PROGRAMMABLE AND ELECTRONICALLY TUNABLE VOLTAGE-MODE UNIVERSAL BIQUADRATIC FILTER BASED ON SIMPLE CMOS OTA

Nishtha rani[1], Rajeev kumar Ranjan[2], Ratnadeep Pal[3], Sajal K. Paul[4]
[1,2,3,4]Electronics engineering dept. Indian School of Mines, Dhanbad, (Jharkhand) PIN: -826004

***Abstract*-High-input impedance voltage-mode single input, single output (SISO) universal biquadartic filter with a new approach of programmability and electronic tunability is presented. The proposed filter is implemented by an operational transconductance amplifier (OTA), whose bias current can be externally controlled by control voltage (V_{CON}), that results in a more reliable circuit. The different types of filter functions (i.e. high pass, low pass, band pass, notch and all pass filters) can be implemented as well as its cutoff frequency and gain can be controlled by applying different control voltages (V_{CON}) to different OTAs, where a choice can be done digitally using microcontroller or microprocessor incorporating programmable compatibility to make it more user friendly. Moreover, this proposed filter enables easy cascading in voltage mode due to its high impedance input terminal. It uses grounded capacitors and requires no resistor, which is suitable for integrated circuit fabrication. Filter's performance parameters ω_0 and Q_0 can be set orthogonally by considering equal value of capacitors and transconductances g_{m1} and g_{m2}. No component matching condition is required. PSPICE result has been used to justify the performance of the circuit.**

I. INTRODUCTION

Filters are one of the most important circuits in the field of instrumentation, communication, control, neural network etc. As filter's function is to capture required frequency and curtail undesired one, it is an integral part of a signal processing circuit. With the advancement of integrated circuit (IC) design technology, there is need to shrink the circuit size along with programmable compatibility to make it more compact, more user friendly and suitable for IC design. Universal filter is a filter which can be used to implement a various filter functions depending on user needs from the same topology. High input impedance of voltage mode filters are great interest to designers because of its cascading property to make higher order filters [1, 2]. Further, the use of grounded capacitors is good for IC implementation [3].

Normally, voltage mode filters are divided into four categories. Explicitly (i) single input, single output (SISO) [4-6] (ii) single input, multiple output (SIMO) [7-10] (iii) multiple input, single output (MISO) [11-14] and (iv) multiple input, multiple output (MIMO) [15-18]. The single input, single output (SISO) is the most accepted analog voltage-mode filter because different filters can be easily implemented by simply altering the component values without changing the input terminal which is highly desirable to make it more user friendly. In last few decades, operational transconductance amplifiers (OTAs) perform very well in circuit design due to its various advantages i.e. electronic tunability of trans-conductance gain, larger bandwidth, high slew rate, low power consumption etc. Moreover, OTA does not need any resistance, as a result, it is suitable for integrated circuit implementation [19].

This paper includes two parts, one is the realization of electronically tunable operational transconductance amplifier (OTA), whose bias current is externally controlled by control voltage. Depending on the control voltage different bias current will be generated, hence transconductance of OTA can be varied. By exploiting this property, OTA can be used as a gain block with variable gain. This property will make filter electronically tunable. Next is an implementation of the proposed universal biquadratic filter uses six electronically tunable OTAs and two grounded capacitors. By varying control voltage of OTAs with the help of a microcontroller or microprocessor, filter function of a particular type can be obtained at output by giving single input only, hence it can be programmed to get a desired filter response. Moreover, this approach is providing high input impedance, which is better for cascading in voltage mode. The reported SISO filter circuits [4-6] enjoy lots of advantages, however these filters suffer from: (i) large number of active components [4, 5, 6], and (ii) programmable compatibility [4, 5, 6], which are overcome by filter presented in this paper.

II. CIRCUIT DESCRIPTION AND ANALYSIS

A. CMOS OTA Realization

The OTA is a voltage controlled current source amplifier, in which output is generated through difference of two input voltages. It has high gain, bandwidth and slew rate. Both the input and output impedances are very high. The functional block diagram is shown in Fig.1 and output current given as

$$I_o = g_m (V_p - V_n) \tag{1}$$

Where, g_m is a transconductance gain of OTA.

