of constant amplitude and varying frequency. For a current input signal of 50uA amplitude over a frequency range of 200 KHz to 1.5 MHz, the corresponding THD values remain within the acceptable limits i.e. 4% as indicated in the frequency versus %THD graph in Fig.10. The time domain response at LP output of the Nth - order filter for N = 6 is shown in Fig.11. It was observed that 100 µA peak to peak sinusoidal input current signal of frequency 200 KHz is acceptable without significant distortions. Thus, both THD analysis and time domain responses of LP output of the Nth - order filter confirms the practical utility and validity of the proposed filter circuit.

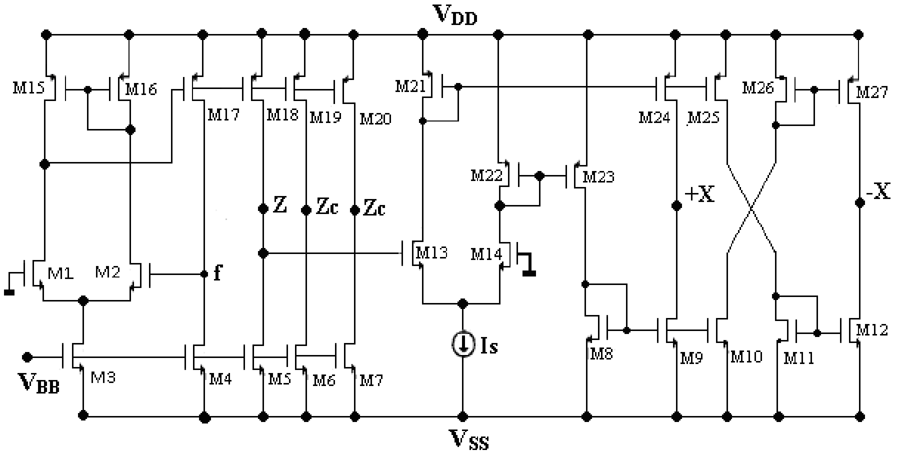
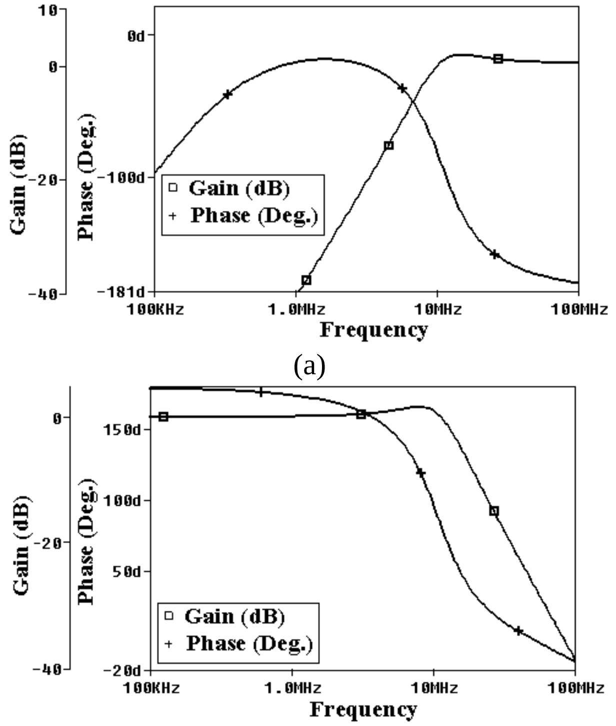


Fig. 3 CMOS implementation of ZC-CFTA



(a)

(b)

Fig. 4 Current gain and phase responses of the (a) HP, (b) LP of two input two output configuration of the proposed circuit in Fig. 2

