Advances in Science, Technology and Engineering Systems Journal Vol. 6, No. 1, 1120-1127 (2021)

www.astesj.com

Special Issue on Multidisciplinary Sciences and Engineering

ASTESJ

ISSN: 2415-6698

Electronically Tunable Triple-Input Single-Output Voltage-Mode Biquadratic Filter Implemented with Single Integrated Circuit Package

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A R T I C L E I N F O

Article history:
Received: 30 September, 2020
Accepted: 31 January, 2021
Online: 25 February, 2021

Keywords:
Commercially available IC LT1228
Voltage mode circuit
Biquadratic filter

A B S T R A C T

This article proposes a compact and simple design of electronically adjustable voltage-mode biquadratic filter using fundamental active cell implemented on a single integrated circuit (IC) package as LT1228. The proposed circuit having triple inputs and single output (TISO) employs namely one resistor and two capacitors as the passive components. All the five possible biquadratic filtering responses, namely low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP), are realized by the appropriate selection of the relevant input signals. The pole angular frequency and the quality factor of the proposed TISO filter are electronically tunable through the bias current of the IC chip LT1228. Non-ideal effects and sensitivity performance are carried out. The theoretical results are satisfactorily validated by both PSPICE simulation results and experimental measurements using commercially available LT1228.

1. Introduction

Over the decade, analog filters always play a role in many important analog signal processing applications, i.e. communication systems, measurement and instrumentation systems, etc. Nowadays, the realization of an active analog filter using versatile active building blocks has been focused by many researchers due to many advantage features, such as simple circuitry, high linearity, and wide dynamic range. In the literature, many modern active electronic elements have been utilized in analog active filter design, such as current conveyor (CC) [1–7], differential difference current conveyor (DDCC) [8–12], differential voltage current conveyor (DVCC) [13–16], fully differential second-generation current conveyor (FDCCII) [17], current differencing buffered amplifier (CDBA) [18–20], current feedback operational amplifier (CFOA) [21–27], current follower transconductance amplifier (CFTA) [28–29], operational transconductance amplifier (OTA) [30–34], voltage differencing buffered amplifier (VDBA) [35–36], voltage differencing inverting buffered amplifier (VDIBA) [37], fully balanced voltage differencing buffered amplifier (FB-VDBA) [38], voltage differencing transconductance amplifier (VDTA) [39–41], and voltage differencing gain amplifier (VDGA) [42–44]. However, so many of them require at least two or more active elements for their realizations [1–5, 7, 8, 10, 11, 13, 18–27, 30–39, 41, 43, 44]. Moreover, the voltage-mode filters presented in [1–17, 19–29, 38, 42] need a large number of passive resistors, while the articles in [1, 4, 16, 22] also contain three passive capacitors. It is also to be emphasized that the realizations of [1–27] suffer from the lack of electronic tuning capability of their important parameters. Even though some similar works were developed by based on various active building blocks in either bipolar junction transistor or (BJT) or complementary metal oxide semiconductor (CMOS) technologies, they are not commercially available chips and reachable in general. Besides, the performances of the research developments in [1–4, 7–20, 22, 24, 25, 28–37, 39–44] have been demonstrated through only simulation results.

In this communication, an electronically tunable voltage-mode biquadratic filter with three input and one output terminals (TISO) consisting of only single active IC package LT1228, one resistor and two capacitors is introduced. The proposed TISO filter can realize the five standard biquadratic filtering responses, namely low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP), all at a single output terminal without modifying a circuit structure. It also provides an electronic adjustability of its pole angular frequency (ω_o) and quality factor (Q) via the external bias current of the LT1228 IC chip. The theoretical propositions are confirmed by PSPICE simulations with LT1228's model parameters, and the simulated results corroborate the theory. In addition, all conclusions discussed in this work are also verified by

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This paper is an extended version from the proceedings of 2020 8th International Electrical Engineering Congress (iEECON) [45]

https://dx.doi.org/10.25046/aj0601125

the measurement results of an experimentally test circuit with a single IC package LT1228, and the experimental findings are found to be in agreement with the theoretical values.

2. Description of IC Package LT1228

Our design utilizes only one active cell of a commercially available IC LT1228 from Linear Technology Company [46]. An active cell LT1228 is internally a combination of an operational transconductance amplifier (OTA) and a current feedback operational amplifier (CFA) in 8-pin IC package, as demonstrated in Figure 1. This device has three high impedance input terminals (p, n, and z), and one low impedance output terminal (o). It provides the output current i_z at intermediate terminal z which is the difference of two input voltages v_p and v_n ($v_p - v_n$) multiplied by transconductance gain (g_m). An external impedance Z_z is connected to the terminal z, and the potential v_z developed across Z_z will transfer to the output voltage v_o at the terminal o by the CFA. Its ideal terminal characteristics can be described as:

$$\begin{bmatrix} i_p \\ i_n \\ i_z \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_p \\ v_n \\ v_z \\ i_o \end{bmatrix} . \quad (1)$$