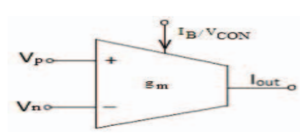

Fig.1 Block diagram of OTA

978-1-5090-2309-7/16/$31.00©2016 IEEE

CMOS OTA internal structure is shown in Fig. 2. OTA characteristic is dependent on its bias current. Here bias current of OTA is generated through saturation region of nMOS (M_5). Current voltage relationship of MOS working under saturation region is

$$I_D = \frac{1}{2}\mu C_{OX} \frac{W}{L} (V_{CON} - V_S - V_{TH})^2 \qquad (2)$$

Cascade MOS mirror is shown in Fig. 3, steered current produced by gate controlled NMOS (M_5), which is working under saturation region. This makes it to have full control on bias current by gate voltage at M_5 transistor. So, by externally providing gate voltage we could control the transconductance of OTA.

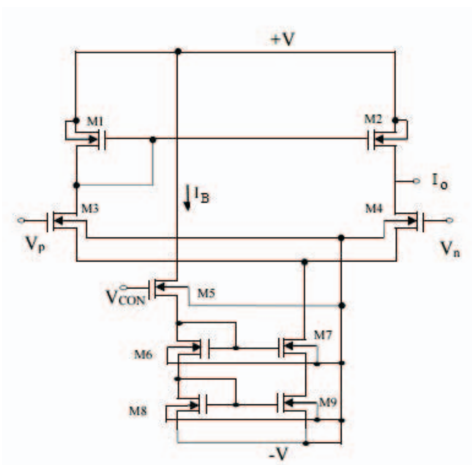

Fig. 2: Internal structure of CMOS OTA

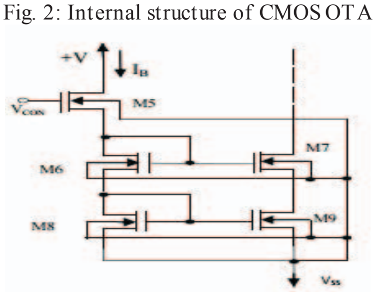

Fig. 3. Current steering circuit

$$I_D = \frac{1}{2}\mu C_{ox} \frac{W}{L} (V_{CON} - V_S - V_{TH})^2 = I_B \qquad (3)$$

All the transistors of OTA are operating in saturation region, and its transconductance (g_m) is defined as [10]

$$g_m = \sqrt{2\mu C_{ox} \left(\frac{W}{L}\right) I_B} \qquad (4)$$

Where, W and L are channel width and channel length of MOS, μ is mobility of carrier in the channel, C_{ox} is oxide capacitance, V_{TH} is threshold voltage of transistor and I_B is bias current of OTA.

B. Proposed Analog Universal Filter

The proposed SISO resistorless analog biquadratic universal filter design is implemented with six active and two grounded passive components, which is shown in Fig. 4. It is easy to fabricate as it contains only two passive grounded components. Depending upon transconductance of OTA 3, OTA 4 and OTA 5, different form of filter response can be obtained.

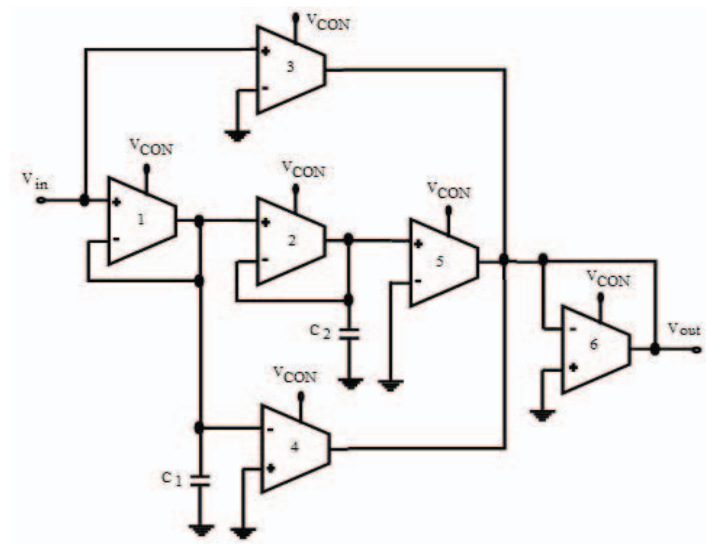

Fig. 4 Proposed universal filter

C. Transfer Function Analysis

The routine analysis of circuit shown in Fig. 4 results second order transfer function as follows

