Hindawi Publishing Corporation
Active and Passive Electronic Components
Volume 2007, Article ID 36849, 6 pages
doi:10.1155/2007/36849

*Research Article*

# Three-Input Single-Output Electronically Controllable Dual-Mode Universal Biquad Filter Using DO-CCCIIs

**M. Siripruchyanun[1] and W. Jaikla[2]**

[1] *Department of Teacher Training in Electrical Engineering, Faculty of Technical Education, King Mongkut's Institute of Technology North Bangkok, Bangsue, Bangkok 10800, Thailand*
[2] *Electric and Electronic Program, Faculty of Industrial Technology, Suan Sunandha Rajabhat University, Dusit, Bangkok 10300, Thailand*

Received 3 May 2007; Revised 7 August 2007; Accepted 14 November 2007

Recommended by Ashok K. Goel

This article presents a dual-mode (voltage-mode and current-mode) universal biquadratic filter performing completely standard functions: lowpass, highpass, bandpass, band-reject, and allpass functions, based on plus-type dual-output second-generation, current controlled, current conveyor (DO-CCCII+). The features of the circuit are that the bandwidth and natural frequency can be tuned electronically via the input bias currents: the circuit description is very simple, consisting of merely 2 DO-CCCIIs and 2 capacitors: the circuit can provide either the voltage-mode or current-mode filter without changing circuit topology. Additionally, each function response can be selected by suitably selecting input signals with digital method. Without any external resistors, the proposed circuit is very suitable to further develop into an integrated circuit. The PSPICE simulation results are depicted. The given results agree well with the theoretical anticipation. The maximum power consumption is approximately 1.81 mW at ±1.5 V supply voltages.



## 1. INTRODUCTION

An analog filter is an important block and widely used for continuous-time signal processing. It can be found in many fields, for example, communication, measurement and instrumentation, and control systems [1, 2]. One of most popular analog filters is a universal biquadratic filter since it can provide several functions. Nowadays, a universal filter working in current-mode has been more popular than voltage-mode one. Since the last decade, there has been much effort to reduce the supply voltage of analog systems. This is due to the command for portable and battery-powered equipment. Since a low-voltage operating circuit becomes necessary, the current–mode technique is ideally suited for this purpose. Actually, a circuit using the current-mode technique has many other advantages, for example, larger dynamic range, higher bandwidth, greater linearity, simpler circuitry, and lower power consumption [3, 4]. However, in present, the voltage-mode circuits are still used in some applications.

The CCII is a reported active component, especially suitable for a class of analog signal processing [5]. The fact that the device can operate in both current and voltage-modes provides flexibility and enables a variety of circuit designs. In addition, it can offer advantageous features such as high-slew rate, higher speed, wide bandwidth, and simple implementation [5, 6]. However, the CCII cannot control the parasitic resistance at $X$ ($R_x$) port so when it is used in some circuits, it must unavoidably require some external passive components, especially the resistors. This makes it not appropriate for IC implementation due to occupying more chip area, high power dissipation and without electronic controllability. On the other hand, the introduced second-generation current-controlled conveyor (CCCII) [7] has the advantage of electronic adjustability over the CCII. Also, the use of dual-output current conveyors is found to be useful in the derivation of current-mode single input three output filters using a reduced number of active components [8, 9].

In many applications, voltage and current-mode circuits are used to be connected which causes some difficulties that can be overcame by using voltage-to-current and current-to-voltage converters at the interface of these circuits. During $V$-$I$ interfacing, it is also possible to perform signal processing at the same time so that the total effectiveness of the

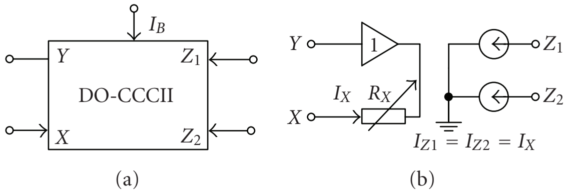


FIGURE 1: The DO-CCCII (a) symbol (b) equivalent circuit.