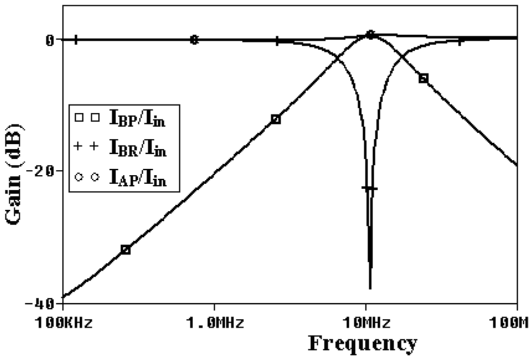
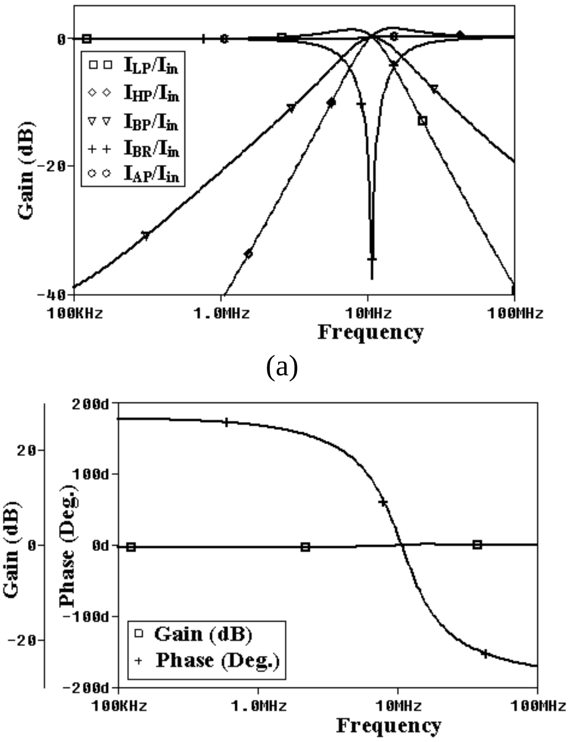


Fig. 5 Current gain responses of the BP, BR and AP of two input two output configuration of the proposed circuit in Fig. 2



(a)

(b)

Fig. 6 For MISO configuration of the proposed circuit in Fig. 2 (a) Current gain responses of the LP, HP, BP, BR and AP (b) Current gain and phase response of the AP

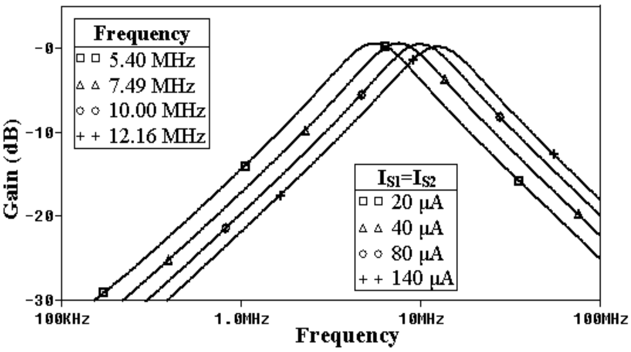


Fig. 7 BP responses of the proposed filter for different value of $I_{S2} = I_{S1}$ when $I_{in3} = I_{in4} = 0$ and $I_{in1} = I_{in2} = I_{in}$

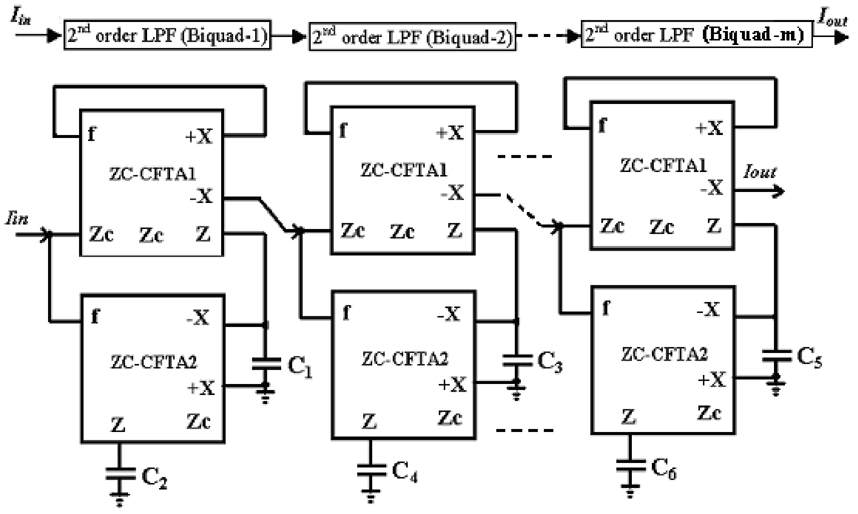


Fig. 8 Nth-Order LP filter, as an application of the proposed biquad filter in Fig. 2 through direct-cascading.