Thanks to the LT1228 manufacturing, the g_m-value can be altered to the desired value through the external DC bias current I_B by the following relation: [46]

$$g_m = 10 I_B . \quad (2)$$

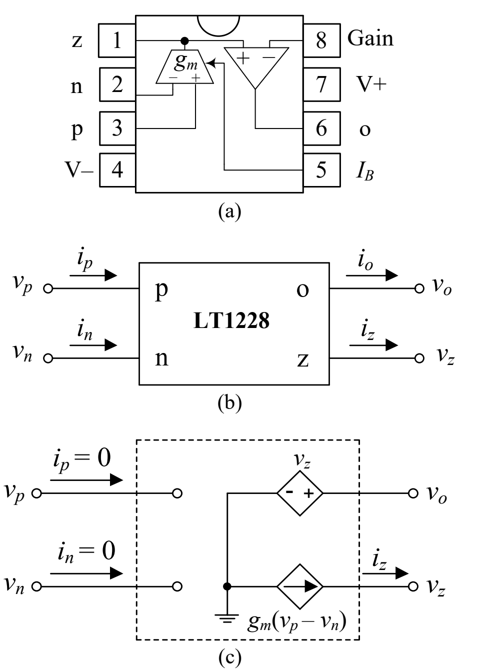


Figure 1: IC device LT1228.
(a) active elements in LT1228 (b) schematic representation
(c) equivalent circuit.

3. Proposed TISO Biquadratic Filter

The realization of an electronically tunable TISO voltage-mode biquadratic filter is given in Figure 2. The proposed TISO filter is implemented with a single LT1228 together with one resistor and two capacitors. A straightforward analysis of the proposed TISO filter reveals the following output voltage function:

$$V_{out}(s) = \frac{s^2 R_1 C_1 C_2 V_3 + s C_1 V_2 + g_m V_1}{D(s)} , \quad (3)$$

where the denominator $D(s)$ is found to be:

$$D(s) = s^2 R_1 C_1 C_2 + s C_1 + g_m . \quad (4)$$

From an inspection of Equations (3)-(4), it appears the five standard biquadratic filter functions can be obtained all at the terminal v_{out} of the proposed circuit by the following conditions.

(i) The LP response is obtained by setting $v_{in} = v_1$ (input voltage signal) and $v_2 = v_3 = 0$ (grounded).

(ii) The BP response is obtained by setting $v_{in} = v_2$ and $v_1 = v_3 = 0$.

(iii) The HP response is obtained by setting $v_{in} = v_3$ and $v_1 = v_2 = 0$.

(iv) The BS response is obtained by setting $v_{in} = v_1 = v_3$ and $v_2 = 0$.

(v) The AP response is obtained by setting $v_{in} = v_1 = -v_2 = v_3$.

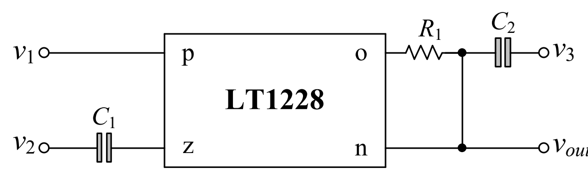


Figure 2: Proposed electronically tunable TISO biquad implementation employing single LT1228.

Therefore, the proposed TISO filter of Figure 2 does not require any element matching conditions or equality constraints for the desired filter function realizations. In all types, the important characteristics ω_o, and Q are respectively found as:

$$\omega_o = 2\pi f_o = \sqrt{\frac{g_m}{R_1 C_1 C_2}} , \quad (5)$$

and

$$Q = \sqrt{\frac{g_m R_1 C_2}{C_1}} . \quad (6)$$

In case of practical design, if $C = C_1 = C_2$, then the ω_o and Q simplify to:

$$\omega_o = \frac{1}{C}\sqrt{\frac{g_m}{R_1}} , \quad (7)$$

and

$$Q = \sqrt{g_m R_1} . \quad (8)$$

In view of the above expressions, the parameters ω_o and Q of the proposed TISO filter can be altered electronically by means of g_m-value. According to Equation (2), the g_m variation can be obtained by an adjustment of the bias current. Also note that since the major contribution of this work is to design a compact and minimum configuration voltage-mode TISO filter with electronic tunability, an orthogonal control of ω_o or Q is not expected.

