Single-Input Five-Output Electronically Tunable Current-Mode Biquad Consisting of Only ZC-CFTAs and Grounded Capacitors

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Abstract. *This paper presents an electronically tunable current-mode biquadratic filter constructing with four Z-copy current follower transconductance amplifiers (ZC-CFTAs) and only two grounded capacitors. The presented filter can realize all the five standard biquadratic functions simultaneously without requiring any component matching conditions and connecting any relevant output currents. The circuit has one low-impedance input and five high-impedance outputs, resulting in easy cascadability in current-mode. Also, the developed circuit exhibits the advantage of non-interactive electronic control of the natural angular frequency (ω_0) and the quality factor (Q) along with low incremental active and passive sensitivities. Computer simulation results using PSPICE program are given to confirm the validity of the theoretical prediction and to point out the attractive performance of the circuit.*

Keywords

Z-Copy Current Follower Transconductance Amplifier (ZC-CFTA), biquad filter, current-mode circuit, electronically tunable.

1. Introduction

When the current differencing transconductance amplifier (CDTA) was introduced in 2003, it has been acknowledged to be a versatile active building block for current-mode signal processing circuits [1]. Numerous current-mode analog signal processing circuits based on CDTA have been proposed in open literature [1]-[13]. However, some earlier circuits described in [5]-[11] do not fully use the potential of the CDTAs, since always one of the input terminals p or n is not used. This may cause some noise injection into the monolithic circuit. Moreover, the current differencing property at an input stage can be achieved by the current feedback connection via the ±x terminals. This implies that the input terminals p or n do not necessarily require for some applications. In order to alleviate the mentioned problems, the simplified version of the CDTA so-called Z-copy current follower transconductance amplifier (ZC-CFTA) was firstly suggested in [14]. The ZC-CFTA is slightly modified from the conventional CDTA by replacing the current differencing unit with a current follower and complementing the circuit with a simple current mirror for copying the z-terminal current. Thus, the ZC-CFTA element can be thought of as a combination of the current follower, the current mirror and the multi-output operational transconductance amplifier. As a consequence, a number of applications based on ZC-CFTAs can be extended. According to the general methodology introduced in [14], the recently introduced active device namely modified current follower transconductance amplifier (MCFTA) is also re-suggested in [15]. Therefore, a lot of interesting researches have been devoted to the realization of current-mode biquadratic filters employing CDTAs and/or ZC-CFTAs/MCFTAs as the major active devices, for example, in [1]-[8], [15]-[21] and in references cited therein.

In this paper, using ZC-CFTAs, a new circuit configuration for realizing an electronically tunable current-mode biqradratic filter with single input and five outputs is presented. The proposed circuit contains only four ZC-CFTAs and two grounded capacitors (Active-C filter structure). Compare with the previously reported configurations [1]-[8], [15]-[21], the proposed circuit is capable of satisfying all the following seven important features simultaneously:

(i) availability of all the five standard biquadratic filtering functions, namely lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS) and allpass (AP), simultaneously from the same configuration;

(ii) orthogonal adjustment of the natural angular frequency (ω_0) and the quality factor (Q) by electronic means;

(iii) exhibits both low-input impedance and high-output impedance terminals, resulting in directly connection in cascade with no need to interpose active separating stages;

(iv) does not require an additional active device for implementing identical input currents;

(v) does not require critical component matching constraints in the design;

(vi) employs only grounded capacitors which is ideal for integrability;

(vii) low active and passive component sensitivities.

A summary of the performance parameters of some recently reported filters in [1]-[8], [15]-[21] and the proposed filter is given in Tab. 1. A careful inspection of Tab. 1 reveals that none of the earlier filters possess all the above described parameters (i)-(vii) simultaneously.

Filters	Properties						
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
[1]	no	yes	yes	yes	yes	no	yes
[2]	no	no	no	no	yes	yes	yes
[3]	no	no	no	yes	no	no	yes
[4]	no	no	yes	no	yes	yes	yes
[5]	no	no	yes	no	yes	no	yes
[6]	no	no	no	yes	yes	yes	yes
[7]	no	no	no	yes	yes	no	yes
[8]	no	no	no	yes	yes	no	yes
[15]	no	no	yes	yes	yes	yes	yes
[16]	no	no	yes	yes	yes	no	yes
[17]	no	no	no	yes	yes	no	yes
[18]	no	no	yes	yes	yes	yes	yes
[19]	no	yes	yes	yes	yes	yes	yes
[20]	no	no	yes	yes	yes	yes	yes
[21]	no	yes	yes	yes	yes	yes	yes
Proposed	yes	yes	yes	yes	yes	yes	yes

Tab. 1. Comparison of the proposed filter with the previously reported filters [1]-[8], [15]-[21].