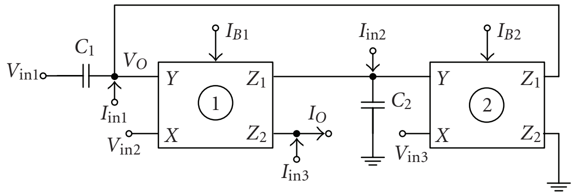


FIGURE 2: Proposed dual-mode universal filter.

electronic circuitry can be increased [10]. The literature surveys show that the dual-mode universal filter circuit using different high-performance active building blocks such as OTAs [11–13], current feedback op-amps (CFOAs) [14], current feedback amplifiers (CFAs) [15, 16], four-terminal floating nullors (FTFNs) [16–19], and current conveyors [20–24] have been reported. Unfortunately, these reported circuits suffer from one or more of following weaknesses:

(i) excessive use of the active and/or passive elements [10, 14–17, 19–24];
(ii) require changing circuit topologies to achieve several functions [11, 12, 15–17];
(iii) lack of electronic adjustability [10, 14–17, 19–23];
(iv) cannot provide completely standard functions [10, 11, 13, 15, 16, 19, 20, 22];
(v) cannot provide functions both in voltage and current-modes with the same topology [13, 15, 17, 19].

Recently, the realized circuits by using minimum active components are interesting because of their compactness and suitability for fabrication. Current differencing *transconductance* amplifier (CDTA) and current differencing buffered amplifier (CDBA) are two active elements which were frequently used to realize the circuits. Our survey found that the universal filter circuits using these elements have been reported [25–29]. Unfortunately, they operate only either in the current or voltage mode.

This work is arranged to propose a new voltage/current-mode universal biquadratic filter, emphasizing on the use of plus-type DO-CCCIIs. The features of proposed circuit are that the proposed universal filter can provide completely standard functions both in voltage-mode and current-mode without changing circuit topology by appropriately selecting the input signals: the circuit description is very simple, it consists of 2 DO-CCCIIs and 2 capacitors, which is suitable for fabricating in monolithic chip: the filter does not require any external resistor. In addition, the natural frequency and the bandwidth can be tuned electronically by adjusting the bias currents. Its performances are illustrated by PSPICE simulations; they show good agreement as mentioned.

TABLE 1: The $V_{\text{in1}}$, $V_{\text{in2}}$, and $V_{\text{in3}}$ values selection for each filter function response.

| Filter responses | Input selections | | |
|---|---|---|---|
| $V_O$ | $V_{\text{in1}}$ | $V_{\text{in2}}$ | $V_{\text{in3}}$ |
| BP | 0 | 0 | 1 |
| HP | 1 | 0 | 0 |
| BR ($R_{X1} = R_{X2}$) | 1 | 1 | 1 |
| AP ($R_{X1} = R_{X2}$) | 1 | 1 | 2 |
| LP ($R_{X1} = R_{X2}$) | 0 | 1 | 1 |

TABLE 2: The $I_{\text{in1}}$, $I_{\text{in2}}$, and $I_{\text{in3}}$ values selection for each filter function response.

| Filter Responses | Input selections | | |
|---|---|---|---|
| $I_O$ | $I_{\text{in1}}$ | $I_{\text{in2}}$ | $I_{\text{in3}}$ |
| BP | 1 | 0 | 0 |
| HP | 1 | 1 | 1 |
| BR | 1 | 0 | 1 |
| AP | 2 | 0 | 1 |
| LP | 0 | 1 | 0 |

## 2. PRINCIPLE OF OPERATION

### 2.1. Dual-output, second-generation, current-controlled, current conveyor (DO-CCCII)

Since the proposed circuit is based on DO-CCCIIs, it will be introduced in this section. Typically, the DO-CCCII is a versatile analog building block which is similar to the conventional current conveyor (CCII) except that the DO-CCCII has a finite input resistance $R_X$ at the $X$ terminal. DO-CCCII has the advantage of electronically adjustability over the CCII, because it allows the adjustment of $R_X$ via the bias current $I_B$ as shown by

$$R_X = \frac{V_T}{2I_B}, \tag{1}$$

where $V_T$ is the thermal voltage. The relationship between the voltage and current variables among $X$, $Y$, and $Z$ ports of an ideal DO-CCCII can be described by

$$i_Y = 0, \qquad V_X = V_Y + R_X I_X, \qquad i_{Z1} = i_{Z2} = i_X. \tag{2}$$

### 2.2. Proposed filter

The proposed dual-mode universal filter is shown in Figure 2, where $I_{B1}$ and $I_{B2}$ are input bias currents of DO-CCCII$_1$ and DO-CCCII$_2$, respectively. They are used to control the corresponding parasitic resistances.

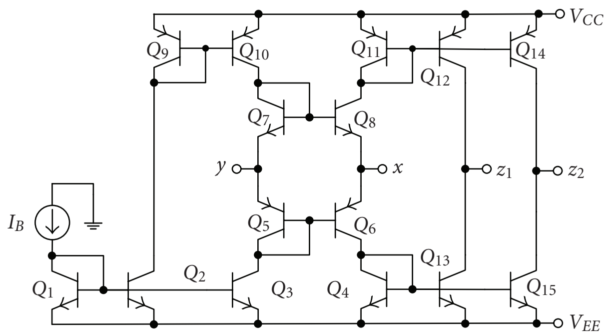


Figure 3: Internal construction of DO-CCCII.

