Novel CMOS Current Follower Transconductance Amplifier Current-Mode universal Filter

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ABSTRACT
A current-mode universal biquad filter structure using two Current Follower Transconductance Amplifiers is proposed in this paper. And it contains two grounded capacitors. The proposed structure can be configured into single input multiple outputs (MIMO). Using the proposed circuit the realization of all the standard filtering responses such as low pass (LP), band pass (BP), high pass (HP), band reject (BR), and all pass (AP), can be done by choosing the output accordingly . The circuit does not require inverted current input signal(s) and it operates at lower supply voltage rails. The most important, component matching constraints are not required for the circuit .The proposed circuit offers an advantage of electronic tunability of pole-frequency independent to the quality factor. Performances of the proposed circuits were examined through P-SPICE programs on cadence tools using standard CMOS technology.

Keywords
Biquad, CFTA, Current-mode, Universal, Filter

1. INTRODUCTION
Now days, the analog integrated circuits working in current mode are more popular due to their specific features such as higher slew-rate, considerable linearity, indigenous large bandwidth, broad dynamic ranges, low complexity and minimum power consumption [55]. Those current-mode (CM) continuous-time (CT) filter structures, capable to realize all the standard filtering responses, such as LP, BP, HP, BR and AP are having prominence in electronic industry. This type of filter structure is known as universal filters [55].
The designing of such type of filters with the concept, idea and availability of the components required for the circuit.
Then the process of reducing the complexity of the circuit and make it operable at low power is being done, so that the device can be portable [57]. Further process of designing is to reduce the number of passive elements such as Capacitors and resistors used in the circuit and considering that there should be no floating elements, floating elements r educes the further integration[1-2].
Another big issue in the process of integrability is electronic tuning of the circuit and for highly accurate performance of any universal filter structure, first need is compatibility and adaptability of the filter parameters to compensate for unwanted variations due to various manufacturing imperfections, thermal drift, malfunctions, etc [3]. These structures are of many types either multiple-input multiple output abbreviate as MIMO or single-input multiple-output abbreviate as SIMO or multiple-input single output abbreviate as MISO configuration [56]. Single input multiple output filter structures [5-10] can realize many filtering functions without any modification requirement in the status of input signal. However, multi input multi output [56, 11-16] and Multi input single output filter structures [17-30] can perform multifunction filtering by modifying the input signals applied [56]. Since an introduction of the current differencing trans conductance amplifier (CDTA) in 2003, it has been acknowledged to be a versatile active building block for current-mode signal processing circuits [57]. Various analog signal processing/signal generation circuit solutions using this device have also been reported [57]. However, all of the previous works need more than one CDTA. In point of view of the low power dissipation and manufacturing cost, it is important to keep the active component count at minimum. Moreover, the earlier reported configurations do not exploit the full capacity of the used CDTAs, since one of the input terminals (p or n terminals) of the CDTA is not used. This may cause some noise injection into the monolithic circuit. Thus, to avoid this problem, the modified version of the CDTA so-called current follower trans conductance amplifier (CFTA) has recently been introduced. [57]
A CFTA, a current-mode universal filter having single input and three outputs (SIMO) and electronically tunable is presented in this paper which provides all the desirable responses such as low pass ,high pass band pass, band stop and all pass filter operation.
The topology is Multiple-Input-Single-Output (MISO) and Single input and multiple output universal biquad, are having orthogonal adjustment facility of ω_0 and Q [58].

In the literature, one input three output SIMO current-mode filter [59]consists of three CFTAs, three grounded passive elements (one resistor and two capacitors), but it realizes only three filtering functions (LP, BP and HP). The SIMO current-mode filters reported [58] employing two grounded capacitors and one floating resistor as passive elements and can realize all the standard filter functions i.e. LP, BP, HP, BR and AP. The structures in [60] realize one input three output biquad current-mode filters by employing CFTA and three Passive elements giving all five results.
The structures in [61] realize one input three output biquad current-mode filters by employing two CCTA and two grounded capacitors and three grouded resistors elements giving all five results.
The structures in [62] realize one input three output biquad mixed-mode filters by employing three VDTA and two grounded capacitors giving all five results.

