New Universal Current-mode Biquad Using Only Three ZC-CFTAs

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Abstract. *The objective of this paper is to present a new universal current-mode biquad capable of providing all the five basic filter functions, namely, low pass (LP), band pass (BP), high pass (HP), band reject (BR) and all pass (AP) from the same configuration using only three Z - copy current follower transconductance amplifiers (ZC-CFTA) along with the provision of independent electronic tunability of the filter parameters ω_0 and Q_0 (or bandwidth) through two separate DC bias currents while employing both grounded capacitors as desirable for integrated circuit implementation. The workability of the proposed structure is verified by PSPICE simulations based on CMOS implementation of the ZC-CFTA.*

Keywords

Analog circuits, current mode circuits, Z-copy current follower transconductance amplifier (ZC-CFTA), universal filters, CMOS circuits.

1. Introduction

Recently, a new active element known as current follower transconductance amplifier (CFTA) has been introduced for analog circuit design in [1] and [2] and its various applications, such as those in realizing universal biquads and oscillators, have been presented in [3-6] and [10] . The universal biquad circuits of [3]-[5], although exhibit the important advantages of (i) realisability of all the five generic filter functions without requiring any component-matching conditions, (ii) independent electronic tunability of the filter parameters ω_0 and Q_0, and (iii) employment of both grounded capacitors as preferred for IC implementation, but suffer from the drawback of employing four CFTAs (which is more than the minimum number of CFTAs actually necessary i.e. three). On the other hand, the circuit proposed in [6] accomplishes the advantages (i)-(iii) above with only three CFTAs but suffers from the drawbacks of (a) realizing neither a voltage mode nor a current mode but instead a transadmittance mode biquad (with voltage input and current outputs) and (b) needing an additional resistor also (apart from two grounded capacitors).

The object of this paper is to present a new ZC-CFTA-based universal biquad which offers all the three advantages (i)-(iii) quoted above like the circuits of [3]-[6], but by contrast, offers following advantages: (i) unlike the circuits of [3]-[5], which need four CFTAs, the new circuit needs only three CFTAs; (ii) unlike the circuit of [6] which needs an additional resistor, the new circuit does not require any additional resistor; (iii) unlike the circuit of [6], which is neither a VM nor a CM, the new circuit realizes all the five standard filter responses in proper current mode (CM). The proposed new circuit provides an additional advantage of the tuning of BW without disturbing angular frequency ω_0 in comparison to the biquad of [7] which although uses only two Z-copy current inverter transconductance amplifiers (ZC-CITAs) (which are almost the same as ZC-CFTAs) but does not offer this advantage. The workability of the proposed structure has been confirmed by PSPICE simulations.

2. Z-copy Current Follower Transconductance Amplifier (ZC-CFTA)

The symbolic representation and the equivalent circuit of the ZC-CFTA are shown in Fig. 1.

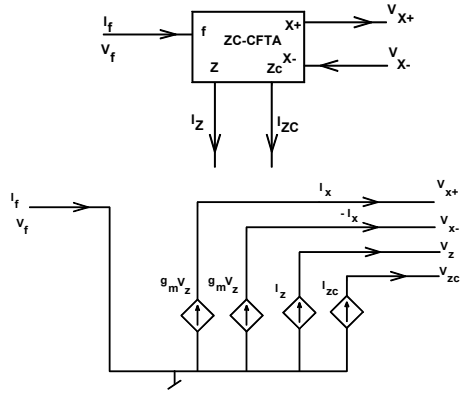

Fig. 1. ZC-CFTA: symbolic representation and equivalent circuit.

The ZC-CFTA is characterized by the following set of equations

$$V_f = 0,\ \ i_z = i_{zc} = i_f,\ \ i_{x+} = g_m V_z,\ \ i_{x-} = -g_m V_z . \quad (1)$$

According to the above equations and equivalent circuit of Fig. 1, the input current i_f is transferred by the current follower to z terminal and the voltage drop at the terminal z is transformed into currents i_{x+} and i_{x-} at the terminals x+ and x- respectively using transconductance g_m, which is electronically-controllable by an external bias current. The copy of z terminal current is conveyed to zc terminal. An exemplary CMOS implementation of the ZC-CFTA is shown in Fig. 2, which has been obtained by an appropriate modification of the structure published earlier in [4]. The transconductance g_m of the ZC-CFTA is given by

$$g_m = \sqrt{I_{set}\mu_0 C_{ox}(W/L)} \quad (2)$$

where I_{set} controls the transconductance g_m, μ_0 is free electron mobility of channel, C_{ox} is the gate oxide capacitance per unit area as W/L is the aspect ratios of the identical MOSFETs M_{13} and M_{14} forming the differential pair.