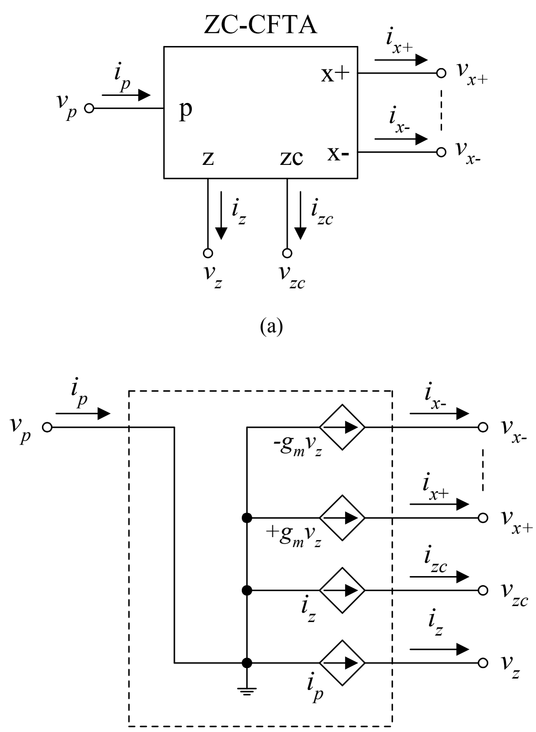
2. Description of Realized Filter

The symbolic notation and equivalent of the ZC-CFTA are shown in Fig.1. The ZC-CFTA element consists of low-impedance input p, high-impedance outputs z, zc, x- and x+. The input current from the terminal p (i_p) is respectively transferred to the terminal z (i_z) and auxiliary terminal zc (i_{zc}) by a current follower and a current mirror. The voltage drop at the terminal z (v_z) is transformed into output currents via a multi-output transconductance stage with a transconductance gain (g_m). Using standard notation, the port relations of the ZC-CFTA can be defined by the following matrix equation [20]-[21]

$$\begin{bmatrix} v_p \\ i_z \\ i_{zc} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_p \\ v_z \\ v_{zc} \\ v_{x+} \\ v_{x-} \end{bmatrix} \tag{1}$$

where $+g_m$ and and $-g_m$ correspond for the positive output current (i_{x+}) and negative output current (i_{x-}), respectively. In general, the g_m-value is electronically controllable by external bias current/voltage.

The filter topology presented in this work is illustrated in Fig. 2. It is configured by four ZC-CFTAs and only two grounded capacitors without needing an external passive resistor. The use of grounded capacitors as passive components is very attractive feature for integrated circuit (IC) implementation point of view.



(a)

(b)

Fig. 1. ZC-CFTA: (a) electrical symbol, (b) equivalent circuit.

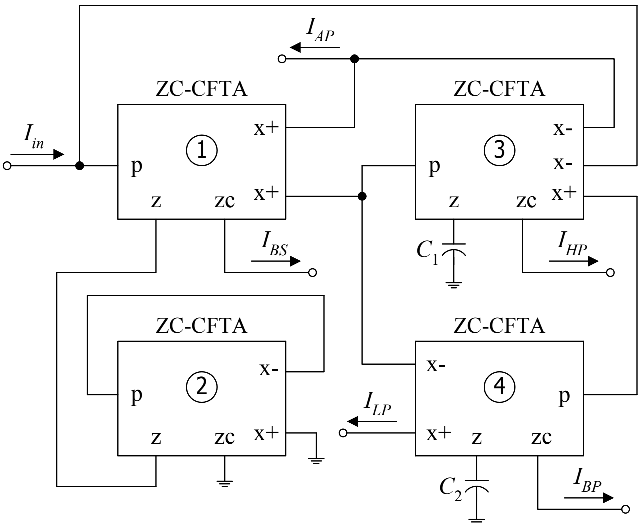


Fig. 2. Proposed filter configuration.