This is just the literature review about the previous research to propose a current-mode biquad universal filter structure, which is configurable into SIMO (single input multiple output) structure and can realize all the standard filtering responses.
The proposed circuit is a biquad filter consists of two CFTAs, two grounded capacitors as active and passive elements. This is a current mode SIMO circuit. This topology is a resistor less topology requires no matching conditions for the realization of all filter responses. In this circuit there is no requirement of inverted current input and operate at low power supply. All the filter responses are obtained at high impedance output terminal(s) which convince the cause of concern for circuit

cascading. The performance of the proposed circuit is verified through P-SPICE 16.3 Orcads programs using 0.25μm TSMC CMOS parameters [32], and various responses are included to verify the theory.

2. BASICS OF CFTA

Basic model and the ideal behavioral model of the CFTA are shown in Fig. 1. It has one f-port low-impedance current input port. The current I_f flows from port z. In some applications, to utilize the current through z terminal, an auxiliary Z_C (z-copy) terminal is used [57]. The internal current mirror provides a copy of the current flowing out of the z terminal to the zc terminal. The voltage V_Z on z terminal is transferred into current using transconductance gm, which flows into output terminal x. The G_m is tuned by I_S. In general, CFTA can contain an arbitrary number of x terminals, providing currents Ix of both directions. The characteristics of the ideal CFTA are represented by the following hybrid matrix:

Table1: Hybrid matrix

$$\begin{bmatrix} V_f \\ I_{z,zc} \\ I_x \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_f \\ V_x \\ V_z \end{bmatrix}.$$

The use of CF (Current Follower) 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 IZ 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 (VZ) across grounded impedance is further transformed into current IX+ and/or IX- by the BOTA(Balanced output transconductance amplifier). The trans-conductance (gm) of BOTA can be controlled by an external biasing current (IS). Because of this feature CFTA can be extended for various electronically tunable current-mode applications [rt]. The schematic of CFTA is shown in Fig. 1. An ideal CFTA can be described mathematically by the following set of equations.

$$I_f = I_z \ , \ I_x = G_m V_z \ , \ V_f = 0 \qquad (1)$$

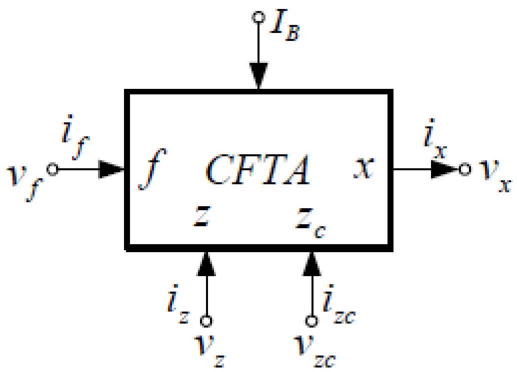

Fig. 1 Schematic symbol of ZC-CFTA

For CMOS implementation of CFTA [2011IP], Gm relates with the biasing current as follows,

$$Gm = \sqrt{KI_S} \qquad (2)$$

$$K = \mu_o C_{OX}(W/_L) \qquad (3)$$

With μ_0, COX 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_{18}-M_{19} forming a differential pair in the trans-conductance stage of employed CFTA.