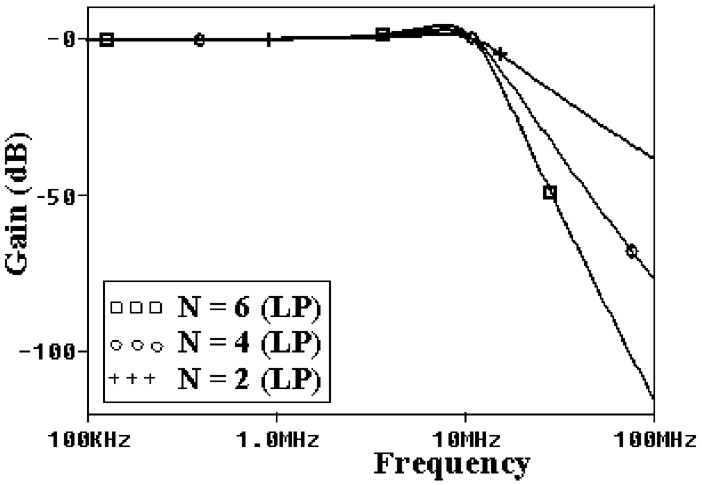


Fig. 9 Simulated frequency responses of Nth-order LP filter in Fig. 8 for N = 2, 4 & 6

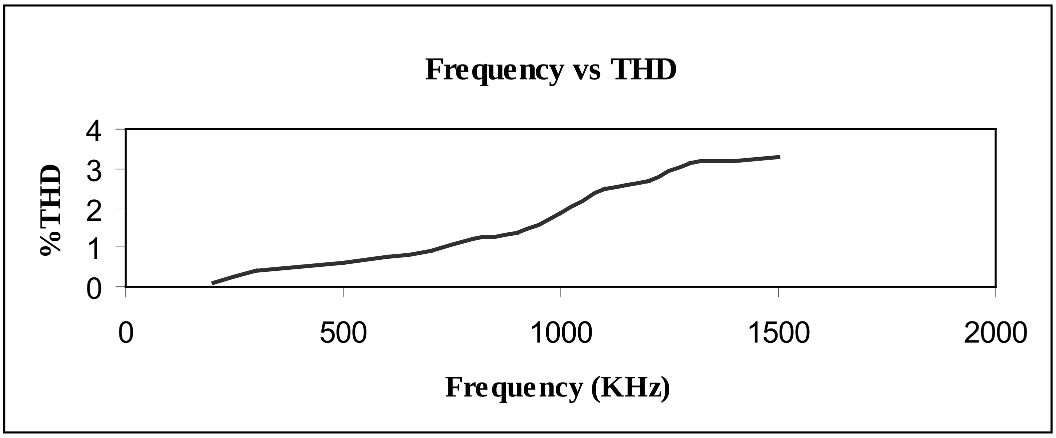


Fig. 10 Variation in THD of the Nth-order (N = 6) LP filter output, for a sinusoidal input of amplitude 50 µA and varying frequency

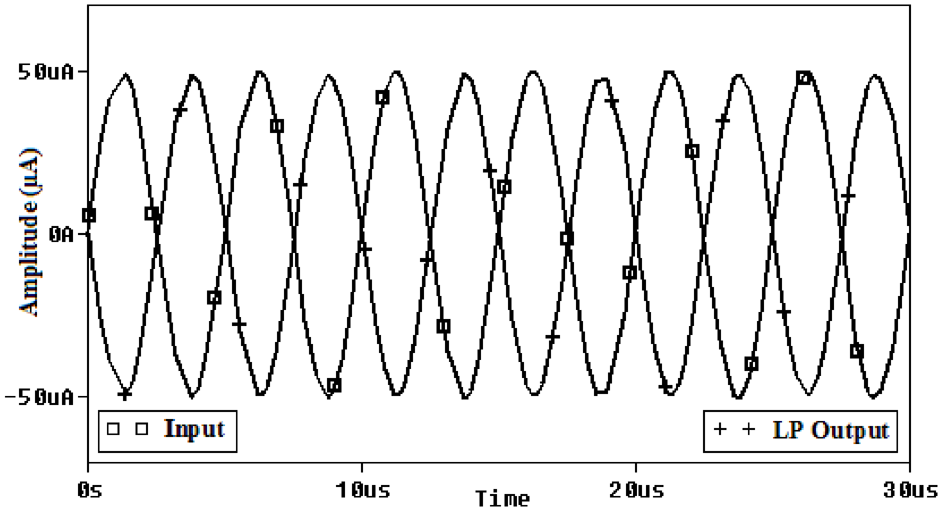


Fig. 11 Time-domain sinusoidal input and LP output waveforms of the Nth-order (N = 6) filter circuit of Fig. 8