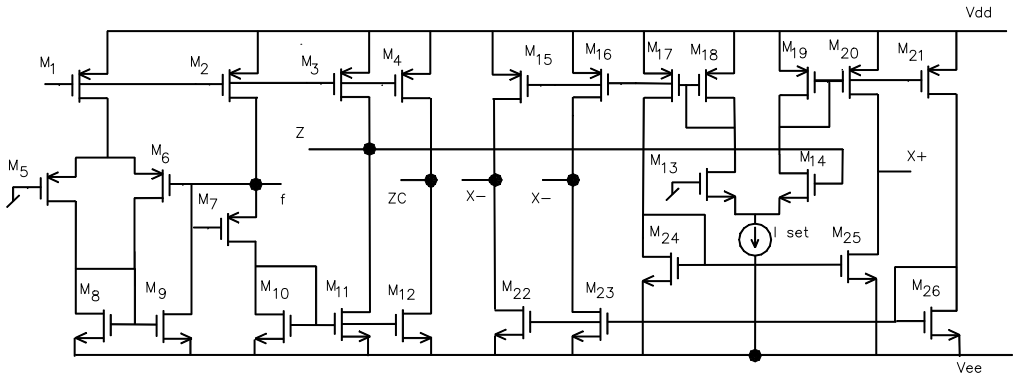

Fig. 2. An exemplary CMOS implementation of the ZC-CFTA.

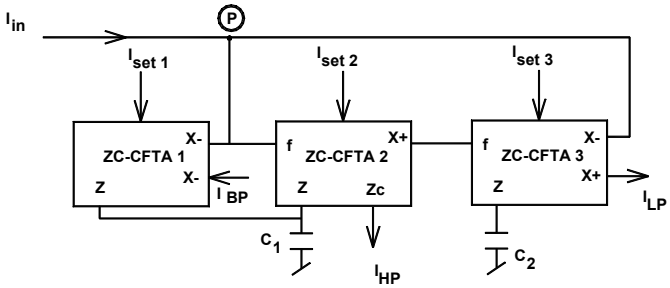

Fig. 3. New current mode universal biquad configuration using ZC-CFTAs.

3. Proposed Universal Biquad Employing only Three ZC-CFTAs

The proposed circuit is shown in Fig. 3. An analysis of the proposed circuit of Fig. 3 reveals the following current transfer functions

$$\frac{I_{BP}}{I_{in}} = \frac{-s\left(\frac{g_{m1}}{C_1}\right)}{D}, \quad (3)$$

$$\frac{I_{LP}}{I_{in}} = \frac{\left(\frac{g_{m2}g_{m3}}{C_1C_2}\right)}{D}, \quad (4)$$

$$\frac{I_{HP}}{I_{in}} = \frac{s^2}{D} . \quad (5)$$

Adding the output currents I_{LP} and I_{HP}, one obtains $I_{BR} = I_{LP} + I_{HP}$ which is given by

$$\frac{I_{BR}}{I_{in}} = \frac{s^2 + \left(\frac{g_{m2}g_{m3}}{C_1C_2}\right)}{D} . \quad (6)$$

Lastly, adding I_{LP}, I_{BP} and I_{HP} to get $I_{AP} = I_{LP} + I_{HP} + I_{BP}$, one obtains

$$\frac{I_{AP}}{I_{in}} = \frac{s^2 - s\left(\frac{g_{m1}}{C_1}\right) + \left(\frac{g_{m2}g_{m3}}{C_1C_2}\right)}{D} \quad (7)$$

where D is given by

$$D = s^2 + s\left(\frac{g_{m1}}{C_1}\right) + \frac{g_{m2}g_{m3}}{C_1C_2} . \quad (8)$$

It is, thus, seen that the proposed circuit is capable of realizing all the five basic functions, without requiring any component-matching or realization conditions.

From (3)-(8), the various filter parameters are given by

$$\omega_0 = \sqrt{\frac{g_{m2}g_{m3}}{C_1C_2}}\ , \tag{9}$$

$$BW = \left(\frac{g_{m1}}{C_1}\right),\ Q_0 = \frac{1}{g_{m1}}\sqrt{\frac{C_1g_{m2}g_{m3}}{C_2}} \tag{10}$$

whereas H_0 is unity in all the cases.