3. PROPOSED CURRENT MODE FILTER CIRCUIT

The proposed current-mode biquad filter with one input terminal (Iin1) and three output terminals (Iout1, Iout2 and Iout3) is shown in Fig. 2. It requires two ZC-CFTAs and two grounded passive elements (two grounded capacitors). The use of grounded capacitors is particularly attractive for integrability [31]. There is some output expressions obtained from the proposed circuit.

$$Iout3 = \frac{S^2C_1C_2I_{IN}}{D(s)} \qquad (4)$$

$$Iout2 = \frac{SC_1Gm_1I_{IN}}{D(S)} \qquad (5)$$

$$Iout1 = \frac{Gm_1Gm_2I_{IN}}{D(S)} \qquad (6)$$

$$D(S) = S^2C_1C_2 + SC_1Gm_2 + Gm_1Gm_2 \qquad (7)$$

From equations (4) - (7) shows that various filtering responses can be obtained, which node providing the desired output is given in Table2

Table 2. Current-mode filter with one input and three outputs

Filter type	Input	Output
High Pass	Iin	Iout1
Low Pass	Iin	Iout3
Band Pass	Iin	Iout2
Band Reject	Iin	Iout1-Iout3
All Pass	Iin	Iout1+Iout2+Iout3

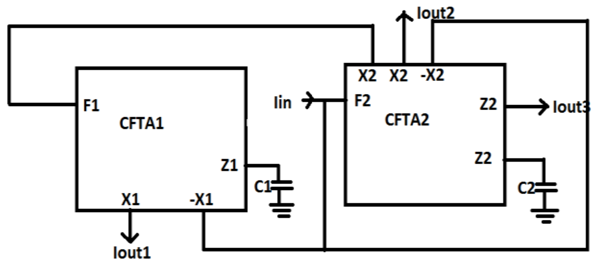

Fig. 2 Proposed current-mode biquad filter

From the given equations, it is shown that the proposed circuit can work as a universal current-mode filter as one input three outputs (SIMO) configuration and can perform LP, BP, HP, BR and AP filtering function .And there is no requirement of component matching condition(s). In Addition, there is no requirement of any type of inverting-type input current signal(s) in the design to realize all the responses.

The filter parameters such as pole frequency (ω0), the quality factor (Q0) and band-width (BW) can be expressed as;

$$\omega_o = \sqrt{\frac{Gm_1Gm_2}{C_1C_2}} \qquad (8)$$

$$Q_o = \sqrt{\frac{Gm_1C_2}{Gm_2C_1}} \qquad (9)$$

$$BW = \frac{Gm_2}{C_2} \qquad (10)$$

Equation (9) shows that the BW can solely be controlled by I_{S2} only. From equations (7) - (8), it is also clear that filter parameter ω0 and Q0 can be adjusted electronically by adjusting bias current I_{S1} without affecting BW.

4. NON-IDEAL ANALYSIS

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

$V_{ft}=0$, $I_{Zi}=\alpha_i I_{fi}$,$I_{ZCi}=\beta_i I_{fi}$,$I_{\pm X}=\Upsilon_i G_{mi} V_Z$

Where $\alpha_i=1-\epsilon_i$ with $|\epsilon_i| << 1$ $\beta_i=1-\sigma_i$ with $|\sigma_i| << 1$

Represent the current tracking errors between f to Z terminal and f to Z-copy terminal of the employed i_{th} ZC-CFTA (ith =1, 2), respectively. Υ_i is the trans-conductance inaccuracy factor between Z to ± X terminal of the i_{th} ZC-CFTA.

$$D(S) = S^2C_1C_2 + \gamma_2\alpha_2SC_1Gm_2 + \gamma_1\alpha_2Gm_1Gm_2 \qquad (11)$$

$$\omega_o = \sqrt{\frac{\alpha_2\gamma_1Gm_1Gm_2}{C_1C_2}} \qquad (12)$$

$$Q_o = \frac{1}{\gamma_2}\sqrt{\frac{\gamma_1Gm_1C_2}{\alpha_2Gm_2C_1}} \qquad (13)$$

$$BW = \frac{\gamma_2\alpha_2Gm_2}{C_2} \qquad (14)$$

Considering these non-ideal parameters of the CFTA and re-analyzing the proposed filter of Fig. 2, we have the denominator of each current output expressions as;

$$D(S) = S^2C_1C_2 + \gamma_2\alpha_2SC_1Gm_2 + \gamma_1\alpha_2Gm_1Gm_2$$

It is seen from above equation that minor deviations are available in ω_0 and Q_0 due to non-ideal analysis. But these deviations are negligible, because non-ideal parameters α, β and γ are tends to unity at working frequency.