4. Non-Ideal Analysis and Sensitivity Performance

In consideration of the non-ideal behavior, the terminal behaviors of LT1228 can be rewritten as:

$$\begin{bmatrix} i_p \\ i_n \\ i_z \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \alpha g_m & -\alpha g_m & 0 & 0 \\ 0 & 0 & \beta & 0 \end{bmatrix} \cdot \begin{bmatrix} v_p \\ v_n \\ v_z \\ i_o \end{bmatrix} , \quad (9)$$

where $\alpha = (1 - \varepsilon_{gm})$ and $\beta = (1 - \varepsilon_v)$, where $|\varepsilon_{gm}| << 1$ and $|\varepsilon_v| << 1$ are the transconductance inaccuracy and the voltage transfer error, respectively. Taking this effect into account, the characteristics ω_o and Q given in Equations (5) and (6) are modified to:

$$\omega_o = \sqrt{\frac{\alpha\beta g_m}{R_1 C_1 C_2}} , \quad (10)$$

and

$$Q = \sqrt{\frac{\alpha\beta g_m R_1 C_2}{C_1}} . \quad (11)$$

In this case, all sensitivity coefficients of ω_o and Q with respect to the active and passive components are derived and found to be as follows:

$$S_{\alpha}^{\omega_o} = S_{\beta}^{\omega_o} = S_{g_m}^{\omega_o} = \frac{1}{2} , \quad (12)$$

$$S_{R_1}^{\omega_o} = S_{C_1}^{\omega_o} = S_{C_2}^{\omega_o} = -\frac{1}{2} , \quad (13)$$

$$S_{\alpha}^{Q} = S_{\beta}^{Q} = S_{g_m}^{Q} = S_{R_1}^{Q} = S_{C_2}^{Q} = \frac{1}{2} , \quad (14)$$

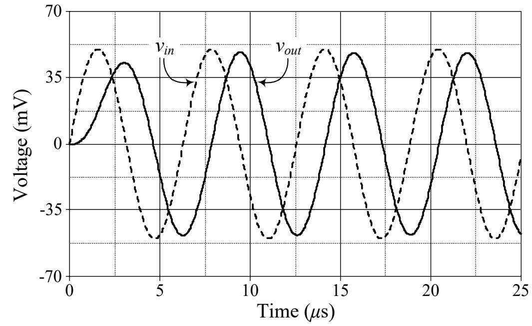
and

$$S_{C_1}^{Q} = -\frac{1}{2} . \quad (15)$$

It is clear from Equations (12)-(15) that the absolute values of the ω_o- and Q-sensitivities are all equal to 0.5. These values ensure that the sensitivity performance of the circuit is to be of low value.

5. Simulation Results

In this section, the proposed circuit and its filtering responses are simulated and discussed through the PSPICE simulation program. For ideal simulation, the LT1228 macro-model parameters obtained from Linear Technology Company and DC supply voltages of ±5V were employed. To demonstrate the functionality of the proposed filter, the circuit is designed for f_o = 159.15 kHz and Q = 1. In this case, the various component values have been set as I_B = 100 µA for g_m = 1 mA/V, R_1 = 1 kΩ and C_1 = C_2 = 1 nF. The simulation results for all filter responses are shown in Figures 3-7, which demonstrates very close agreement with the theoretical responses. For time-domain responses, a 159-kHz sine-wave input voltage with 50 mV peak amplitude was applied to the filter. The simulation results show that the error in f_o-value was found to be less than 1%.



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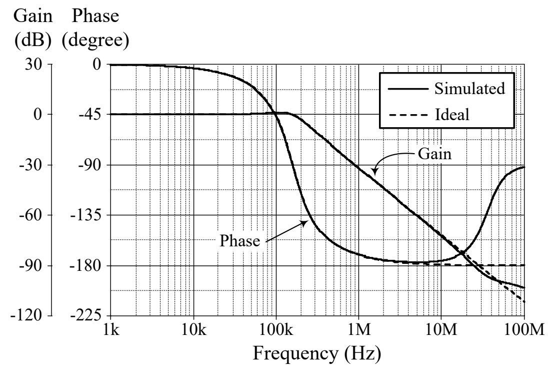

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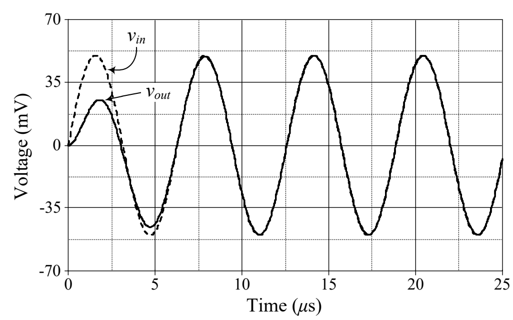
Figure 3: Ideal and simulated LP characteristics
(a) time-domain responses (b) frequency responses



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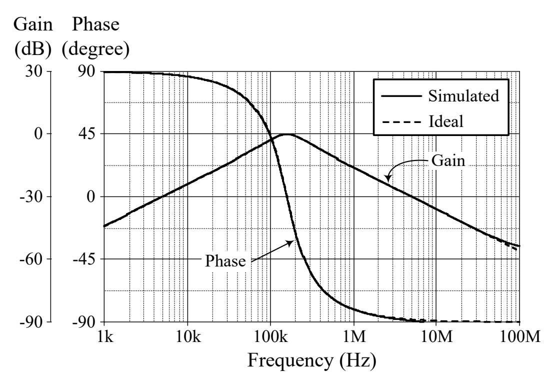