It is clear from (9) and (10) that ω_0 can be tuned independently of BW in case of band pass and notch filter, former by g_{m2} and /or g_{m3} and the later by g_{m1}, while keeping the gain constant.

In order to attain all the five filter outputs simultaneously, one requires ZC-CFTA1 with two more outputs of X- type, ZC-CFTA2 with two more ZC outputs and ZC-CFTA3 with two more X+ type outputs.

It is, thus, seen that the proposed circuit employs one less active building block (ABB) in comparison to the universal biquads published earlier in [3]-[6] and yet exhibits all the properties of the earlier circuits, in that, it realizes all the five basic filter functions with electronic tunability of two parameters[1] namely, ω_0 and Q_0 (or bandwidth), offers ideally zero input impedance and explicit current outputs at high impedance nodes in all cases while employing both grounded capacitors as preferred for IC implementation.

4. Sensitivity Analysis

The effect of changes in active/passive element values on the various filter parameters is determined by evaluating sensitivity coefficients which are found to be as follows

$$S_{g_{m2}}^{\omega_0} = S_{g_{m3}}^{\omega_0} = -S_{C_2}^{\omega_0} = -S_{C_1}^{\omega_0} = \frac{1}{2}\ , \tag{11}$$

$$S_{g_{m1}}^{Bw} = -S_{C_1}^{Bw} = 1\ , \tag{12}$$

$$S_{g_{m1}}^{Q_0} = -1\ , \tag{13}$$

$$S_{g_{m3}}^{Q_0} = S_{g_{m2}}^{Q_0} = -S_{C_2}^{Q_0} = S_{C_1}^{Q_0} = \frac{1}{2}\ . \tag{14}$$

From (11)-(14) it is clear that all the sensitivities of the various parameters of the filters realized from the proposed configuration are very low.

5. Effect of Main Parasitic Impedances and Non- idealities

For more accurate analysis, the effects of main parasitic impedances and non idealities are to be taken into account. The model for ZC-CFTA including various parasitics is shown in Fig. 5. In case of non-ideal ZC-CFTA, relationships of current and voltages given in equation (1) can be rewritten as

$$V_f = 0,\ i_z = i_{zc} = \alpha i_f,\ i_{x+} = \beta g_m V_z,\ i_{x-} = -\beta g_m V_z\ . \tag{15}$$

where $\alpha = 1 - \varepsilon_i$ and ε_i ($|\varepsilon_i| << 1$) is the current tracking error from f to Z and ZC terminals. The transconductance inaccuracy factor from Z to X+/- terminal is denoted by β.

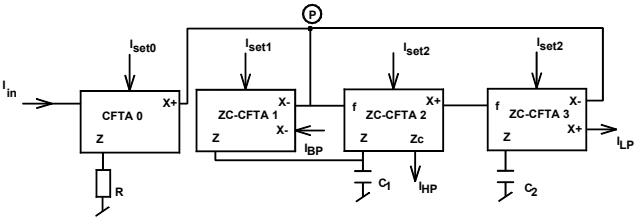

Fig. 4. Modified structure to obtain independent control of gain also.

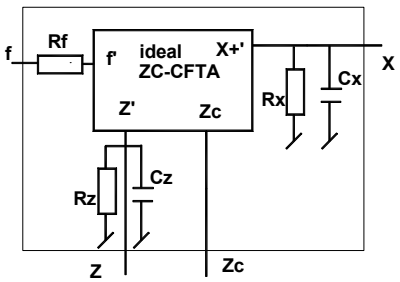

Fig. 5. Model of ZC-CFTA including parasitic elements.

From Fig. 5 it is clear that the parasitic resistance R_x and the parasitic capacitance C_x appear between the high impedance X+/- terminal and ground. To eliminate the effect of these parasitic impedances in the proposed circuit of Fig. 3, ZC-CFTA2 and ZC-CFTA3 should be designed to have a very low input parasitic resistance R_f. Ideally, the value of R_f is zero and terminal f is virtually grounded. Since these parasitic impedances are connected between true ground and virtual ground, these are, therefore almost ineffective.

The parasitic impedances R_z and C_z appear between high impedance Z terminal and ground as shown in Fig. 5.