$$\frac{V_{out}}{V_{in}} = \frac{1}{g_{m6}}\left[\frac{g_{m3}C_1C_2\ s^2 + [g_{m3}(g_{m1}C_2 + g_{m2}C_1) - g_{m1}g_{m4}C_2]s + g_{m1}g_{m2}(g_{m3} + g_{m5} - g_{m4})}{[C_1C_2s^2 + s(g_{m2}C_1 + g_{m1}C_2) + g_{m1}g_{m2}]}\right] \qquad (5)$$

By considering, $C_1 = C_2 = C$ and $g_{m1} = g_{m2} = k$ then (5) reduces to

$$\frac{V_{out}}{V_{in}} = \frac{1}{g_{m6}}\left[\frac{g_{m3}C^2s^2 + kCs\,(2g_{m3} - g_{m4}) + k^2(g_{m3} + g_{m5} - g_{m4})}{(C^2s^2 + 2kCs + k^2)}\right] \qquad (6)$$

With different transconductance of OTA 3, OTA 4 and OTA 5, we obtain of the filter responses at the output terminal.

To design, low pass filter, the transconductance are taken as $g_{m3} = g_{m4} = 0$. It is obtained as

$$\frac{V_{out}}{V_{in}} = \frac{k^2 g_{m5}}{g_{m6}(C^2\ s^2 + 2kCs + k^2)} \qquad (7)$$

The high pass filter is obtained, when $g_{m3} = g_{m5}$, $g_{m4} = 2g_{m3}$.

$$\frac{V_{out}}{V_{in}} = \frac{g_{m3}C^2s^2}{g_{m6}(C^2s^2 + 2kCs + k^2)} \qquad (8)$$

When $g_{m3} = 0$, $g_{m4} = g_{m5}$, then band pass filter is obtained as

$$\frac{V_{out}}{V_{in}} = \frac{-kcsg_{m4}}{g_{m6}(C^2s^2 + 2kCs + k^2)} \quad (9)$$

When $2g_{m3} = g_{m4}$, $g_{m4} = g_{m5}$, Notch filter is obtained as,

$$\frac{V_{out}}{V_{in}} = \frac{g_{m3}(C^2s^2 + k^2)}{(C^2s^2 + 2kCs + k^2)g_{m6}} \quad (10)$$

All pass filter is obtained, when $4g_{m3} = g_{m4}$, $g_{m4} = g_{m5}$, as

$$\frac{V_{out}}{V_{in}} = \frac{g_{m3}(C^2s^2 - 2kCs + k^2)}{g_{m6}(C^2s^2 + 2kCs + k^2)} \quad (11)$$

By comparing the denominator of (5) with the standard characteristic equation as, $H(s) = s^2 + \frac{\omega_0}{Q_0}s + \omega_0^2$ we get

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad (12)$$

$$Q_0 = \frac{\sqrt{g_{m1}g_{m2}C_1C_2}}{g_{m2}C_1 + g_{m1}C_2} \quad (13)$$

As ω_0 and Q_0 are functions of transconductances (g_{m1} and g_{m2}) and capacitors (C_1 and C_2),They may be varied by control voltage (V_{CON}).