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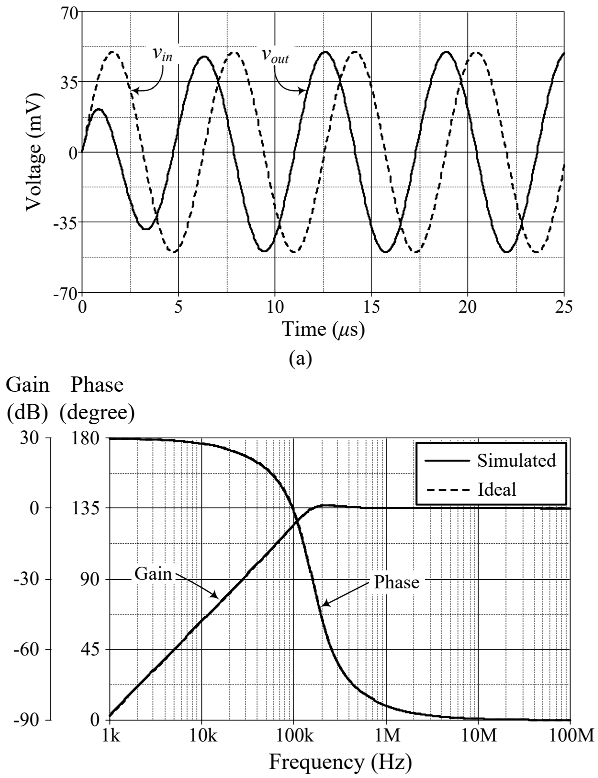
Figure 4: Ideal and simulated BP characteristics
(a) time-domain responses (b) frequency responses



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(b)

Figure 5: Ideal and simulated HP characteristics
(a) time-domain responses (b) frequency responses

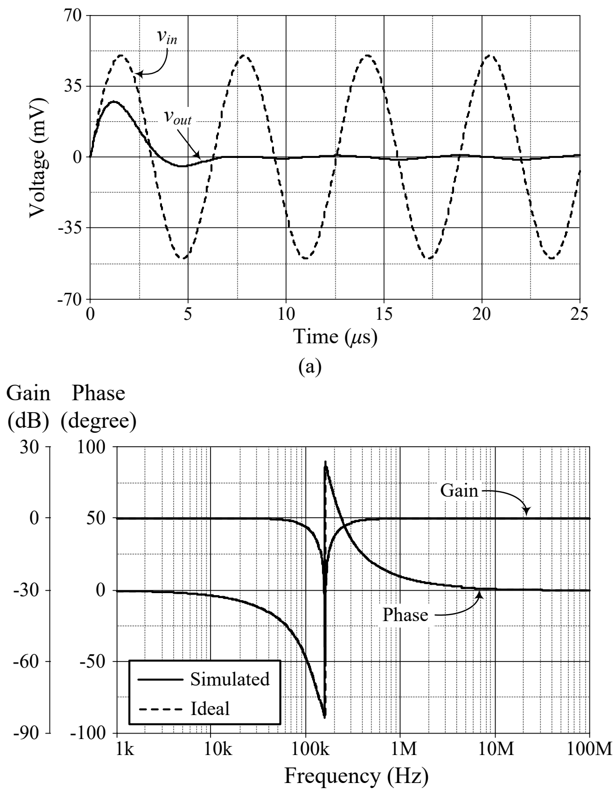

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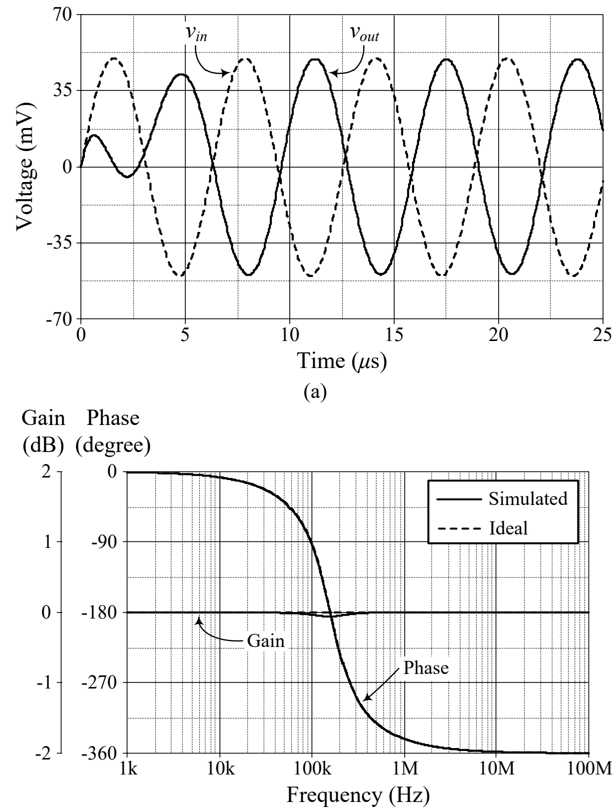
Figure 6: Ideal and simulated BS characteristics
(a) time-domain responses (b) frequency responses



(a)

(b)

Figure 7: Ideal and simulated AP characteristics
(a) time-domain responses (b) frequency responses

Furthermore, the electronic tuning of gain characteristic for BP filter concerning I_B is observed. The related gain expressions of the proposed BP filter, as shown in Figure 8, are plotted for $I_B = 50$ μA, 200 μA, and 500 μA, which resulted in $g_m = 0.5$ mA/V, 2 mA/V, and 5 mA/V, respectively. From Figure 8, the simulation conditions, and corresponding theoretical and simulated f_o and Q are summarized in Table 1.