[1] The independent control of gain may also be achievable if the circuit is modified as shown in Fig. 4 by adding one more CFTA along with an additional resistor R connected from its Z terminal to ground with input I_{in} applied at terminal f of this additional CFTA and its output x+ connected at node P of the circuit, with I_{set0} being the external DC bias current for this CFTA. In this case, the grounded resistor R can be realized by a simple two-MOSFET-resistor [8] to obtain a version suitable for CMOS implementation. With this modification, the gain factor H_0 of all the realized filters can also be independently tuned by this additional bias current I_{set0}. It is worth pointing out that for voltage mode circuits, an interesting method of achieving gain control has been outlined in [9].

The effect of above mentioned parasitic impedances consists in adding the R_z parasitic resistance at terminal Z and increasing the working capacitances C_1 and C_2 to C_1' and C_2' respectively by absorbing the parasitics as addition to these external capacitances. Non ideality of current gain parameter α, transconductance inaccuracy factor β, parasitic resistances and capacitances at terminal Z, modify the current transfer function in equation (3) to

$$\frac{I_{BP}}{I_{in}} = \frac{-S\left(\frac{\alpha_2\beta_1 g_{m1}}{C_1'}\right) - \frac{\alpha_2\beta_1 g_{m1}}{C_1'C_2'R_{Z3}}}{S^2 + S\left(\frac{1}{C_2'R_{Z3}} + \frac{1}{C_1'R_{Z2}'} + \frac{\alpha_2\beta_1 g_{m1}}{C_1'}\right) + \frac{g_{m3}g_{m2}}{C_1'C_2'}\left(\frac{1}{R_{Z2}'R_{Z3}g_{m3}g_{m2}} + \frac{\alpha_2\beta_1 g_{m1}}{g_{m3}g_{m2}R_{Z3}} + \beta_2\beta_3\alpha_3\alpha_2\right)} \tag{16}$$

where

$$C_1' = C_1 + C_{z1} + C_{z2} \ , \tag{17}$$

$$C_2' = C_2 + C_{z3} \ , \tag{18}$$

$$R_{z2}' = R_{z2} \,||\, R_{z1} \tag{19}$$

and R_z and C_z are the parasitic resistance and capacitance appearing at terminal Z of respective number of ZC-CFTA. Natural frequency, bandwidth and gain for the circuit shown in Fig.3 are now modified to

$$\omega_0' = \sqrt{\frac{g_{m2}g_{m3}}{C_1'C_2'}\left(\beta_2\beta_3\alpha_3\alpha_2 + \frac{1}{g_{m2}g_{m3}R_{z2}'R_{z3}} + \frac{\alpha_2\beta_1 g_{m1}}{g_{m3}g_{m2}R_{z3}}\right)} \tag{20}$$

$$BW' = \frac{g_{m1}}{C_1'}\left(\alpha_2\beta_1 + \frac{C_1'}{C_2'R_{z3}g_{m1}} + \frac{1}{R_{z2}'g_{m1}'}\right) \tag{21}$$

$$H_0' = \frac{1}{1 + \frac{1}{\alpha_2\beta_2 g_{m1}}\left(\frac{C_1'}{C_2'R_{Z2}'} + \frac{1}{R_{Z3}}\right)} \tag{22}$$

Since gain H_0 (ideally unity) gets modified as H_0' and turns out to be dependent on g_{m1}, from the expression for H_0', it is found that nonideally, the gain H_0' increases from -1.52 dB to -1.02 dB and then to 0.82 dB when I_{set1} is varied from 20 µA to 60 µA and then to 180 µA. This explains the different values of the gain as observable in Fig. 7. The appearance of parasitic resistance R_{z3} changes the type of impedance at Z terminal of ZC-CFTA for the circuit of Fig. 3, which should be purely capacitive in character. The possible solution to this problem is to make the operating frequency $\omega_0 > 1/(R_{z3}C_2)$.

6. SPICE Simulation Results

The proposed biquad has been simulated in PSPICE using CMOS ZC-CFTA of Fig. 2 with component values: $C_1 = C_2 = 16$ pF and DC power supply voltages taken as $V_{cc} = 1.5$ V, $V_{ee} = -1.5$ V and $V_1 = 0.5$ V. The dimensions of the MOSFETs were taken as shown in Tab. 1. The simulation was carried out using TSMC 0.35µm CMOS technology parameters shown in Tab.2.