If $C_1 = C_2 = C$ and $g_{m1} = g_{m2} = k$, then

$$\omega_0 = \frac{k}{C} \quad \text{and} \quad Q_0 = \frac{1}{2} \quad (14)$$

Hence, ω_0 can be orthogonally controlled. The sensitivity of proposed circuits for various parameters is evaluated as $S_k^{\omega_0} = -S_C^{\omega_0} = 1$

D. Non-Ideal Analysis

The non-ideal effects of the OTA operating in the linear region include (i) finite input and output conductances/impedances ($G_{i,i}$, $G_{o,i}$),(ii) Frequency dependence of the transconductance $(g_{mk} = g_{mk}\ (1 - sT_k))$,where $T_k = 1/\omega_{gk}$ is the first order pole (iii) input and output parasitic capacitances ($C_{i,p,k}$, $C_{i,n,k}$, $C_{o,k}$) of the k^{th} OTA. Where, i stands for input terminal, "o" stands for output terminal, "p" stands for positive terminal and "n" stands for negative terminal of OTA. Since input impedance of CMOS based OTA is very large, so it can be ignored, input and output conductance are much smaller than that of the transconductance i.e. $G_{i,k}$, $G_{o,k} << g_{mk}$. The external capacitances C_1 and C_2 can be chosen much greater than that of parasitic capacitance of the OTA i.e. $C_{i,p,k}$, $C_{i,n,k}$, $C_{o,k}$ << C_1 ,C_2. Considering non-idealities of OTA [20], the circuit transfer function is approximately given by

$$\frac{V_{out}}{V_{in}} \approx \frac{\beta_4 s^4 + \beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}{\alpha_4 s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0} \quad (15)$$

Where

$\beta_4 = -C_0'C_1'C_2'T_3g_{m3}$

$\beta_3 = C_0'C_1'C_2'g_{m3} + C_2'C_0'g_{m1}g_{m2}(T_1 + T_2)$
$-C_0'g_{m3}[T_3(C_1'g_{m2} + C_2'g_{m1}) + C_2'g_{m1}T_1 + C_1'g_{m2}T_2]$

$\beta_2 = g_{m3}C_2'(G_0C_1' + g_{m1}C_0') + C_0'g_{m2}(g_{m3}C_1' - g_{m1}C_2') +$
$G_0g_{m3}[C_1'(g_{m2}T_3 + T_2g_{m2}) - C_2'(g_{m1}T_3 + T_1g_{m1})] +$
$C_0'g_{m2}g_{m1}[g_{m4}(T_1 + T_2 + T_4) - g_{m3}(T_1 + T_3 + T_2) - g_{m5}(T_1 + T_2 + T_5)]$

$\beta_1 = G_0g_{m3}(C_2'g_{m1} + C_1'g_{m2}) + C_0'g_{m1}g_{m2}(g_{m3} - g_{m4} + g_{m5})$
$+ g_{m1}g_{m4}G_0C_2' - g_{m1}g_{m2}G_0[g_{m3}(T_1 + T_2 + T_3) -$
$g_{m4}(T_1 + T_2 + T_4) + g_{m5}(T_1 + T_2 + T_5)]$

$\beta_0 = G_0g_{m1}g_{m2}(g_{m3} - g_{m4} + g_{m5})$

$\alpha_4 = -C_1'C_2'g_{m6}T_6C_0'$

$\alpha_3 = C_0'g_{m6}[C_1'C_2' - C_1'T_2g_{m2} + C_2'T_1g_{m1} - T_6(C_2'g_{m1} + g_{m2}C_1')]$

$\alpha_2 = (1 + g_{m6}G_0)(C_1'C_2' - C_1'T_2g_{m2} - C_2'T_1g_{m1})$
$-T_6g_{m6}[C_0'g_{m1}g_{m2} + G_0(g_{m1}C_2' + g_{m2}C_1')]$
$+ C_0'g_{m6}[g_{m1}(C_2' - T_2g_{m2}) + g_{m2}(C_1' - T_1g_{m1})]$

$\alpha_1 = (C_0'g_{m6} - T_6g_{m6}G_0)g_{m1}g_{m2} + (1 + g_{m6}G_0)[g_{m1}(C_2' - T_2g_{m2}) +$
$g_{m2}(C_1' - T_1g_{m1})]$

$\alpha_0 = g_{m1}g_{m2}(1 + G_0g_{m6})$

$C_1' = C_1 + C_{i,n,1} + C_{i,p,2} + C_{o,1} + C_{i,n,4}$

$C_2' = C_2 + C_{i,n,2} + C_{o,2} + C_{i,p,5}$

$G_1 = G_{o,1}$

$G_2 = G_{o,2}$

$G_o = G_{o,3} + G_{o,5} + G_{o,4} + G_{o,6}$

$C_o' = C_{o,3} + C_{o,5} + C_{o,4} + C_{o,6} + C_{i,n,6}$

From (15), it can be seen that filter characteristics deviate from the ideal values because of parasitic capacitances and frequency dependence of the transconductance. On comparing (15) with the ideal expression (5), it can be seen that both numerator and denominator are increased in order. But the non-ideal effects can be made negligible by making the frequency dependence of transconductance to be as small as possible.