Table 3: Parameters of the transistors.

```
.model PX PNP
+RB=327 IRB=0 RBM=24.55 RC=50 RE=3
+IS=73.5E-18 EG=1.206 XTI=1.7 XTB=1.866 BF=110
+IKF=2.359E-3 NF=1 VAF=51.8 ISE=25.1 E-16 NE=1.650
+BR=0.4745 IKR=6.478E-3 NR=1 VAR=9.96 ISC=0 NC=2
+TF=0.610E-9 TR=0.610E-8 CJE=0.180E-12 VJE=0.5
+MJE=0.28 CJC=0.164E-12 VJC=0.8 MJC=0.4 XCJC=0.037
+CJS=1.03E-12 VJS=0.55 MJS=0.35 FC=0.5

.model NX NPN
+RB=524.6 IRB=0 RBM=25 RC=50 RE=1
+IS=121E-18 EG=1.206 XTI=2 XTB=1.538 BF=137.5
+IKF=6.974E-3 NF=1 VAF=159.4 ISE=36E-16 NE=1.713
+BR=0.7258 IKR=2.198E-3 NR=1 VAR=10.73 ISC=0 NC=2
+TF=0.425E-9 TR=0.425E-8 CJE=0.214E-12 VJE=0.5
+MJE=0.28 CJC=0.983E-13 VJC=0.5 MJC=0.3 XCJC=0.034
+CJS=0.913E-12 VJS=0.64 MJS=0.4 FC=0.5
```

For voltage-mode case, where $I_{\text{in}1} = I_{\text{in}2} = I_{\text{in}3} = 0$, straightforwardly analyzing the filter in Figure 2, the output voltage can be obtained as

$$V_O = \frac{V_{\text{in}1} s^2 C_1 C_2 R_{x1} R_{x2} + V_{\text{in}2}(1 + sC_2 R_{x2}) - V_{\text{in}3} sC_2 R_{x1}}{s^2 C_1 C_2 R_{x1} R_{x2} + sC_2 R_{x2} + 1}. \tag{3}$$

From (3), $V_{\text{in}1}$, $V_{\text{in}2}$, and $V_{\text{in}3}$ can be chosen as in Table 1 to obtain a standard function of the second-order network.

From Table 1, it should be remarked that, in case of the LP, BR and AP, the circuit condition: $R_{X1} = R_{X2}$ is required. Moreover, $V_{\text{in}3}$ must be double of $V_{\text{in}1}$ and $V_{\text{in}2}$ in the case of AP. So to achieve this condition, the voltage amplifier which has gain of 2 is required.

For current-mode case, where $V_{\text{in}2} = V_{\text{in}3} = 0$ and $V_{\text{in}1}$ is not applied into the proposed filter, straightforwardly analyzing the circuit in Figure 2, the output current can be obtained as

$$I_O = \frac{I_{\text{in}1} sC_2 R_{x2} + I_{\text{in}2} - I_{\text{in}3}(s^2 C_1 C_2 R_{x1} R_{x2} + sC_2 R_{x2} + 1)}{s^2 C_1 C_2 R_{x1} R_{x2} + sC_2 R_{x2} + 1}. \tag{4}$$

From (4), the magnitudes of input currents $I_{\text{in}1}$, $I_{\text{in}2}$ and $I_{\text{in}3}$ can be chosen as in Table 2 to obtain a standard function of the network. The circuit of digital selection can be seen in [30].

From (3) and (4), for dual-mode, the natural frequency ($\omega_0$), and quality factor ($Q_0$) of each filter response can be expressed as

$$\omega_0 = \sqrt{\frac{1}{C_1 C_2 R_{X1} R_{X2}}}, \qquad Q_0 = \sqrt{\frac{C_1 R_{X1}}{C_2 R_{X2}}}. \tag{5}$$

Substituting intrinsic resistances as depicted in (1), it yields

$$\omega_0 = \frac{2}{V_T}\sqrt{\frac{I_{B1} I_{B2}}{C_1 C_2}}, \qquad Q_0 = \sqrt{\frac{C_1 I_{B2}}{C_2 I_{B1}}}. \tag{6}$$

From (6), by maintaining the ratio $I_{B1}$ and $I_{B2}$ to be constant, it can be remarked that the pole frequency can be adjusted by $I_{B1}$ and $I_{B2}$ without affecting the quality factor. In addition, bandwidth (BW) of the system can be expressed by

$$\text{BW} = \frac{\omega_0}{Q_0} = \frac{2I_{B1}}{C_1 V_T}. \tag{7}$$

We found that the bandwidth can be linearly controlled by $I_{B1}$. Moreover, it can be seen that the natural frequency can be adjusted orthogonally from the bandwidth by varying $I_{B2}$. Moreover, in current-mode case due to high output impedance, it is easy cascading in current-mode but in voltage-mode the output impedance is quit low.