The tunability of f_0 for band pass filter has been verified by the circuit of Fig. 3 designed for values of f_0 as 1.157 MHz, 1.735 MHz, 2.268 MHz, by varying g_{m1}, g_{m2} and g_{m3} simultaneously with the values of bias currents I_0 (i.e $I_0 = I_{set1} = I_{set2} = I_{set3}$) taken as 20 µA, 60 µA and 180 µA respectively, at constant $Q = 1$ (Fig. 6). The bandwidth values 1.348 MHz, 1.915 MHz, 2.45 MHz, were obtained by varying g_{m1} through the bias currents I_{set1} taken as 20 µA, 60 µA, and 180 µA respectively and $I_{set2} = I_{set3} = 180$ µA for maintaining a constant center frequency of 2.286 MHz (see Fig. 7). The circuit is designed to obtain LP, BR, BP, HP and AP responses with $f_0 = 1.1$ MHz and $Q = 1$ (simulation results for the same are shown in Fig. 8 and Fig. 9.

Transistor type	Transistor name	W(µm)	L(µm)
PMOS	M_5, M_6	1.4	0.35
PMOS	M_1- M_4	2.8	0.35
PMOS	M_7	2.71	0.35
PMOS	M_{15}- M_{21},	4	1
NMOS	M_8- M_{12}	0.7	0.35
NMOS	M_{13} , M_{14}, M_{22}-M_{26}	4	1

Tab. 1. Dimensions of CMOS transistors.

NMOS: Level= 3 T_{ox}= 7.9E-9 NSUB = 1E17 GAMMA = 0.5827871 PHI = 0.7, VTO = 0.5445549, DELTA = 0, U0 = 436.256147 ETA = 0 THETA = 0.1749684 KP = 2.055786E-4 VMAX = 8.309444E4 KAPPA = 0.2574081 RSH = 0.0559398 NFS = 1E12 TPG = 1 XJ = 3E-7 LD = 3.162278E-11 WD = 7.046724E-8 CGDO = 2.82E-10 CGSO = 2.82E-10 CGBO = 1E-10 CJ = 1E-3 PB = 0.9758533 MJ = 0.3448504 CJSW= 3.777852E-10 MJSW = 0.3508721
PMOS: Level = 3 T_{ox}=7.9E-9 NSUB = 1E17 GAMMA = 0.4083894 PHI = 0.7 VTO = -0.7140674 DELTA = 0 U0= 212.2319801 ETA = 9.999762E-4 THETA = 0.2020774 KP= 6.733755E-5 VMAX = 1.181551E5 KAPPA = 1.5 RSH = 30.0712458 NFS = 1E12 TPG = -1 XJ = 2E-7 LD = 5.000001E-13 WD = 1.249872E-7 CGDO = 3.09E-10 CGSO = 3.09E-10 CGBO = 1E-10 CJ = 1.419508E-3 PB = 0.8152753 MJ = 0.5 CJSW = 4.813504E-10 MJSW = 0.5

Tab. 2. CMOS process parameters.

In addition to the above, transient response of the band pass filter is shown in Fig. 10, with a 1.157 MHz sinusoidal input current signal having 15 µA peak value applied at the input of the filter. Total harmonic distortion (THD) analysis has been carried out on BP filter at $f_0 = 1.157$ MHz at various sinusoidal peak input currents and results for the same are shown in Fig. 13.

Simulated DC transfer characteristics are shown in Fig. 14 where it is shown that linear range of ZC-CFTA is from -25 µA to 22.5 µA. The dynamic range is 1 nA to 35 µA and THD percentage would be low till input current

does not exceed ± 22.5 μA (at $f_0 = 1.1$ MHz). The simulation results of the proposed circuit shown in Fig.6 – 14, thus, are seen to confirm the validity of the theoretical results.

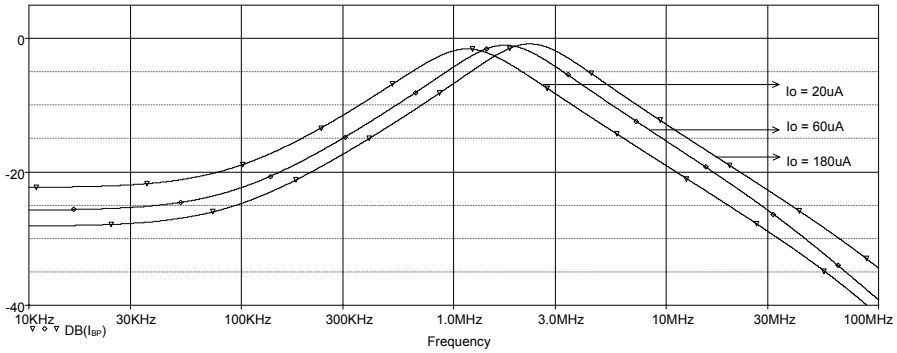

Fig. 6. Simulated result of BP filter with different f0 (keeping $Q = 1$).