III. Simulation Results and Discussion

To confirm the theory, the proposed OTA internal structure shown in Fig. 2 has been simulated with PSPICE using 0.5 µm CMOS process parameter. The circuit was biased by voltage of ±5 V. The aspect ratio of PMOS and NMOS transistors are listed in Table I.

TABLE I
ASPECT RATIO OF VARIOUS TRANSISTORS

Transistor	W (µm)	L (µm)
M1, M2	40	2
M3, M4	2	2
M5, M6, M7, M8, M9	5	3

DC sweep analysis of output current against input differential voltage is shown in Fig. 5, where (Vn) port is grounded and (Vp) is varied from -1V to 1V range in which the transconductance remains constant, and output current is plotted. From the Fig. 5, it is quite clear that linear range is suitable for the proper filter design. DC sweep analysis of control voltage (V_{CON}) and OTA transconductance is shown in Fig. 6. Frequency response of this CMOS OTA is shown in Fig. 7. which tells that its 3dB cut off frequency f_{3dB} = 113 MHz upto which it can work properly.

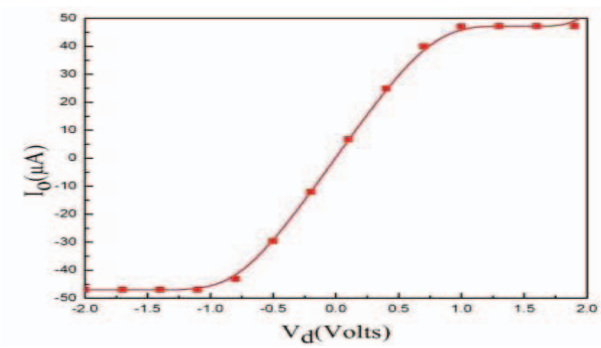

Fig.5 Input differential voltage, when V_{CON} = 0

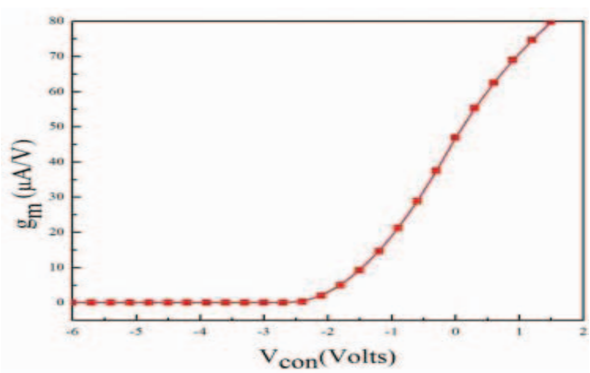

Fig.6 Transconductance versus control voltage (V_{CON})