### 2.3. Circuit sensitivities

The sensitivities of the proposed circuit can be found as

$$\begin{aligned} &S^{\omega_0}_{C_1,C_2} = -\frac{1}{2}, \qquad S^{\omega_0}_{I_{B1},I_{B2}} = \frac{1}{2}, \qquad S^{\omega_0}_{V_T} = -1, \\ &S^{Q_0}_{C_2,I_{B1}} = \frac{1}{2}; \qquad S^{Q_0}_{C_1,I_{B2}} = -\frac{1}{2}, \\ &S^{\text{BW}}_{C_2,V_T} = -1, \qquad S^{\text{BW}}_{I_{B1}} = 1. \end{aligned} \tag{8}$$

Therefore, all the active and passive sensitivities are equal or less than unity in magnitude.

### 2.4. Nonideal case

For nonideal case, the DO-CCCII can be, respectively, characterized with the following equations:

$$i_Y = 0, \qquad V_X = \beta V_Y + R_X I_X, \qquad i_{Z1} = \alpha i_X, \qquad i_{Z2} = \gamma i_X. \tag{9}$$

In the case of nonidea and reanalysis of proposed filter circuit in Figure 2, it, respectively, yields the output voltage and current as

$$\begin{aligned} V_O &= \frac{s^2 C_1 C_2 R_{X1} R_{X2} V_{\text{in}1} + (\beta_1\beta_2\alpha_1\alpha_2 + \beta_1 sC_2 R_{X2}) V_{\text{in}2}}{D_{(n)}(s)} \\ &\quad - \frac{\alpha_2 sC_1 R_{X1} V_{\text{in}3}}{D_{(n)}(s)}, \\ I_O &= \frac{1}{D_{(n)}(s)}\left[I_{\text{in}1} sC_2 R_{x2}\gamma_1 + I_{\text{in}2}\alpha_2\beta_2\gamma_1 - I_{\text{in}3} D_{(n)}(s)\right], \end{aligned} \tag{10}$$

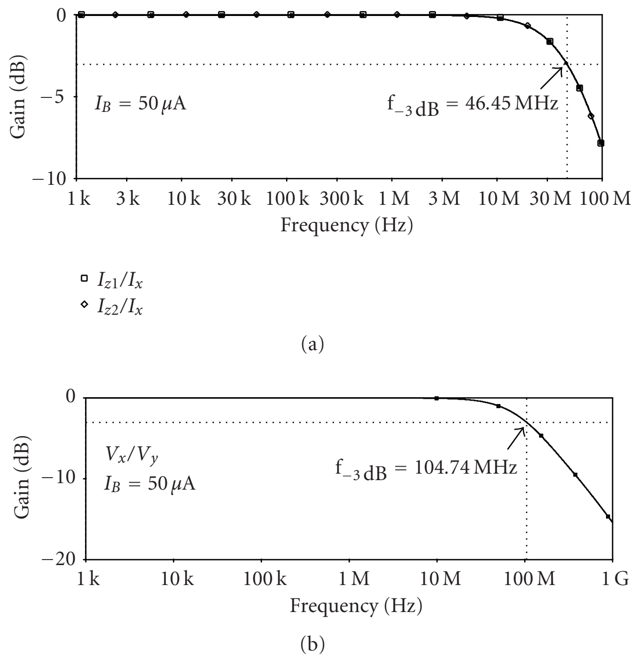


Figure 4: The −3 dB frequency response of DO-CCCII.

where

$$D_{(n)}(s) = s^2 C_1 C_2 R_{X1} R_{X2} + sC_2 R_{X2} + \beta_2 \alpha_1 \alpha_2. \quad (11)$$