Table 2: Dimensions of MOS transistors

MOS Transistors	Dimensions
NMOS	**W(µm)/L(µm)**
M1, M2	1/0.25
M3-M12	3/0.25
M13, M14	15/0.25
PMOS	**W(µm)/L(µm)**
M15-M22& M24-M27	5/0.25
M23	4.5/0.25

7 Conclusion

A current tunable current-mode universal biquad filter employing two ZC-CFTAs and two grounded capacitors is proposed. It is canonical by the way of using only two capacitors and permits cascadibility for obtaining higher order filter functions as all the output currents are available at high impedance output terminals. Moreover, the proposed circuits were found to enjoy the advantages of independent current tunability of ω_0 and Q_0 with bias current(s) of ZC-CFTAs, low active and passive sensitivities and the versatility to realize LP, BP, HP, BR and AP responses with two input two output or three input one output from the same structure, without requiring any inverted input current signal(s) and matching conditions. As an application of proposed circuit a unity gain Nth - order LP filter is realized through cascading. The proposed biquad filter circuit in this paper were simulated using PSPICE with CMOS implementation and then the simulated results have been studied which agree quite well in all aspects of the circuit with theoretical ones as expected. The proposed circuit structure is expected to be employable for different applications in communication, instrumentation and measurement systems, specially at high frequency range.

References:

[1] C. Toumazou, F. J. Lidgey, and D. G. Haigh, *Analogue ICs design: the current-mode approach*, Peter Peregrinus, London, UK, 1990, Chapter 13.

[2] B. Wilson, Recent developments in current-mode circuits, *Proceeding of the IEE, Pt. G.*, Vol. 137, 1990, pp. 63-77.

[3] B. Metin, *Electronic tunability in current-mode filters*, PhD Thesis, 2007.

[4] N. Herencsar, J. Koton, K. Vrba, and I. Lattenberg, Current follower transconductance amplifier (CFTA)- a useful building block for analog signal processing, *J. active and passive electron devices*, Vol. 6, 2011, pp. 217-219.

[5] S. Maheshwari, S. V. Singh and D. S. Chauhan, Electronically tunable low voltage mixed-mode universal biquad filter, *IET Circuits, Devices and Systems*, Vol. 5, 2011, pp. 149-158.

[6] E. Yuce, S. Minaei and O. Cicekoglu, Universal current-mode active-C filter employing minimum number of passive elements, *Analog Integrated Circuits and Signal Processing*, Vol. 46, 2006, pp. 169-171.

[7] T. Katoh, T. Tsukutani, Y. Sumi and Y. Fukui, Electronically tunable current-mode universal filter employing CCCIIs and grounded capacitors, *In Proceeding of 2006 Int'l Conf. On Intelligent Signal Processing and Communication (ISPACS)*, 2006, pp. 107-110.

[8] A. Ü. Keskin, D. Biolek, E. Hancioglu and V. Biolkova, Current-mode KHN filter employing current differencing transconductance amplifiers, *Int'l J. Electronics and Communications (AEÜ)*, Vol. 60, 2006, pp. 443-446.

[9] W. Tangsrirat, Single input three output electronically tunable universal current-mode filter using current follower transconductance amplifiers, *Int'l J. Electronics and Communication (AEÜ)*, Vol. 65, 2011, pp. 783-787.

[10] B. Singh, A. K. Singh and R. Senani, New universal current-mode biquad using only three ZC-CFTA, *Radioengineering J.* vol. 21, pp. 273-280, 2012.

[11] A. Uygur, H. Kuntman and A. Zeki, A multi-input multi-output CDTA based KHN filter, *In Proceeding of 4th Int'l Conf. On Electrical and Electronics, Bursa, Turkey,* 2005 pp. 46-50.

[12] S. V. Singh, S. Maheshwari and D. S. Chauhan, Current-mode electronically tunable biquad filter, *In IEEE Int'l Conf. On Multimedia, Signal Processing and Communication Technologies (IMPACT-2011),* 2011, pp. 176-179.

[13] W. Tangsrirat, Current-tunable current-mode multifunction filter based on dual-output current controlled conveyors, *Int'l J. Electronics and communication (AEU),* Vol. 61, 2007, pp. 528-533.

[14] W. Tangsrirat, W. Surakampontom, High output impedance current-mode universal filter employing dual-output current-controlled conveyors and grounded capacitors, *Int'l J. Electronics and communication (AEU),* Vol. 61, 2007, pp. 127-131.