5. SIMULATION RESULTS

The proposed current-mode universal biquad filter in Fig. 2 was implemented using standard CMOS technology

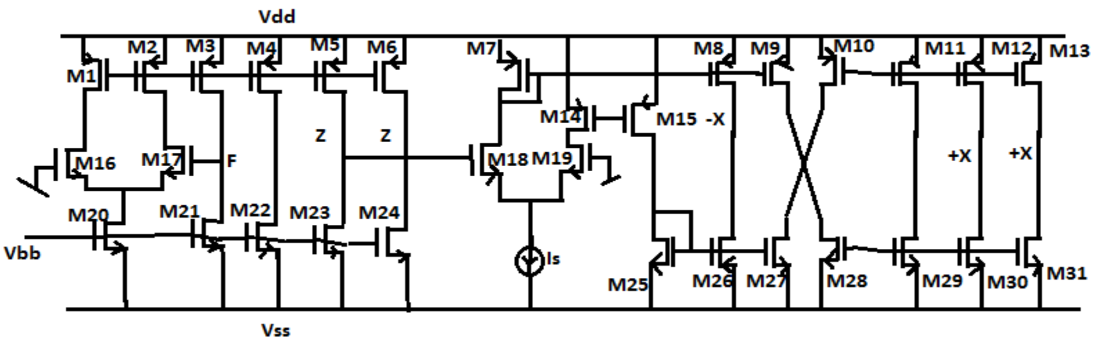

Fig. 3 CMOS implementation of CFTA

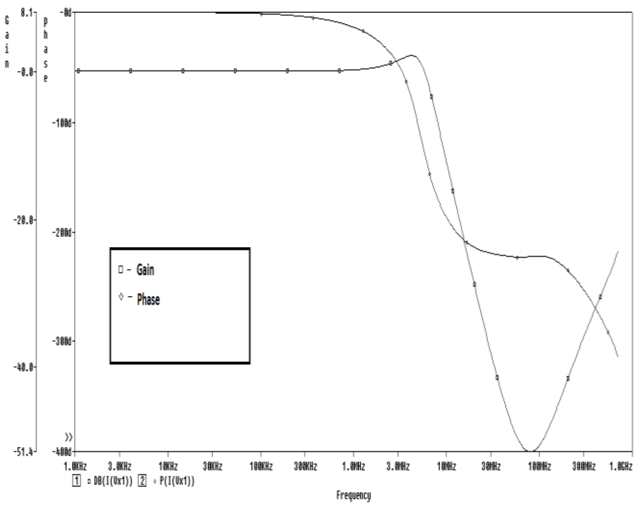

Fig. 4(a) LOW Pass Gain and Phase

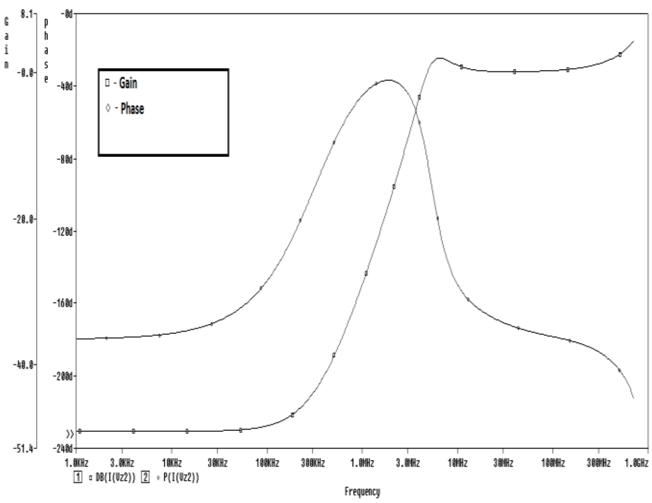

Fig. 4(b) HIGH Pass Gain and Phase

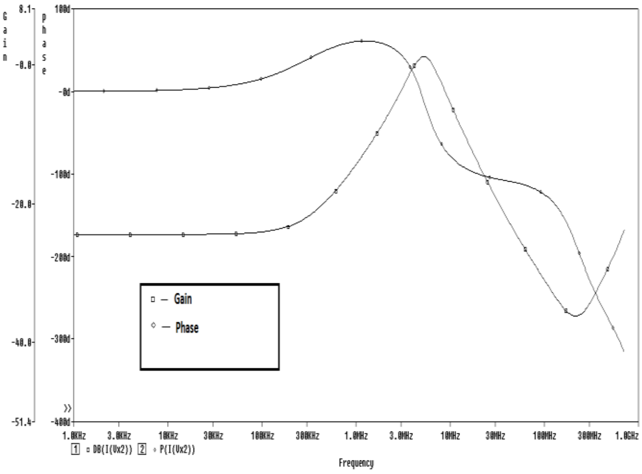

Fig. 4(c) Band Pass Gain and Phase

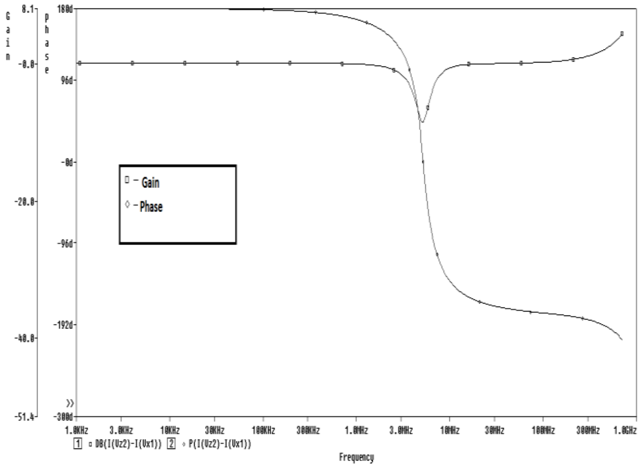

Fig. 4(d) Band Reject Gain and Phase

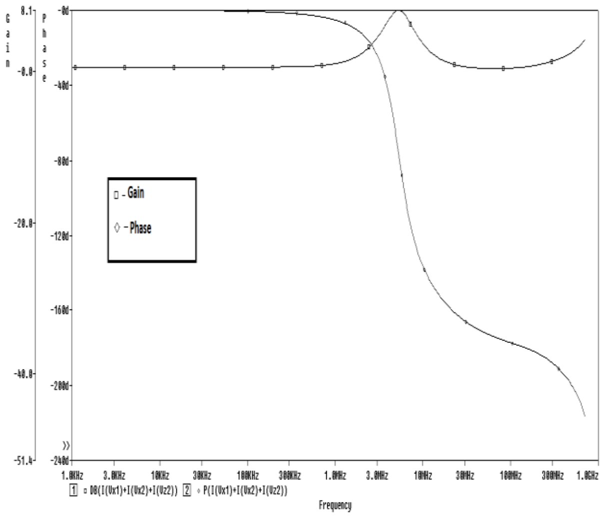

Fig. 4(e) All Pass Gain and Phase

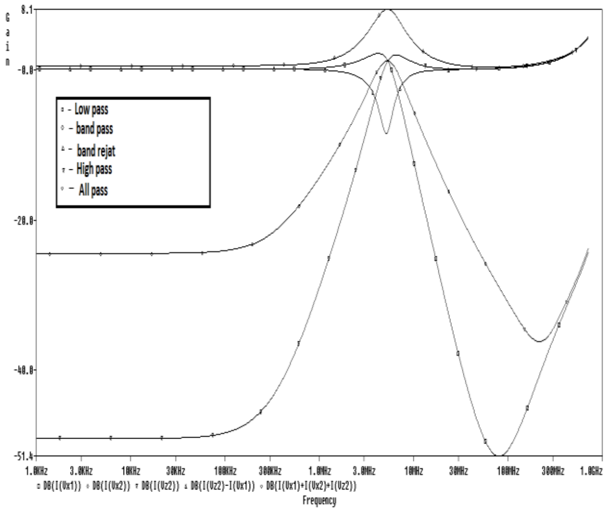

Fig. 5(a) Gain of all responses

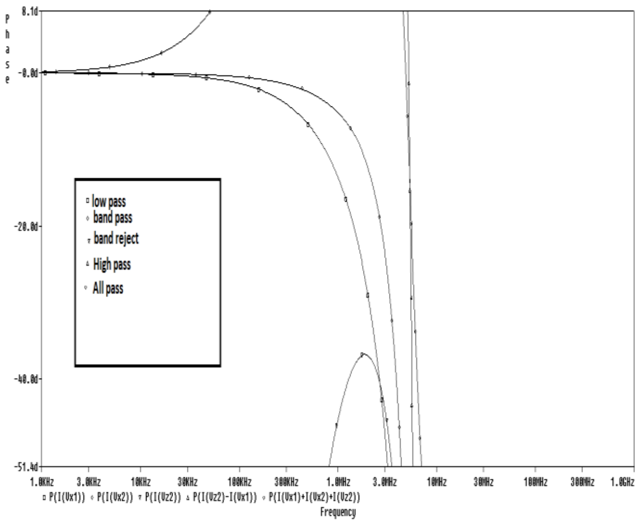

Fig. 5(b) phase of all response

(TSMC 0.25μm) and examined using PSPICE simulation on cadence tools to verify the theoretical expectations. For this, CFTA was implemented using CMOS transistors as shown in Fig. 3.