In this case, the $\omega_0$ and $Q_0$ are changed to

$$\omega_0 = \sqrt{\frac{\alpha_1\alpha_2\beta_2}{C_1 C_2 R_{X1} R_{X2}}}, \qquad Q_0 = \sqrt{\frac{\alpha_1\alpha_2\beta_2 C_1 R_{X1}}{C_2 R_{X2}}}, \quad (12)$$

while BW is still equal to (7). The sensitivities of the proposed circuit in nonideal case can be found to be

$$S^{\omega_0}_{C_1,C_2,R_{x1},R_{x2}} = -\frac{1}{2}, \qquad S^{\omega_0}_{\alpha_1,\alpha_2,\beta_2} = \frac{1}{2},$$
$$S^{Q_0}_{C_1,R_{x2}} = -\frac{1}{2}; \qquad S^{Q_0}_{C_2,R_{x1},\alpha_1,\alpha_2,\beta_2} = \frac{1}{2}. \quad (13)$$

Actually, these deviations are very small and can be ignored. Practically, from (10)–(12), $\alpha$, $\gamma$ and $\beta$ originate from intrinsic resistances and stray capacitances in the active elements. These errors affect the sensitivity to temperature and high frequency response of the proposed circuit. From (10), it is found that the current and voltage gains depend on the temperature and frequency variations, then the DO-CCCII should be carefully designed to achieve these errors as low as possible.

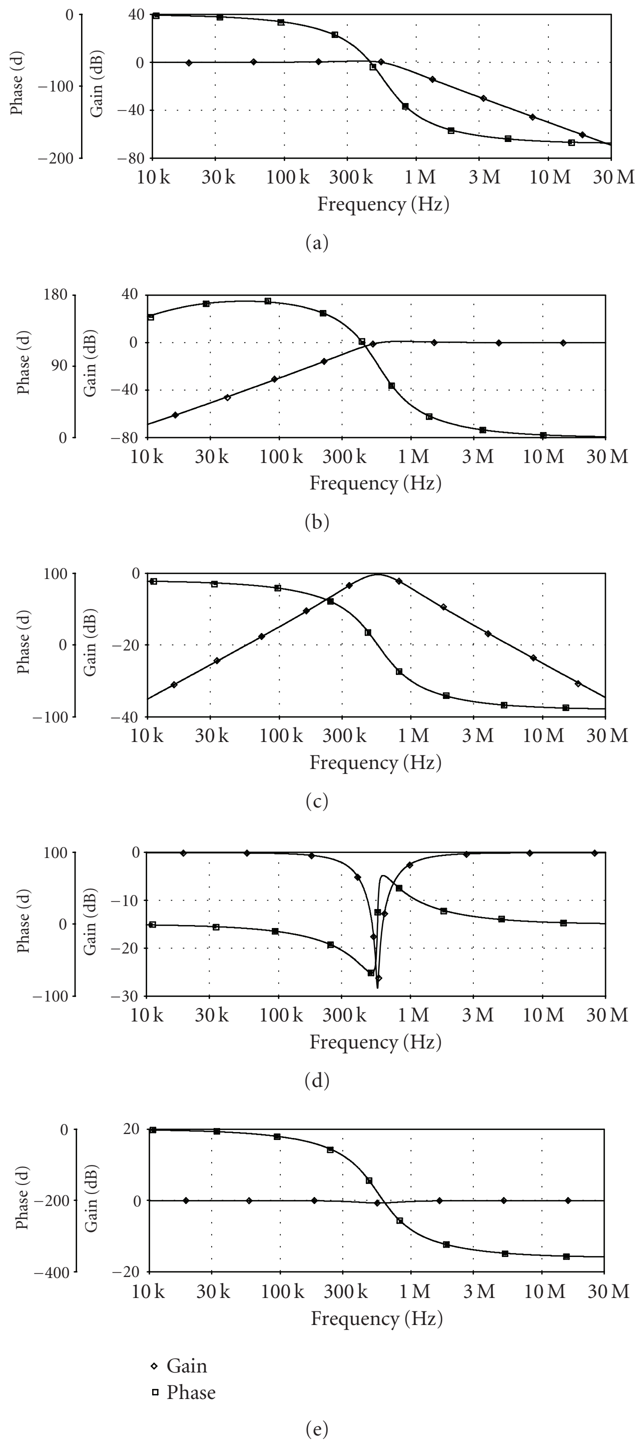


Figure 5: Gain and phase responses of the biquad filter in voltage-mode for (a) LP, (b) HP, (c) BP, (d) BR, (e) AP.