[15] T. Dumawipata, W. Tangsrirat and W. Surakampontom, Cascadable current-mode multifunction filter with two inputs and three outputs using CDTAs, *In Proceeding of 6th Int'l Conf. On Information, Communications and Signal Processing,* 2007, pp. 1-4.

[16] M. T. Abuelmatti, A. Bentrcia, New universal current-mode multiple-input multiple-output OTA-C filter, *In Proceeding of 2004 IEEE Asia Pacific Conf. on Circuits and Systems,* 2004, pp. 1037-1040.

[17] E. Arslan, B. Metin and O. Ciekoglu, Multi-input single output cascadable current-mode universal filter topology with a single current conveyor, *In Proceedings of Third IASTED Int'l Conf. on Circuits, Signals, and Systems, Marina Del Rey (CA, USA),* 2005, pp. 62 – 66.

[18] S. Özcan, H. Kuntman and O. Çiçekoglu, A novel multi input single-output filter with reduced number of passive elements using single current conveyor, *In Proceedings of the 43rd IEEE Midwest Symposium on Circuits and Systems, Lansing (MI, USA),* 2000, pp. 1030 – 1032.

[19] J. W. Horng, High output impedance current-mode universal biquadratic filters with five inputs using multi-output CCIIs, *Microelectronics J.,* Vol. 42(5), 2011, pp. 693-700.

[20] M. T. Abuelma'atti and N. A. Tassaduq, A novel three inputs and one output universal current-mode filter using plus-type CCIIs, *Microelectronics J.,* Vol. 30, 1999, pp. 287-292.

[21] W. Jaikla, S. Siripongdee and P. Suwanjan, MISO current-mode biquad filter with independent control of pole frequency and quality factor, *Radioengineering J.* Vol. 21, No. 3, 2012, pp. 886-891.

[22] S. Lawnwisut and M. A. Siripruchyanun, Current-mode multifunction biquadratic filter using CFTAs, *J. KMUTNB,* Vol. 22, No. 1, 2012, pp. 479-484.

[23] W. Tangsrirat and W. Surakampontom, Electronically tunable current-mode universal filter employing only plus type current-controlled conveyors and grounded capacitors, *Circuits, Systems and Signal Processing,* Vol. 27, No. 6, 2006, pp. 701-713.

[24] W. Tangsrirat and T. Pukkalanun, Structural Generation of two integrator loop filters using CDTAs and Grounded Capacitors, *Int'l J. Circuit Theory and Applications,* Vol. 39, No. 1, 2011, pp. 31-45.

[25] W. Chunhua, L. Haiguang and Z. Yan, Universal current-mode filter with multiple inputs and one output using MO-CCII and MO-CCCA, *Int'l J. Electronics and communication (AEU),* Vol. 63, No. 6, 2009, pp. 448-453.

[26] M. T. Abuelma'atti, M. L. Al-qahtani, Universal current-controlled current-mode filter with three inputs and one output using current controlled conveyor, *Active Passive Electronic Components,* Vol. 21, 1998, pp. 33-41.

[27] C. M. Chang, T. H. Huang, S. H. Tu, C. L. Hou, J. W. Horng, Universal active current filter using single second-generation current controlled conveyor, *Circuits Systems and Signal Processing,* Vol. 1, 2007, pp. 194-198.

[28] E. Yuce, A. Kircay and S. Tokat, Universal resistor less current-mode filters employing CCCIIs, *Int'l J. Circuit Theory and Application,* Vol. 36, 2008, pp. 739-755.

[29] S. V. Singh and S. Maheshwari, Current-processing current controlled universal biquad filter, *Radioengineering J.,* Vol. 21, No. 1, 2012, pp. 317-323.

[30] W. Tangsrirat, T. Dumawipata, W. Surakampontom, Multiple-input single-output current-mode multifunction filter using current differencing transconductance amplifiers, *Int'l J. Electronics and Communications (AEÜ),* Vol. 61, 2007, pp. 209-214.

[31] M. Bhusan, R. W. Newcomb, Grounding of capacitors in integrated circuits, *Electronics Letters,* Vol. 3, 1967, pp. 148-149.

[32] P. Prommee, K. Angkeaw, M. Somdunyakanok, K. Dejhan, CMOS- based near zero-offset multiple inputs max-min circuits and its applications, *Analog Integrated Circuits and Signal Processing,* Vol. 61, 2009, pp. 93-105.