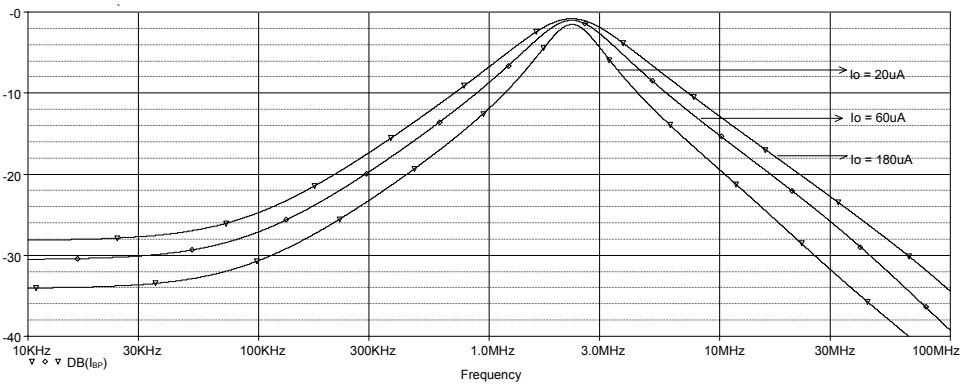

Fig. 7. Simulated result of BP filter showing variation in BW with change in g_{m1}.

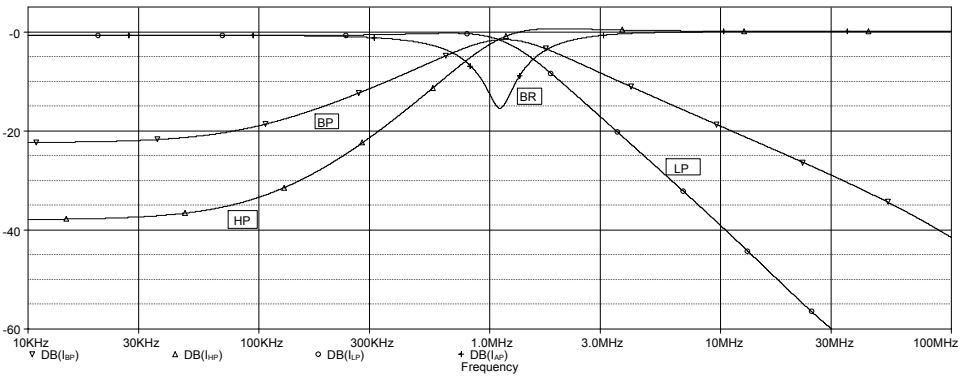

Fig. 8. Simulated frequency response of BP, LP, HP and BR filter.

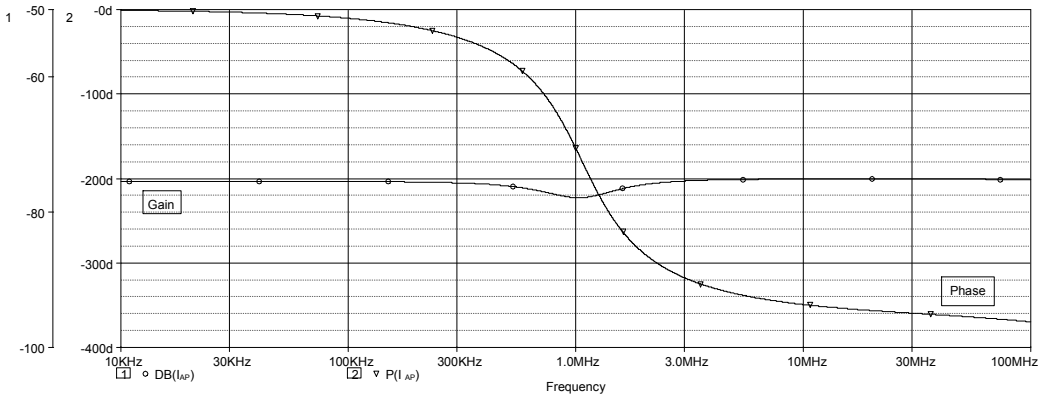

Fig. 9. Simulated gain and phase response of AP filter.