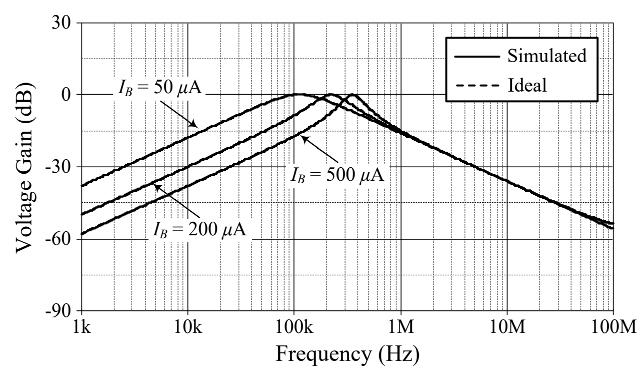


Figure 8: Ideal and simulated frequency responses of the proposed BP filter with an adjustment of I_B.

6. Experimental Results

To further validate the practical workability of the TISO biquadratic filter in Figure 2, the prototype circuit built with readily available IC element LT1228 and discrete passive elements were used to execute experimentally laboratory tests. The circuit was measured using Keysight EDUX1002G digital storage oscilloscope. All of the measured results were performed

Table 1: f_o and Q adjustment of the proposed filter by varying I_B

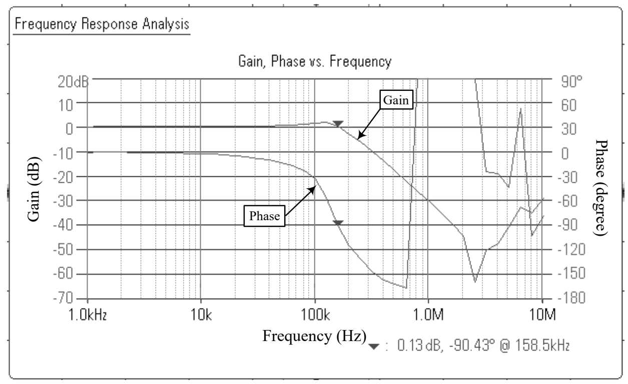
I_B (μA)	g_m (mA/V)	R_1 (kΩ)	C (nF)	Q	f_o (kHz)		% f_o deviation
					Simulated	Ideal	
50	0.5	1	1	0.7	111.43	112.54	0.99
100	1	1	1	1	157.70	159.15	0.91
200	2	1	1	1.4	222.84	225.08	0.99
500	5	1	1	2.2	352.37	355.88	0.99

at symmetrical supply voltages of ±5 V, and I_B = 100 μA (g_m = 1 mA/V), R_1 = 1 kΩ, and $C_1 = C_2$ = 1 nF. This results in f_o = 159.15 kHz and Q = 1. To observed transient response, the measurement was carried out with a 159-kHz sine-wave signal input of 50 mV peak amplitude. The experimental results for the transient and frequency responses as well as the associated frequency spectrums are displayed in Figures 9-13. Also from Figures 9(c)-13(c), the measured results of the percentage total harmonic distortion (%THD) of the v_{out} for each filtering responses are noted in Table 2. It can be concluded that the measured results are close to the theoretical analysis, and also verify the functionality of the proposed circuit.

Table 2: Total harmonic distortions of v_{out} in Figure 2.

Filter	THD (%)
LP	0.67
BP	4.47
HP	0.73
BS	2.4
AP	0.32

Another set of measurements have been carried out to examine the electronic adjustability of the proposed TISO filter. BP filter response is used for illustrative purposes. Figure 14 illustrates the measured BP frequency responses for various bias current I_B. The g_m-values of the considered filter have been set as 0.5 mA/V, 2 mA/V, and 5 mA/V, for I_B = 50 µA, 200 µA, and 500 µA, respectively. As follows from Equations (5) and (6), the f_o values have been obtained as 112.54 kHz, 225.08 kHz, and 355.88 kHz, while the Q values have been obtained as 0.7, 1.4, and 2.2, respectively.