Furthermore, from Fig. 2, it is interesting to note that the proposed circuit has superiority in having both low-input and high-output impedance terminals, which is highly desirable in current-mode operation. Using the relationship defined in (1) and routine circuit analysis for Fig. 2, the current transfer functions can respectively be derived as:

$$LP(s) = \frac{I_{LP}(s)}{I_{in}(s)} = \left(\frac{g_{m1}}{g_{m2}}\right)\left[\frac{\frac{g_{m3}g_{m4}}{C_1C_2}}{D(s)}\right], \tag{2}$$

$$BP(s)=\frac{I_{BP}(s)}{I_{in}(s)}=\left(\frac{g_{m1}}{g_{m2}}\right)\left[\frac{\frac{g_{m2}g_{m3}}{g_{m1}C_1}s}{D(s)}\right] , \tag{3}$$

$$HP(s)=\frac{I_{HP}(s)}{I_{in}(s)}=\left(\frac{g_{m1}}{g_{m2}}\right)\left[\frac{s^2}{D(s)}\right] , \tag{4}$$

$$AP(s)=\frac{I_{AP}(s)}{I_{in}(s)}=\left(\frac{g_{m1}}{g_{m2}}\right)\left[\frac{s^2-\frac{g_{m2}g_{m3}}{g_{m1}C_1}+\frac{g_{m3}g_{m4}}{C_1C_2}}{D(s)}\right] , \tag{5}$$

$$BS(s)=\frac{I_{BS}(s)}{I_{in}(s)}=\left[\frac{s^2+\frac{g_{m3}g_{m4}}{C_1C_2}}{D(s)}\right] \tag{6}$$

where denominator $D(s)$ is found as :

$$D(s)=s^2+\frac{g_{m2}g_{m3}}{g_{m1}C_1}+\frac{g_{m3}g_{m4}}{C_1C_2} . \tag{7}$$

Observe that all the five standard biquadratic filtering functions are available from the same topology without the interconnection of the relevant output currents. It is also found from their transfer functions that no design constraints/cancellation condition is required for any response.

Accordingly, the natural angular frequency ω_0 and the quality factor Q of the biquad can be given respectively as follows :

$$\omega_0=\sqrt{\frac{g_{m3}g_{m4}}{C_1C_2}} , \tag{8}$$

and

$$Q=\frac{g_{m2}}{g_{m1}}\sqrt{\frac{g_{m4}C_1}{g_{m3}C_2}} . \tag{9}$$

From above equations, it should be noted that the important parameters ω_0 and Q can be independently/electronically adjusted. It means that the parameter ω_0 can be tuned electronically without disturbing Q by simultaneously changing g_{m3} and g_{m4} and keeping g_{m3}/g_{m4} constant, for equal-valued capacitor design. This manner is easily achievable in practice by setting equal-valued transconductance $g_{m3} = g_{m4}$. Also, one can adjust the parameter Q electronically without influencing ω_0 by changing g_{m2}/g_{m1}, thus the high-Q biquad can be further obtained by increasing g_{m2} and decreasing g_{m1} at the same time.

3. Non-ideal Effects

In the non-ideal case, the port relation of the ZC-CFTA given in (1) can be rewritten as:

$$\begin{bmatrix} v_p \\ i_z \\ i_{zc} \\ i_{x+} \\ i_{x-} \end{bmatrix}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_p \\ v_z \\ v_{zc} \\ v_{x+} \\ v_{x-} \end{bmatrix} \tag{10}$$

where $\alpha = 1- \varepsilon$ and ε ($|\varepsilon| << 1$) is the current tracking error from p to z and zc terminals. Taking the ZC-CFTA non-idealities into account, the modified parameters ω_o and Q of the proposed filter given in Fig. 2 are given by:

$$\omega_0=\sqrt{\frac{\alpha_3\alpha_4 g_{m3}g_{m4}}{C_1C_2}} \tag{11}$$

and

$$Q=\frac{\alpha_2 g_{m2}}{\alpha_1 g_{m1}}\sqrt{\frac{\alpha_4 g_{m4}C_1}{\alpha_3 g_{m3}C_2}} . \tag{12}$$

Slight deviations are expected in the results due to the appearance of the ZC-CFTA non-idealities. However, this effect can be minimized by pre-distorting the g_m-values appropriately.