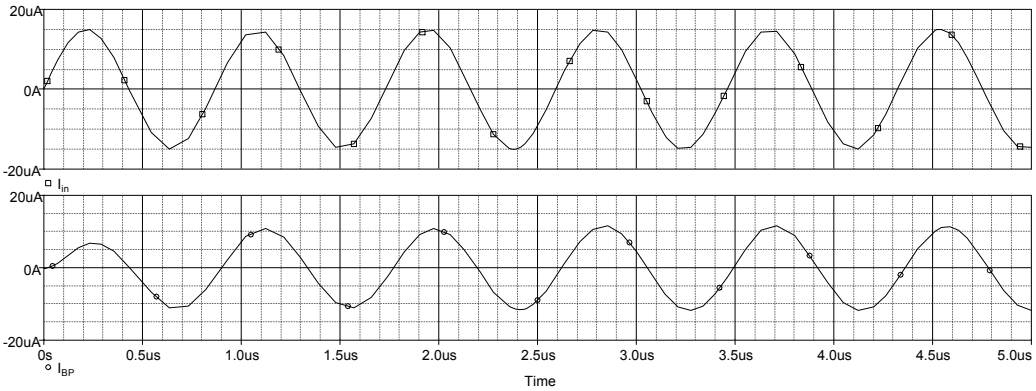

Fig. 10. Transient response of BP filter at f_0 = 1.157 MHz.

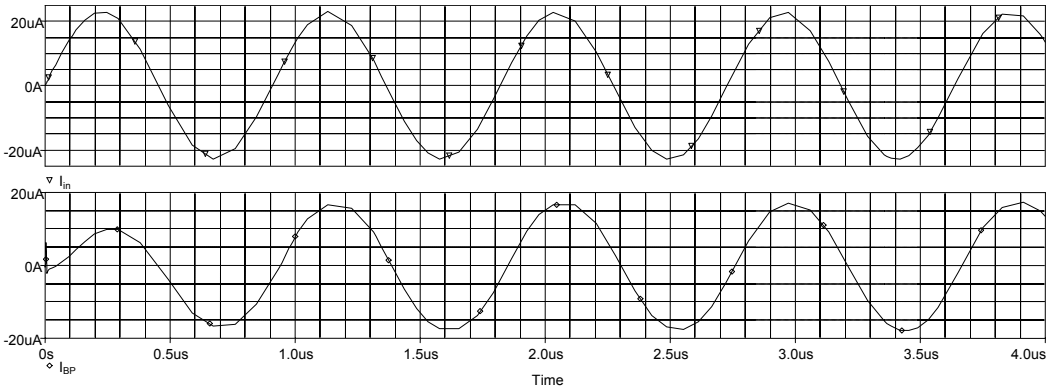

Fig.11. Large signal behavior of the bandpass filter (at f_0 =1.1 MHz with peak input of 23 μA).

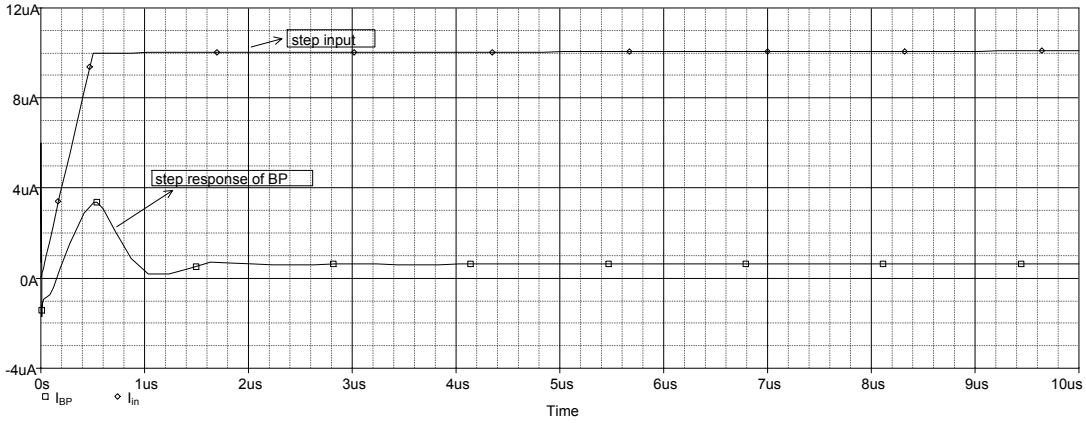

Fig.12. Step response of the BP filter.