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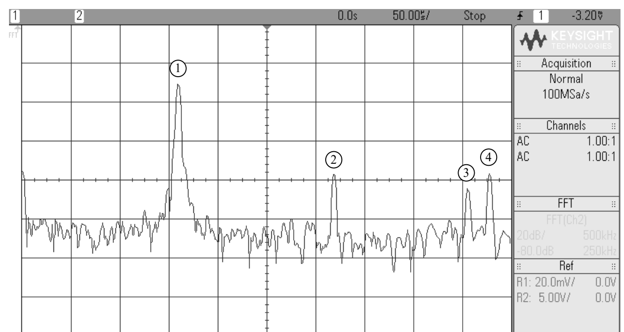
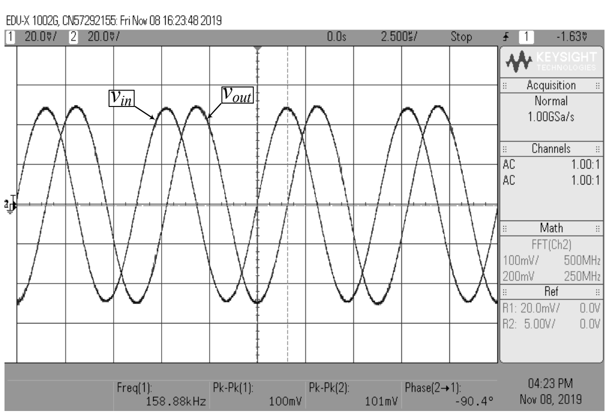


	Frequency (kHz)	Gain (dB)
①	159.1	-30.625
②	318.5	-78.875
③	455.8	-84.375
④	477.7	-76.250

(c)

Figure 9: Experimental results of the proposed LP filter.
(a) time-domain responses (b) frequency responses
(c) frequency spectrum



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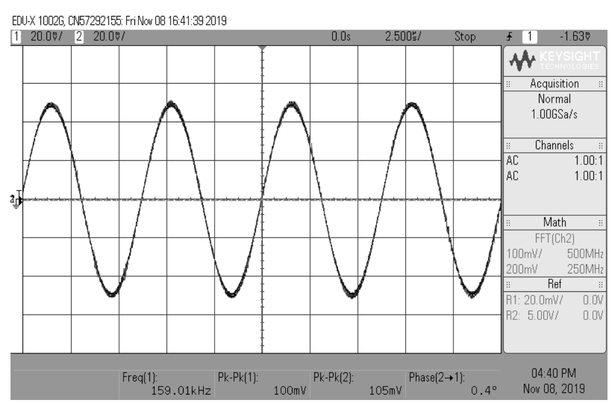

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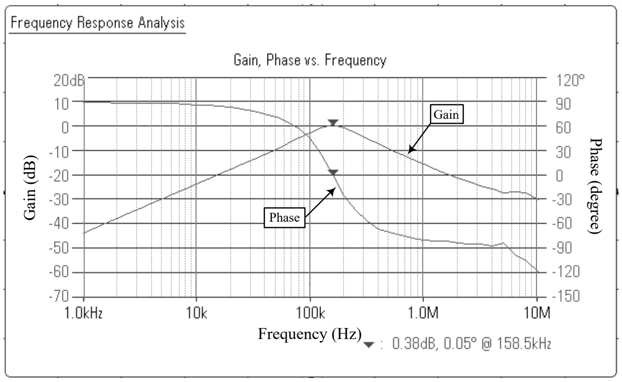

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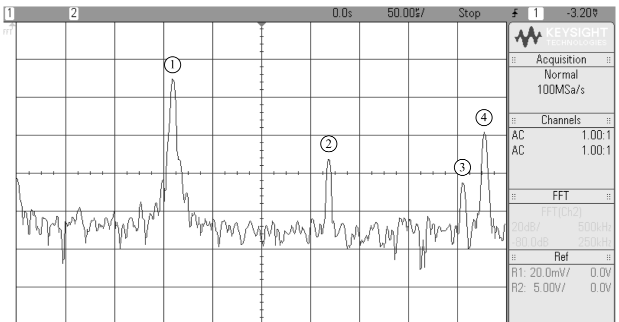
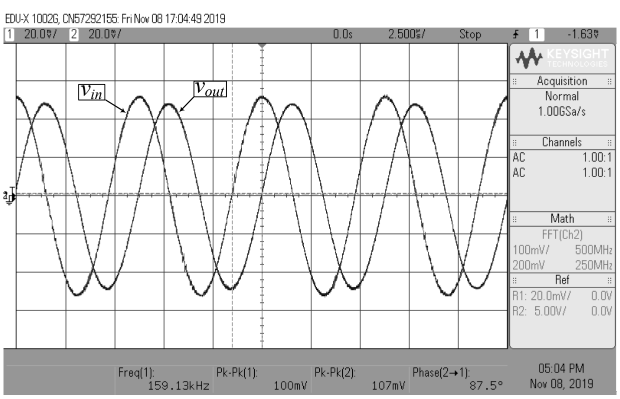


	Frequency (kHz)	Gain (dB)
①	159.1	-30.000
②	318.5	-72.500
③	455.1	-84.375
④	477.7	-57.125

(c)

Figure 10: Experimental results of the proposed BP filter
(a) time-domain responses (b) frequency responses
(c) frequency spectrum