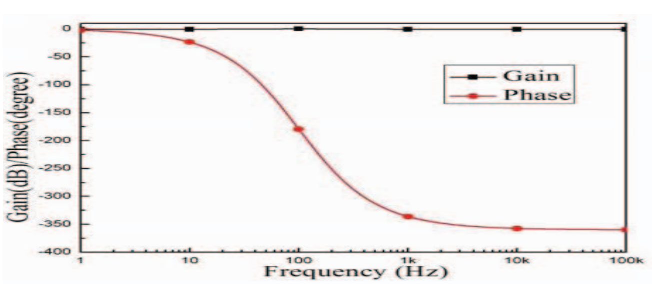

Fig. 9 Response of phase and gain of all pass filter

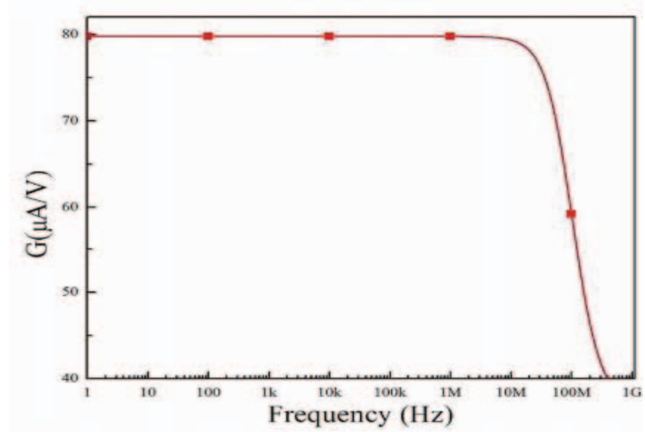

Fig. 7. Frequency response of CMOS OTA at V_{CON} = 1V

For design of different filter's response, we require different OTA transconductances, which is availed by different discrete voltage level of V_{CON}. Table II shows some discrete voltage level of control voltage (V_{CON}) and corresponding transconductance of OTA.

According to value of OTA transconductance shown in Fig. 6, it is quite clear that at -0.812 V, transconductance is half of V_{CON} at 0 V and at -1.364 V its one fourth and at -5 V its zero. Suitably substituting these values along with capacitor C_1 = C_2 = 10 pF in (5), we obtain different filter functions responses. For all kinds of filter responses, the value of control voltage (V_{CON}) for different OTAs is given in the Table III. The theoretical and simulated response of all types of filter response is shown in Fig. 8. Moreover, all pass filter is shown in Fig. 9 with gain and phase.

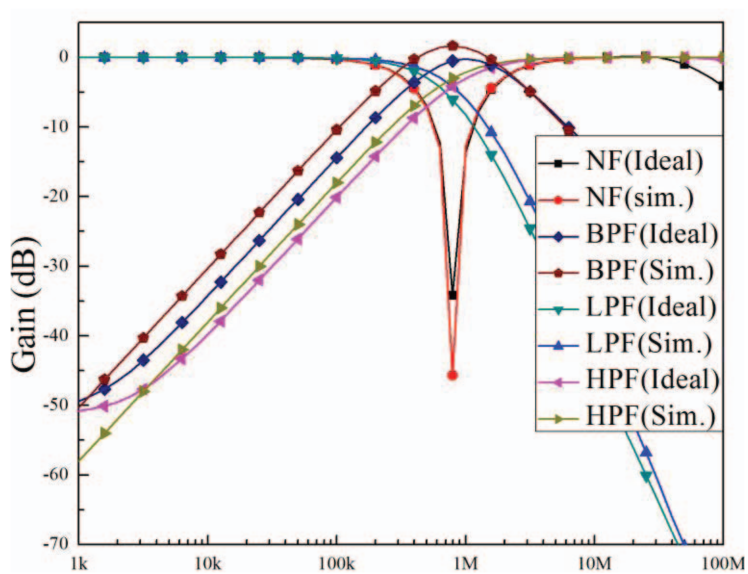

Fig. 8 Theoretical and simulated response of universal filter.

TABLE II

[USED DISCRETE VOLTAGE LEVEL OF VCON & TRANSCONDUCTANCE OF OTA]

V_{CON} (Volt)	Transconductance (µA/V)
0	46.89
-0.812	23.433
-1.364	11.702
-5	0

TABLE III

[VALUE OF V_{CON} (V) FOR DIFFERENT FILTERS]

Response	OTA1	OTA2	OTA3	OTA4	OTA5
LP	0	0	-5	-5	non-zero
HP	0	0	non-zero	non-zero	-5
BP	0	0	-5	non-zero	non-zero
NOTCH	0	0	-0.812	0	0
ALL	0	0	-1.364	0	0

IV. CONCLUSION

A CMOS OTA based programmable and electronically tunable single input single output (SISO) resistorless analog universal filter has been proposed theoretically and verified by PSPICE simulation using CMOS 0.5 µm technology. All simulation results shown here agreed well with the theoretical expectation. The proposed universal filter is well suited for IC fabrication, because of having only two grounded passive components and no resistor. In contrast with existing SISO universal filter the presented filter is programmable with a microprocessor or microcontroller and electronically tunable which makes this universal filter more versatile analog device and more users friendly.