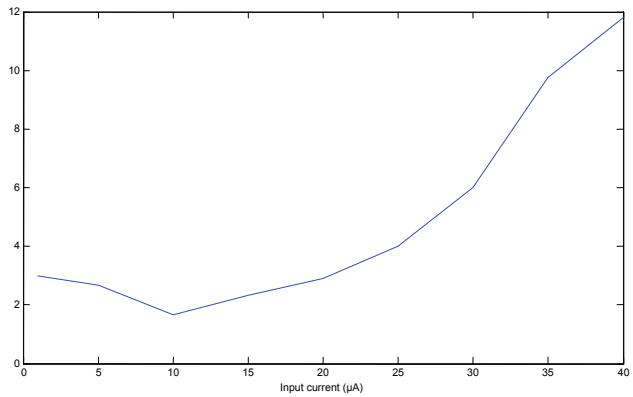

Fig.13. THD variations of the output waveform of the BP filter.

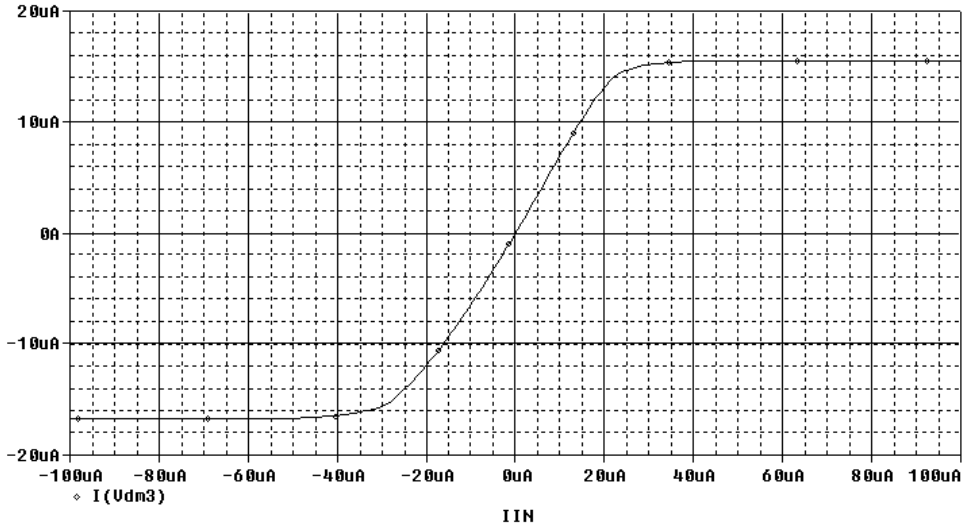

Fig.14. Simulated DC transfer Characteristics of ZC-CFTA.

7. Concluding Remarks

A new CFTA-based universal biquad has been presented which offers all the advantages of its predecessors of [3]-[6] namely, (i) realisability of all the five generic filter functions without requiring any component-matching conditions; (ii) independent electronic tunability of the filter parameters ω_0 and BW; and (iii) employment of both grounded capacitors as preferred for IC implementation. When compared with the four-CFTA circuits of [3]-[5], the new circuit has the advantage of requiring only three CFTAs. On the other hand, when compared to three-CFTA biquad of [6], the new circuit has the advantage of (i) not requiring any additional resistor as in [6], and (ii) providing a true CM operation unlike the transadmittance operation as in the circuit of [6]. The workability of the proposed structure has been confirmed by PSPICE simulation results.

The paper has, thus added a new universal biquad, having advantageous features as shown above, to the existing repertoire [3]-[6] of CFTA-based analog circuits.

Lastly, it may be mentioned that for realizing electronically controllable functions use of OTAs is well established, the use of CCCIIs is rigorously being investigated recently but by contrast, CDTAs as well as CFTAs are relatively newer building blocks from a wide variety of possible new building blocks, see [1]. Consequently, very few publications have appeared on CFTAs and its full potential is still to be exploited. In view of this, we believe that newer applications of CFTAs deserve to be investigated further.

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