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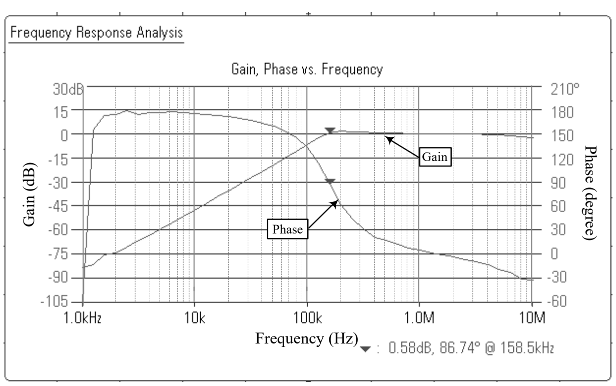

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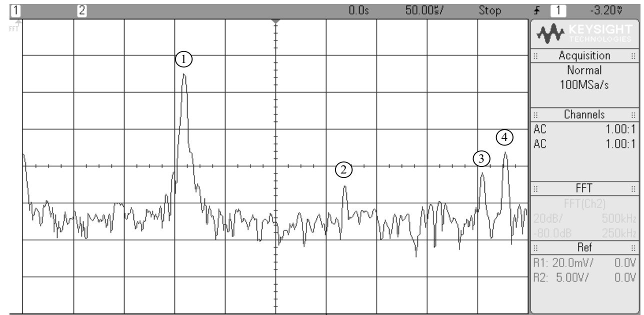
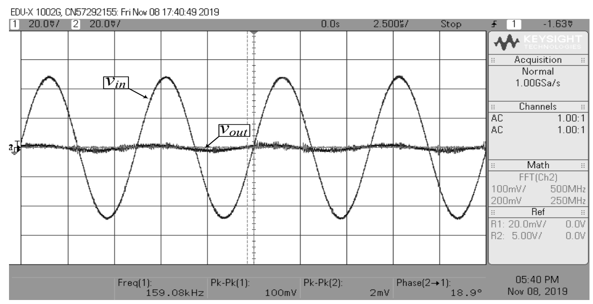


	Frequency (kHz)	Gain (dB)
①	159.1	-29.375
②	318.5	-90.625
③	454.9	-83.750
④	477.7	-72.500

(c)

Figure 11: Experimental results of the proposed HP filter
(a) time-domain responses (b) frequency responses
(c) frequency spectrum



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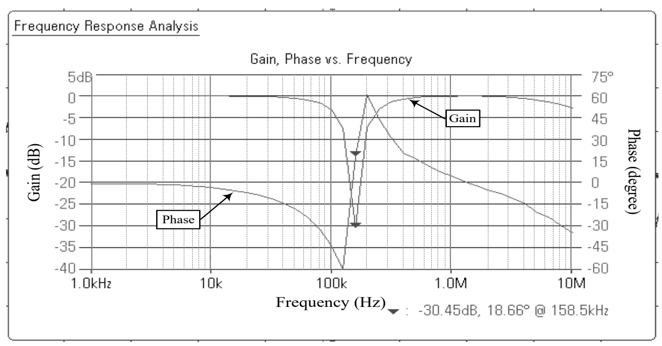

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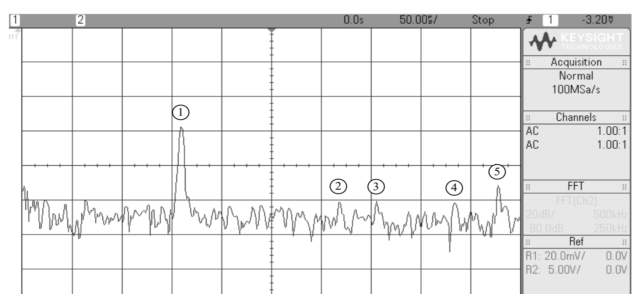
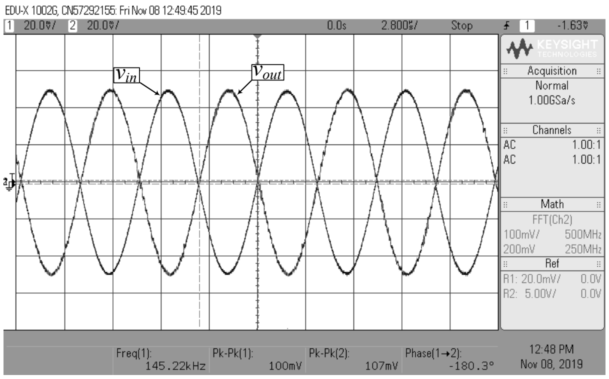


	Frequency (kHz)	Gain (dB)
①	159.1	-57.500
②	318.5	-100.625
③	365.8	-100.000
④	434.0	-100.625
⑤	477.7	-91.250

(c)

Figure 12: Experimental results of the proposed BS filter
(a) time-domain responses (b) frequency responses
(c) frequency spectrum