The dimensions of MOS transistors were taken as specified in Table 3. The proposed circuit was designed for $f0 = \omega 0/2\pi = 10$ MHz by selecting IS1 = IS2 = 20 μA and C1 = C2 = 10 pF. The voltage supply rails were used as VDD = -VSS = 1.0 V with bias VBB = -0.5V. For SIMO (one input three outputs) configuration of the proposed current-mode filter circuit, the simulated gain and phase responses of HP , LP, BP,BR,AP output is shown in Fig.4(a),4(b),4(c),4(d),4(e) respectively. Whereas, the simulated gain response of HP, LP, BP, BR and AP filtering functions are illustrated in Fig. 5(a). And the simulated gain response of HP, LP, BP, BR and AP filtering functions are illustrated in Fig. 5(b)

Table 3: Dimensions of MOS transistors MOS Transistors Dimensions

NMOS	W(µm)/L(µm)
M16-M17	**2.5/.25**
M18-M19	**25/.25**
M20-M31	**7.5/.25**

PMOS	W(µm)/L(µm)
M1-M14	**7.5/.25**
M15	**8.5/.25**

6. CONCLUSIONS

An electronic tunable universal biquad filter working in a current mode is made up of two CFTAs and two grounded capacitors are proposed. This circuit is having two grounded capacitors as a passive elements only so they permits cascadibility for obtaining higher order filter functions as all the output currents are available at high impedance output terminals. There is no need of inverted current input of circuit this is the advantage and operating at low power supply. All the filter responses are obtained at high impedance output terminal(s) which convince the cause of concern for circuit cascading. Another advantage of the proposed circuits were found is independent current tunability of ω0 and Q0 with bias current(s) of CFTAs.Some other advantages are low active and passive sensitivities and the versatility to realize LP, BP, HP, BR and AP responses with one input and three output , without requiring any matching conditions. The proposed universal filter circuit was simulated using PSPICE with CMOS implementation. The proposed circuit structure is expected to be usable for different applications in communication, instrumentation and measurement systems, specially at high frequency range.

7. 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 OTAC 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, Currentmode 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.