The active and passive sensitivities of the filter parameters ω_0 and Q are found as :

$$S^{\omega_0}_{\alpha_1,\alpha_2}=S^{\omega_0}_{g_{m1},g_{m2}}=0 , \tag{13}$$

$$S^{\omega_0}_{\alpha_3,\alpha_4}=S^{\omega_0}_{g_{m3},g_{m4}}=\frac{1}{2} , \tag{14}$$

$$S^{\omega_0}_{C_1,C_2}=-\frac{1}{2} , \tag{15}$$

$$S^{Q}_{\alpha_1,g_{m1}}=-S^{Q}_{\alpha_2,g_{m2}}=-1 , \tag{16}$$

$$S^{Q}_{\alpha_3,g_{m4}}=-S^{Q}_{\alpha_4,g_{m4}}=-\frac{1}{2} \tag{17}$$

and

$$S^{Q}_{C_1}=-S^{Q}_{C_2}=\frac{1}{2} \tag{18}$$

which are equal or less than unity in magnitude. Thus, the proposed filter of Fig. 2 has small component sensitivities.

4. Computer Simulation Results and Discussions

The proposed filter circuit given in Fig. 2 has been simulated with PSPICE simulation program. The ZC-CFTA has been simulated using the bipolar technology structure of Fig. 3, which is modified from the structure reported in [17], [19]. The PNP and NPN transistors in ZC-CFTA realization were simulated using the typical parameters of bipolar transistor model PR100N (PNP) and NP100N (NPN). The DC supply voltages and bias currents were respectively selected as: +V = -V = 3 V and I_B= 50 μA. In this case, the transconductance gain g_m of the

ZC-CFTA is directly proportional to the external bias current I_O, which is approximately equal to

$$g_m = \frac{I_O}{2V_T} \tag{19}$$

and $V_T \cong 26$ mV at 27°C.

As an example, the following component setting for the proposed filter of Fig. 2 have been selected as: $C_1 = C_2 = 1$ nF and $I_{O1} = I_{O2} = I_{O3} = I_{O4} = 50\ \mu$A ($g_{m1} = g_{m2} = g_{m3} = g_{m4} = 1$ mA/V), which result in $f_0 = \omega/2\pi \cong 159$ kHz and $Q = 1$. Fig. 4 shows the simulated frequency characteristics for LP, BP, HP and BS responses of the proposed filter in Fig. 2. Similarly, ideal and simulated AP responses are depicted in Fig. 5. From the simulation results, the total power dissipation is found as: 12.2 mW.

In addition, the simulated time domain results for BP response is also shown in Fig. 6, in which a 159-kHz sinusoidal input current signal with 20 μA peak value is applied to the filter. In the figure, the dashed and solid lines are used to represent the ideal and simulated responses, respectively. It can be observed from Figs. 4-6 that the proposed filter performs all the standard biquadratic filtering functions well and the simulation results agree well with the theory as expected.