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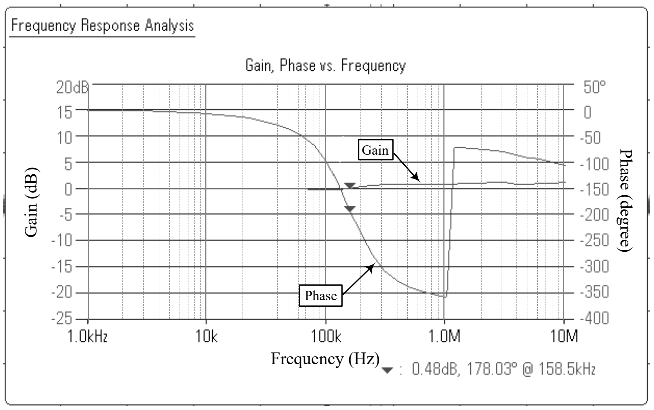

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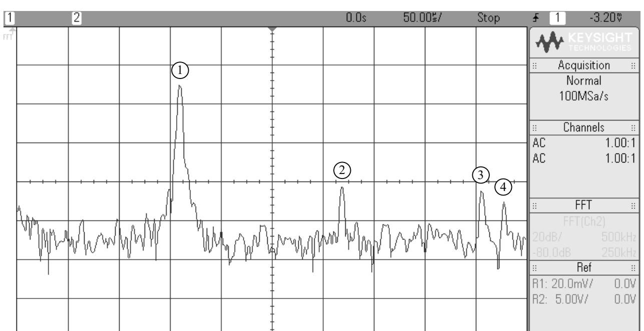
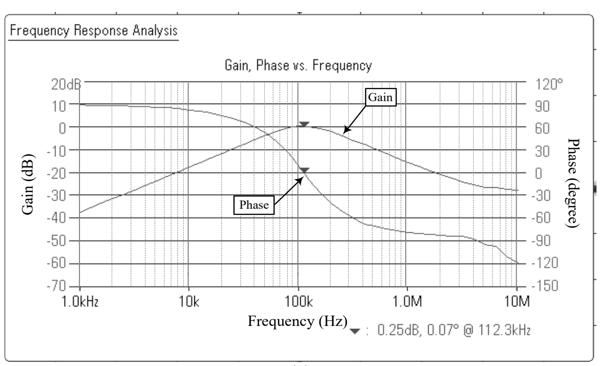


Frequency (kHz)		Gain (dB)
①	159.1	-30.000
②	318.5	-82.500
③	455.8	-84.375
④	477.7	-90.000

(c)

Figure 13: Experimental results of the proposed AP filter
(a) time-domain responses (b) frequency responses
(c) frequency spectrum



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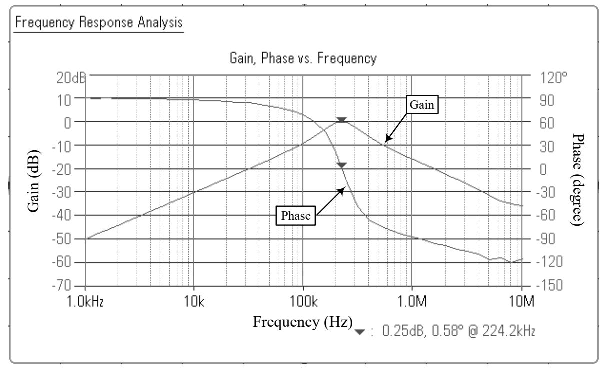

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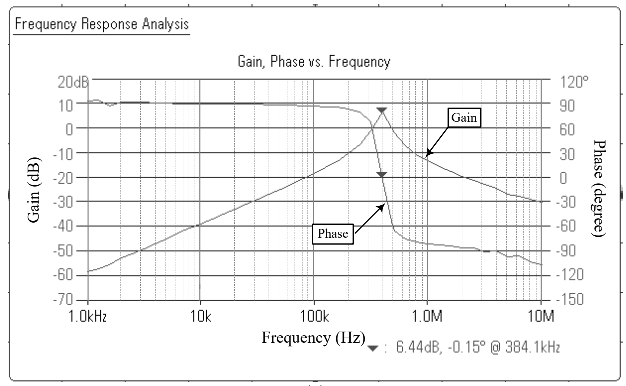

(c)

Figure 14: Measured gain responses for the proposed BP filter with an adjustment of I_B.
(a) $I_B = 50\ \mu$A (b) $I_B = 200\ \mu$A (c) $I_B = 500\ \mu$A

7. Conclusions

This contribution describes the practical implementation of an electronically tunable voltage-mode biquadratic filter with triple input terminals and single output terminal. The proposed filter employs only a single commercially available IC LT1228 together with one resistor and two capacitors. The filter can realize all five standard biquadratic filtering functions all at a single output terminal by an appropriate input signal selection. The characteristics of ω_o and Q can be controlled electronically and linearly in an electronic manner via the external bias current. Simulation results obtained from the PSPICE macro-model of the LT1228 by Linear Technology as well as constructed in prototype hardware using commercially available IC LT1228 are performed to confirm the properties of the proposed circuit.

Conflict of Interest

The authors declare that they have no conflict of interest.

Acknowledgment

This work was supported by the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL) under the contract number 2563-02-01-002.

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