## 3. SIMULATION RESULTS

To prove the performances of the proposed circuit, the PSPICE simulation program was used for the examinations. The PNP and NPN transistors employed in the proposed circuit were simulated by, respectively, using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [31] with parameters tabulated in Table 3. Figure 3 depicts schematic description of the DO-CCCII used in the simulations. The circuit was biased with $\pm 1.5$ V supply voltages. Figure 4 shows the −3 dB frequency response of DO-CCCII. $C_1 = C_2 = 1$ nF and $I_{B1} = I_{B2} = 50\,\mu$A are chosen to obtain both intrinsic resistances values of 260 Ω. It yields the natural frequency of 540.75 kHz, while

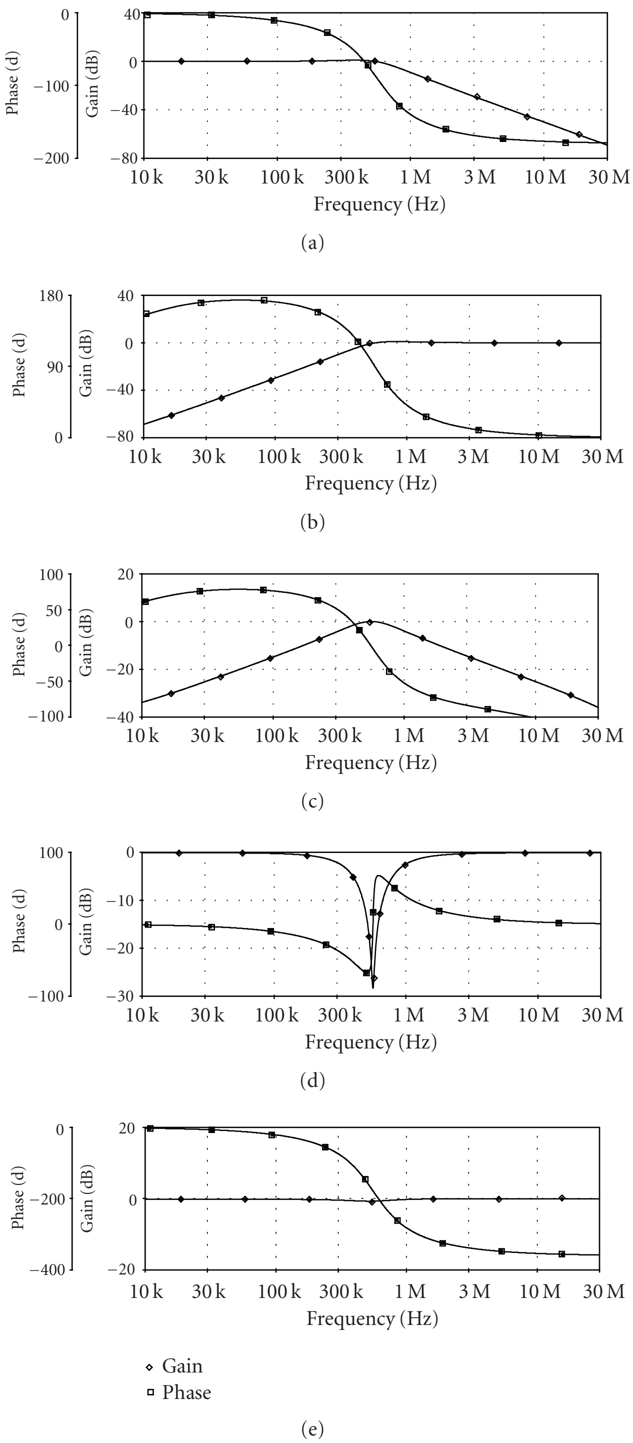


FIGURE 6: Gain and phase responses of the biquad filter in current-mode for (a) LP, (b) HP, (c) BP, (d) BR, (e) AP.

calculated value of this parameter from (6) is 612.45 kHz. The results shown in Figure 5 are the gain and phase responses of the proposed biquad filter in voltage-mode obtained from Figure 2, where $I_{B1} = I_{B2} = 50\,\mu$A. There are seen that the proposed filter in voltage-mode can provide lowpass, highpass, bandpass, band-reject, and allpass functions dependent on selection as shown in Table 1, without modifying circuit topology.

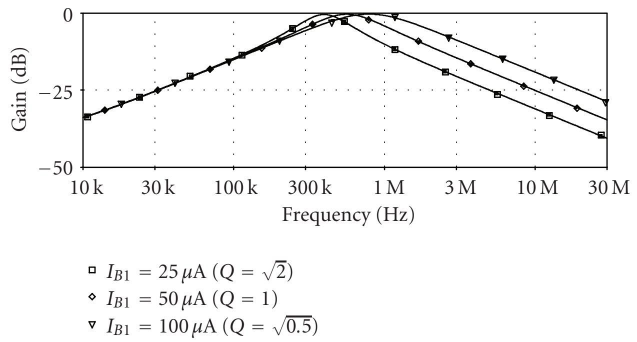


FIGURE 7: Current-mode bandpass responses for different values of $I_{B1}$.