[33] J. Koton, N. Herencsar, K. Vrba, Single-Input Three-Output Current-Mode Filter Using Dual- Output Current Conveyors, In Proc.*Int. Conference on Electrical and Electronics Engineering* - ELECO 2009, Vol. 2, Turkey: EMO Yayinlari, 2009, pp. 263-266.

[34] H. P. Chen, P. L. Chu, Versatile universal electronically tunable current-mode filter using CCCIIs,*IEICE Electronics Express*, Vol. 6, No. 2, 2009, pp. 122-128.

[35] M. Sagbas, K. Fidaboylu, Electronically tunable current-mode second order universal filter using minimum elements,*Electronics Letters*, Vol.40, 2004, pp. 2-4.

[36] H. Chen, Current-mode dual-output ICCII based tunable universal biquadratic filter with low-input and high-output impedances, *Int. J. Circ. Theor. Appl*., Vol. 42, Issue 4, Oct. 2012, pp. 376–393.

[37] H. Chen, Tunable versatile current-mode universal filter based on plus-type DVCCs, *AEU - International Journal of Electronics and Communications*, Vol. 66, Issue 4, 2012, pp. 332–339.

[38] J. Jerabek, R. Sotner, K. Vrba, Tunable universal filter with current follower and transconductance amplifiers and study of parasitic influences, *Journal of Electrical Engineering*, Vol. 62, No. 6, 2011, pp. 317- 326.

[39] R. Sotner, J. Petrzela, J. Slezak, Current- Controlled Current-Mode Universal Biquad Employing Multi-Output Transconductors. *Radioengineering*, Vol. 18, No. 3, 2009, pp.285-294.

[40] J. Jerabek, K. Vrba, Design of Fully Differential Filters with Basic Active Elements Working in the Current Mode. *Elektrorevue – Online Journal* (http://www.elektrorevue.cz), Vol. 2010, No. 87, pp. 1-5.

[41] N. A. Shah, M. Quadri, S. Z. Iqubal, Realization of CDTA based current-mode universal filter, *Indian J. pure & applied physics*, Vol. 46, 2008, pp. 283-285.

[42] D. Biolek, V. Biolkova, CDTA-C current-mode universal 2nd-order filter, *in proc. of the 5th WSEAS Int. Conf. on APPLIED INFORMATICS and COMMUNICATIONS*, Malta, September 15-17, 2005, pp. 411-414.

[43] R. S. Tomar, S. V. Singh, D. S. Chauhan, Cascadable Low Voltage Operated Current- Mode Universal Biquad Filter, *WSEAS TRANSACTIONS on SIGNAL PROCESSING*, Vol. 10, 2014, pp. 345-353.

[44] S. V. Singh, S. Maheshwari, J. Mohan, D. S. Chauhan, Electronically tunable current-mode universal biquad filter based on the CCCCTA, In Proc. of *IEEE Int. Conf. on Advances in Recent Technologies in Comm. and Computing* (ARTCOM), 2009, pp. 424-429.

[45] A. Chaichana, M. Kumngern, W. Jaikla, Electronically Tunable Versatile Current-Mode MISO Universal Filter Including Minimum Component Count Circuits, *The 11th International Conference Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 2014, 14-17 May, Nakhon Ratchasima, Thailand, pp. 1-4.

[46] D. Biolek, V. Biolkova, Z. Kolka, J. Bajer, Single Input Multi-Output Resistorless Current-Mode Biquad, In proc. *of the European Conference on Circuit Theory and WSEAS TRANSACTIONS on CIRCUITS and SYSTEMS* L. Langhammer, J. Jerabek, J. Polak, P. Cika E-ISSN: 2224-266X 66 Volume 14, 2015 *Design ECCTD 2009*, Antalya, Turkey, 23-27 Aug. 2009, pp. 225 - 228.

[47] D. Biolek, V. Biolkova, Current-Input Current- Output 2nd-Order All-Pass Filter Employing Two ZC-CITAs, In proc. of *the 20th International Conference*

Radioelektronika (RADIOELEKTRONIKA) 2010, Brno, Czech Republic, 19-21 Apr. 2010, pp. 1-4.