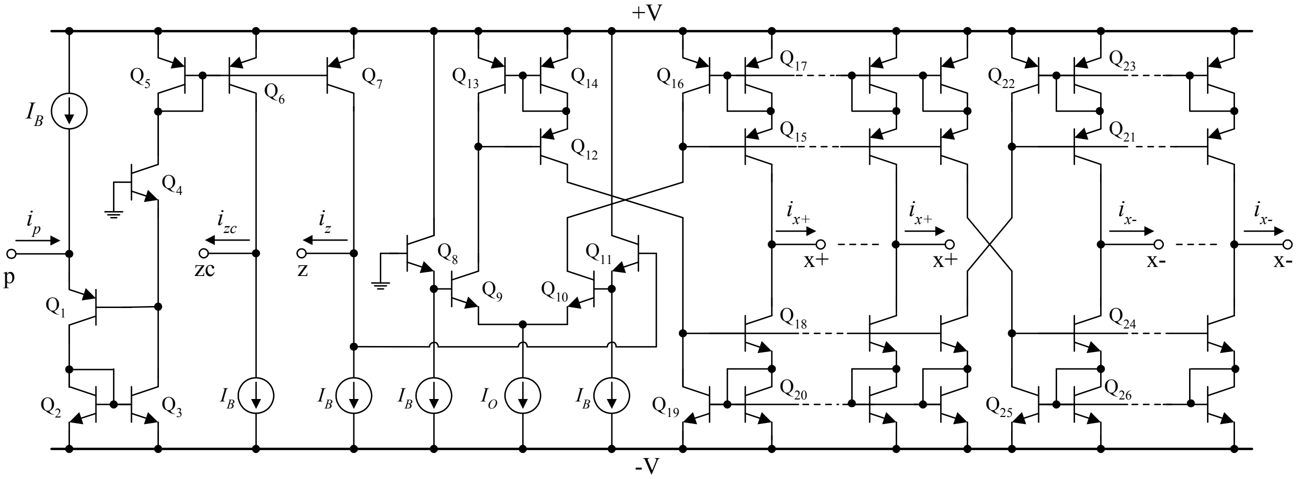


Fig. 3. Bipolar realization of the ZC-CFTA used in simulations.

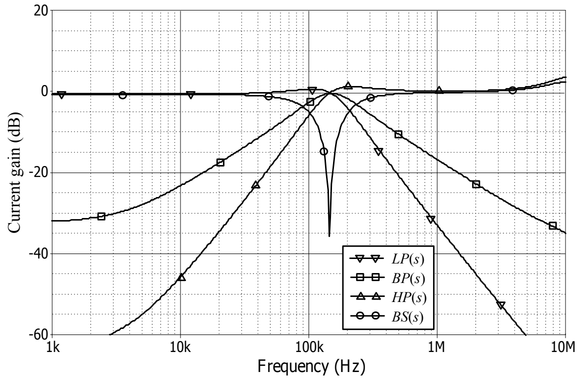


Fig. 4. Simulated frequency characteristics for LP, BP, HP and BS responses of the proposed filter in Fig. 2.

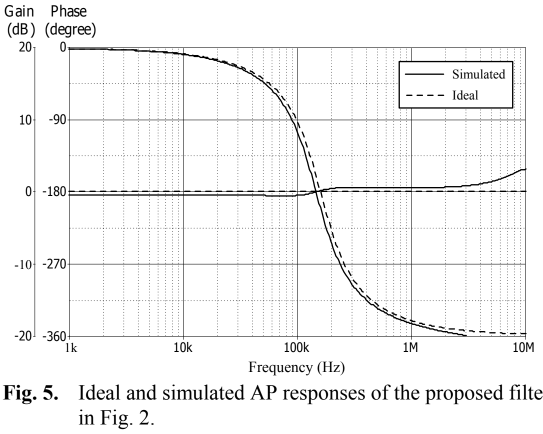


Fig. 5. Ideal and simulated AP responses of the proposed filter in Fig. 2.

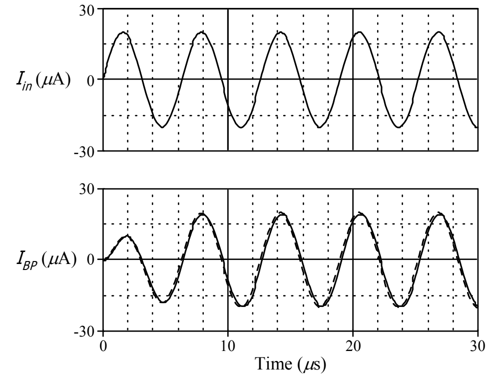


Fig. 6. Time domain responses of the BP response in Fig. 2 at $f_o = 159$ kHz.

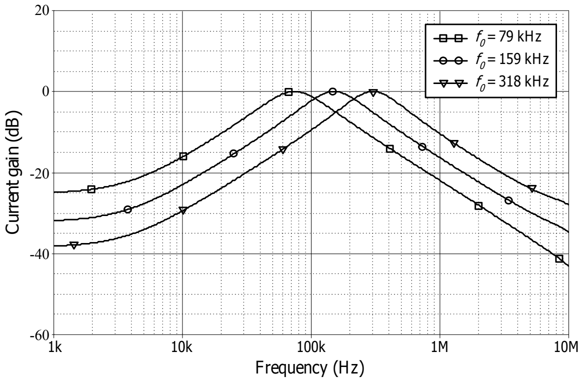


Fig. 7. Simulated results of the BP response with different f_o (keeping $Q = 1$).