REFERENCES

[1] Fabre. A, Dayoub.F, Duruisseau. L, and Kamoun.M, "High input Impedance insensitive second-order Filters implemented from Current Conveyors," *IEEE Transactions on circuits and Systems-I*, 41, pp. 918-921, 1994.

[2] Naqshbendi S.F.H. and Sharma R. S, "High input impedance current conveyor Filters*," International Journal of Electronics*, 55, pp. 499-500, 1983.

[3] Bhusan.M., and Newcomb.R.W, "Grounding of Capacitors in Integrated Circuits," *Electronics Letters,3,* pp 148-149, 1967.

[4] Nowrocki. R and Klein.U, "New OTA-Capacitor realization of a universal biquad,"*Electronics letter (22)*, pp 50-51, 1986.

[5] Sun ,Y., Fidler J.K., "Novel OTA-C realization of biquadratic transfer functions", *International Journal of Electronics*,75, pp 333-340, 1993.

[6] Acar,C., Anday, F.,Kuntman, H., "On the realization of OTA-C filters", *International Journal of Circuit Theory and Applications*,21, pp 331-4, 1993.

[7] Chang. C. M, " New Multifunction OTA-C Biquads," *IEEE Transactions on Circuits and Systems-II*, 46, pp 820-824, 1999.

[8] Mohan.P.V.A, "Generation of OTA-C filter structures from active RC filter Structures," *IEEE Transactions on circuits and Systems*,37, pp. 656-660, 1990.

[9] Horng J.W, "Voltage–mode universal biquadratic filter with one input and five outputs using OTAs,"*International Journal of Electronics*, 89, pp 729-737, 2002.

[10] Chang.C.M, "Analytical Synthesis of the digitally programmable voltage-mode OTA-C universal biquad," *IEEE Transactions on circuits and Systems-II*,53, pp.607-611, 2006.

[11] Abueima'atti. M.T,and Bentrcia. A., "A novel mixed mode OTA-C universal filter," *International Journal of Electronics*, 92, pp 375-383, 2005.

[12] Tsukutani. T, Sumi. Y, Kiugasa. Y, Higashimura. M and Fukui. Y, "Versatile voltage- mode active-only biquad circuits with loss-less and lossy integrators,"*International Journal of Electronics*, 91, pp 525-536, 2004.

[13] Khan I.A, Ahmed M.T, Minhaj,N., " A simple realization for OTA-C universal biquadratic filter," *International Journal of Electronics*,72, pp 419-429, 1992.

[14] Kumngern. M, Knobnob. B and Dejhan. K, " Electronically tunable high-input impedance voltage-mode universal biquadratic filter based on simple CMOS OTAs," *Int. J. Electron. Commun. (AEU¨) 64*, pp 934-939, 2010.

[15] Wu, J., Xie, C.Y, "New multifunction active filter using OTAs", *International Journal of Electronics*,74, pp 235-239, 1993.

[16] Wu. J and El-Masry. I. E, "Universal Voltage-mode and Current-mode OTAs Based Biquads,"*International Journal of Electronics*, 85, 553-560, 1998.

[17] Horng J.W, "Voltage–mode universal biquadratic filter using two OTAs,",*Active and Passive Electronics Components,*27, pp 85-89, 2004.

[18] Horng J.W, "Voltage –mode universal biquadratic filter using two OTAs and two capacitors," *IEICE Trans Fundam,* 86A(2), pp 411-2,2003.

[19] Sanchez-Sinencio. E, Geiger. R. L and Nevarez-Lozano. H, "Generation of continous-time two integrator loop OTA filter structure," *IEEE Transactions on circuits and Systems:* CAS-35, pp 936-949, 1988.

[20] Sun.Y, Filder. J. K, "Synthesis and performance analysis of universal minimum component integrator-based IFLF OTA-grounded capacitor filter,"*IEE Proc.-Circuits Devices Syst*., Vol. 143, No. 2, 1996.