[48] L. Langhammer, J. Jerabek, Fully Differential Universal Current-Mode Frequency Filters Based on Signal-Flow Graphs Method, *International Journal of Advances in Telecommunications, Electrotechnics, Signals and Systems*, Vol. 3, No. 1, 2014, pp. 1-12.

[49] J. Jerabek, K. Vrba, Comparison of the Fully- Differential and Single-Ended Solutions of the Frequency Filter with Current Followers and Adjustable Current Amplifier, In Proc. *ICN2012 The Eleventh International Conference on Networks*, Reunion, France: IARIA, 2012, pp. 50-54.

[50] J. Jerabek, J. Koton, R. Sotner, K. Vrba, Adjustable band-pass filter with current active elements: two fully-differential and singleended solutions, *Analog Integr. Circ. Sig. Process*., Vol. 74, 2013, pp.129–139.

[51] J. Koton, N. Herencsar, K. Vrba, I. Koudar, Fully differential current-mode filters using digitally adjustable current amplifier, *Elektrorevue - Online Journal* (http://www.elektrorevue.cz), No. 45, pp. 45-1– 45-4.

[52] W. Tangsrirat, D. Prasertsom, Electronically tunable low-component-count current-mode biquadratic filter using dual-output current followers, *Electr. Eng.*Vol. 90, 2007, pp. 33– 37.

[53] H. A. Alzaher, A CMOS Digitally Programmable Universal Current-Mode Filter, *IEEE Transactions on circuits and systems—II: Express briefs*, Vol. 55, No. 8, 2008, pp. 758- 762.

[54] D. Prasertsom W. Tangsrirat, CMOS Digitally Controlled Current Follower and Its Application, In proc. of the *12th International Symposium on Integrated Circuits, ISIC '09*, Singapore, Republic of Singapore, 14-16 Dec. 2009, pp. 486 - 489.

[55] Ravindra Singh Tomar Sajai Vir Singh Durg Singh Chauhan, Current Processing Current Tunable Universal Biquad Filter Employing Two CCTAs and Two Grounded Capacitors pub.in.Int.J. Circuits and Systems, 2013, 4, 443-450.

[56] Ravindra Singh Tomar Sajai Vir Singh Durg Singh Chauhan, Cascadable Low Voltage Operated Current-Mode Universal Biquad Filter proc in WSEAS TRANSACTIONS on SIGNAL PROCESSING Volume 10, 2014, E-ISSN: 2224-3488

[57] Worapong Tangsrirat, Single-input three-output electronically tunable universal current-mode filter using current follower transconductance amplifiers pub.in Int. J. Electron. Commun. (AEÜ) 65 (2011) 783– 787

[58] N A Shah F A Khaday,Multiple Input Multiple Output Log Domain Biquad Filter proc in Indian Journal of Pure and Applied physics,Volume 50,December 2012,pp.928-934

[59] Xinhua Nie Zhongming Pan, Multiple-input single-output low-input and high output impedance current-mode biquadratic filter employing five modified CFTAs and only two grounded capacitors. Pub. in Microelectronics Journal 44(2013), 802–806.

[60] Ravindra Singh Tomar Sajai Vir Singh Durg Singh Chauhan, Current Processing Current Tunable Universal Biquad Filter Employing Two CCTAs and Two Grounded Capacitors pub.in.Int.J. Circuits and Systems, 2013, 4, 443-450.

[61] Roam Sotner Josef Slezak Tomas dostal ,Tunable oscillator using two CCTA-s and only grounded passive elements pub.in Int.Conf. Environmental and Electrical Engineering, 2010, 447-450.

[62] Montree Siripruchyanun Kangwal Payakkakul Paisit Pipatthitikorn Pracharat Satthaphol, A Current-mode Square/Triangular ware Generator based on Multiple-output VDTAs pub. In Int.J. International Electrical Engineering Congress, 2016, 152 – 155.