In order to demonstrate the electronic tuning of f_0 without effecting Q, the bias currents I_O ($= I_{O3} = I_{O4}$) were respectively adjusted to 25 μA, 50 μA, 100 μA, while keeping $I_{O1} = I_{O2} = 50$ μA for $Q = 1$. In this setting, the f_0-values calculated from (8) when $C_1 = C_2 = 1$ nF are approximated to 79 kHz, 159 kHz and 318 kHz, respectively. The resulting responses of the BP filter corresponding to different bias currents I_O are given in Fig. 7. From the simulations, the corresponding f_0 can be measured as 74.13 kHz, 151.35 kHz and 302 kHz, respectively.

Fig. 8 shows the simulated BP responses with Q-tuning (i.e., $Q = 25$, 50 and 100). In this case, the bias currents were chosen as : $I_{O3} = I_{O4} = 50$ μA, $I_{O1} = 10$ μA, and $I_{O2} = 250$ μA, 500 μA, 1000 μA, respectively. Note that the high-Q filter can be realized from high value of I_{O2}/I_{O1}. It should be further noted that the maximum achievable Q value is limited by the minimum acceptable passband gain of the proposed filter. This is due to the fact that, for $g_{m3} = g_{m4}$ and $C_1 = C_2$, the passband gain value is inversely proportional to the Q-value (see (2)-(5) and (9)). Furthermore, for different Q values, variations of the total harmonic distortion (THD) for BP response on the amplitude of the sinusoidal input current signal at 159 kHz are given Tab. 2. It can be observed that the percentage THD is low and remains less than 3% till input current of 45 μA peak.

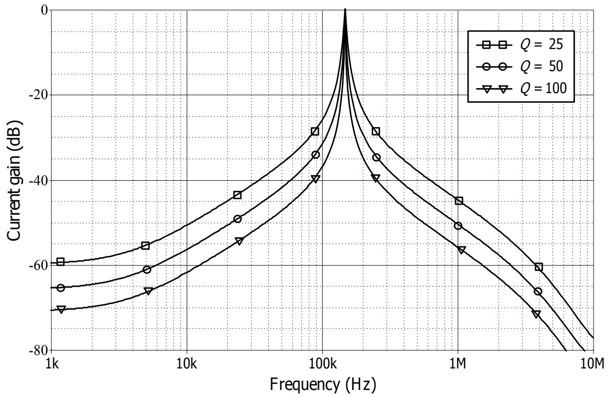


Fig. 8. Simulated results of the BP filter with different Q (keeping $f_o = 159$ kHz).

Magnitude of I_{in} (μA)	THD (%)		
	$Q = 25$	$Q = 50$	$Q = 100$
1	1.12	2.08	1.90
5	0.36	0.67	0.77
10	0.19	0.50	0.85
15	0.42	0.55	0.69
20	0.61	0.91	0.78
25	0.67	1.35	0.96
30	0.86	1.71	1.33
35	1.54	1.95	1.71
40	2.45	1.80	2.14
45	2.95	1.36	2.56
50	3.05	2.34	11.8

Tab. 2. THD variations of BP response of filter in Fig.2 with $f_0 = 159$ kHz.

Also, the intermodulation distortion (IMD) for BP response of filter in Fig. 2 is investigated. The results are summarized in Tab. 3, where Q is set to be constant at unity and the sinusoidal input current signal of 20 μA peak at 159 kHz and a parasitic current signal of 1 μA peak at different frequencies are applied to the filter.

Frequency of parasitic signal (kHz)	THD (%)
100	2.31
200	2.61
400	3.15
600	2.38
800	2.01
1000	1.80

Tab. 3. IMD results of BP response of filter in Fig. 2 with $Q = 1$.

5. Conclusion

In this work, an active-C current-mode biquad filter design using ZC-CFTAs is described. It comprises only four ZC-CFTAs and two grounded capacitors, and realizes all the five generic current-mode biquadratic filtering responses. The described filter still had the following advantages: use of only grounded capacitors, low-input and high-output impedances, no need to impose component choice, without the connection of proper output currents to realize any filter responses, independent electronic control of ω_0 and Q through ZC-CFTA's transconductance, and low sensitivity performance. It was demonstrated from simulation results that the ideal and simulated responses are in good agreement.

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