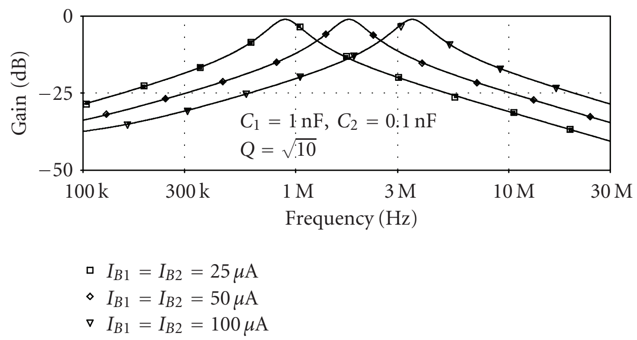


FIGURE 8: Current-mode bandpass responses for different values of $I_{B1}$ and $I_{B2}$ with keeping their ratios constant.

The gain and phase responses of the proposed biquad filter in current-mode are shown in Figure 6, where $I_{B1} = I_{B2} = 50\,\mu A$. There are seen that the proposed filter in current-mode can also provide completely standard functions dependent on selection as shown in Table 2.

Figure 7 displays gain responses of current-mode bandpass function with different $I_{B1}$ values. It is shown that the bandwidth of the responses can be adjusted by the input bias current $I_{B1}$. Figure 8 shows gain responses of bandpass function where $I_{B1}$ and $I_{B2}$ are equally set to keep the ratio to be constant and changed for several values. It is found that pole frequency can be adjusted without affecting the quality factor, as depicted in (6). Maximum power consumption is about 1.81 mW.

## 4. CONCLUSIONS

The dual-mode universal biquadratic filter based on DO-CCCIIs has been presented. The advantages of the proposed circuit are that it performs lowpass, highpass, bandpass, band-reject, and allpass functions dependent on an appropriate selection of three signals in dual-mode: the bandwidth and the natural frequency can be electronically controlled via input bias currents, it is easily modified to use in control systems using a microcontroller [3]. The circuit description comprises only 2 DO-CCCIIs and 2 capacitors. With mentioned features, it is very suitable to realize the proposed circuit in monolithic chip to use in battery-powered, portable electronic equipments such as wireless communication system devices.

## REFERENCES


[1] A. S. Sedra and K. C. Smith, *Microelectronic Circuits*, Holt, Rinehart and Winston, Orlando, Fla, USA, 5th edition, 2003.

[2] M. A. Ibrahim, S. Minaei, and H. Kuntman, "A 22.5 MHz current-mode KHN-biquad using differential voltage current conveyor and grounded passive elements," *International Journal of Electronics and Communications*, vol. 59, no. 5, pp. 311–318, 2005.

[3] C. Toumazou, F. J. Lidgey, and D. G. Haigh, *Analogue IC Design: The Current-Mode Approach*, chapter 13, Peter Peregrinus, London, UK, 1990.

[4] D. R. Bhaskar, V. K. Sharma, M. Monis, and S. M. I. Rizvi, "New current-mode universal biquad filter," *Microelectronics Journal*, vol. 30, pp. 837–839, 1999.

[5] K. C. Smith and A. Sedra, "The current conveyor—a new circuit building block," *Proceedings of the IEEE*, vol. 56, no. 8, pp. 1368–1369, 1968.

[6] A. Sedra and K. C. Smith, "A second-generation current conveyor andits applications," *IEEE Transactions Circuit Theory*, vol. 17, pp. 132–134, 1970.

[7] A. Fabre, O. Saaid, F. Wiest, and C. Boucheron, "Current controlled bandpass filter based on translinear conveyors," *Electronics Letters*, vol. 31, no. 20, pp. 1727–1728, 1995.

[8] K. Ikeda and Y. Tomita, "Realization of current-mode biquadratic filter using CC IIs with current followers," *Electronics and Communications in Japan, Part II*, vol. 77, no. 1, pp. 99–107, 1994.

[9] A. M. Soliman, "New current-mode filters using current conveyors," *International Journal of Electronics and Communications*, vol. 51, no. 5, pp. 275–278, 1997.

[10] N. A. Shah and M. A. Malik, "Multifunction mixed-mode filter using FTFNs," *Analog Integrated Circuits and Signal Processing*, vol. 47, no. 3, pp. 339–343, 2006.

[11] J. Wu and E.I. El-Masry, "Universal voltage- and current-mode OTAs based biquads," *International Journal of Electronics*, vol. 85, no. 5, pp. 553–560, 1998.

[12] D. R. Bhaskar, R. K. Sharma, A. K. Singh, and R. Senani, "New dual-mode biquads using OTAs," *Frequenz*, vol. 60, no. 11-12, pp. 246–252, 2006.

[13] D. R. Bhaskar, A. K. Singh, R. K. Sharma, and R. Senani, "New OTA-C universal current-mode/trans-admittance biquads," *IEICE Electronics Express*, vol. 2, pp. 8–13, 2005.

[14] N. Pandey, S. K. Paul, A. Bhattacharyya, and S. B. Jain, "A new mixed mode biquad using reduced number of active and passive elements," *IEICE Electronics Express*, vol. 3, no. 6, pp. 115–121, 2006.

[15] C.-L. Hou, C.-C. Huang, Y.-S. Lan, J.-J. Shaw, and C.-M. Chang, "Current-mode and voltage-mode universal biquads using a single current-feedback amplifier," *International Journal of Electronics*, vol. 86, no. 8, pp. 929–932, 1999.

[16] N. A. Shah and M. A. Malik, "Voltage/current-mode universal filter using FTFN and CFA," *Analog Integrated Circuits and Signal Processing*, vol. 45, no. 2, pp. 197–203, 2005.

[17] S.-I. Liu and J.-L. Lee, "Insensitive current/voltage-mode filters using FTFNs," *Electronics Letters*, vol. 32, no. 12, pp. 1079–1080, 1996.

[18] N. A. Shah and M. A. Malik, "Multifunction mixed-mode filter using FTFNs," *Analog Integrated Circuits and Signal Processing*, vol. 47, no. 3, pp. 339–343, 2006.

[19] N. A. Shah, S. Z. Iqbal, and B. Parveen, "SITO high output impedance transadmittance filter using FTFNs," *Analog Integrated Circuits and Signal Processing*, vol. 40, no. 1, pp. 87–89, 2004.

[20] C.-L. Hou, "A filter with three voltage-inputs and one voltage-output and one current-output using current conveyors," *Tamkang Journal of Science and Engineering*, vol. 7, no. 3, pp. 145–148, 2004.

[21] N. Pandey, S. K. Paul, A. Bhattacharyya, and S. B. Jain, "A new mixed mode biquad using reduced number of active and passive elements," *IEICE Electronics Express*, vol. 3, no. 6, pp. 115–121, 2006.

[22] A. Toker, O. ÇiÇekoglu, S. Özcan, and H. Kuntman, "High output impedance transadmittance type continuous time multifunction fillter with minimum active elements," *International Journal of Electronics*, vol. 88, no. 10, pp. 1085–1091, 2001.

[23] M. T. Abuelma'atti and A. Bentrcia, "A novel mixed-mode CCII-based filter," *Active and Passive Electronic Components*, vol. 27, no. 4, pp. 197–205, 2004.

[24] M. T. Abuelma'atti, "A novel mixed-mode current-controlled current-conveyor-based filter," *Active and Passive Electronic Components*, vol. 26, no. 3, pp. 185–191, 2003.

[25] A. U. Keskin, "Voltage-mode high-Q band-pass filters and oscillators employing single CDBA and minimum number of components," *International Journal of Electronics*, vol. 92, no. 8, pp. 479–487, 2005.

[26] A. U. Keskin and E. Hancioglu, "Current mode multifunction filter using two CDBAs," *International Journal of Electronics and Communications*, vol. 59, no. 8, pp. 495–498, 2005.

[27] A. U. Keskin, D. Biolek, E. Hancioglu, and V. Biolková, "Current-mode KHN filter employing current differencing transconductance amplifiers," *International Journal of Electronics and Communications*, vol. 60, no. 6, pp. 443–446, 2006.

[28] W. Tangsrirat, T. Dumawipata, and W. Surakampontorn, "Multiple-input single-output current-mode multifunction filter using current differencing transconductance amplifiers," *International Journal of Electronics and Communications*, vol. 61, no. 4, pp. 209–214, 2007.

[29] M. Siripruchyanun and W. Jaikla, "CMOS current-controlled current differencing transconductance amplifier and applications to analog signal processing," *International Journal of Electronics and Communications*, vol. 60, 2007.

[30] W. Tangsrirat, "Low-voltage digitally programmable current-mode universal biquadratic filter," *International Journal of Electronics and Communications*, 2007.

[31] D. R. Frey, "Log-domain filtering: an approach to current-mode filtering," *IEE Proceedings G: Circuits, Devices & Systems*, vol. 140, no. 6, pp. 406–416, 1993.