Voltage-Mode Biquad Filter Using Three LT1228s with Independent and Electronic Control of Center Frequency and Quality Factor

May Phu Pwint Wai, Winai Jaikla, Amornchai Chaichana*, Chaiyan Chanapromma, Peerawut Suwanjan, and Wisuit Sunthonkanokpong

Abstract— **In this paper, we describe a voltage-mode (VM) biquad universal filter with one input and four outputs that can be tuned electronically. The filter proposed here is composed of three LT1228 commercial integrated circuits (ICs), seven resistors and two grounded capacitors. The proposed versatile biquad filter simultaneously provides four filtering functions: an inverting low-pass filter (LP), an inverting high-pass filter (HP), a non-inverting bandpass filter (BP), and an inverting notch filter (BR) without changing its topology. Employing two grounded capacitors minimizes the influence of parasitic resistances and capacitances on the proposed circuit's performance. Also, the output voltage nodes of the HP and BR functions have low output impedances. This means that these two filtering functions don't need voltage buffers to connect to other voltage-mode topologies. The center frequency (ω_0) of the presented filter is electronically controlled and does not influence the quality factor (Q). In addition, they can also be tuned linearly without affecting each other. PSPICE software was used to analyze the modelling results, while a laboratory experiment was performed using LT1228 commercial ICs.**

Index Terms—**Biquad filter, LT1228, electronic control, independent controllability, Voltage-mode circuit**

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I. INTRODUCTION

ANALOG active filters utilizing active building blocks (ABBs) for application in analog signal processing systems have been extensively investigated. Using ABBs to design filtering circuits has many benefits, such as the ability to cascade without buffers due to high input and low output impedances at input and output nodes for voltage-mode circuits and low input and high output impedances at input and output nodes for current-mode circuits, flexibility in design, and a small number of active and passive elements. Furthermore, various filter parameters, including the -3 dB cutoff frequency, bandwidth, passband gain, quality factor, and phases [1–3], can be electronically tuned. The universal filter with single-input, multiple-output (SIMO) configuration is an illustration of a filter type that offers many filtering functions in a single configuration. The SIMO filter is utilized in many applications, such as phase-locked loop (PLL) circuits, touch-tone telephone decoders, FM stereo demodulators, and three-way crossover networks [4–6]. The synthesis of SIMO universal analog filters can be achieved by using different varieties of active building blocks like extra X current conveyor transconductance amplifier (EXCCTA) [6], fully differential current conveyor (FDCCII) [7–10], second-generation voltage conveyor (VCII) [11], operational transconductance amplifier (OTA) [12–14], voltage differencing current conveyor (VDCC) [15] second-generation current conveyor (CCII) [16–17], inverting second-generation current conveyor (ICCII) [18], differential voltage current conveyor (DVCC) [19–20], voltage differencing transconductance amplifier (VDTA) [21–24], differential difference current conveyors transconductance amplifier (DDCCTA) [25], differential difference current conveyors (DDCC) [26–28], current-feedback amplifiers (CFAs) [29], current feedback operational amplifier (CFOA) [30], voltage differencing differential difference amplifier (VDDDA) [31–32], voltage differencing differential inverted buffered amplifier (VD-DIBA) [33–34], etc.

In recent years, interest has grown in the design of analog signal processing circuits using the LT1228, a commercially available active building block manufactured by Linear Technology Corporation [35]. LT1228 includes an operational transconductance amplifier (OTA) with electronic tuning capabilities and a current feedback amplifier (CFA). The property of the electronic tuning can be achieved by changing the transconductance gain via the

TABLE I
COMPARISON BETWEEN THE PROPOSED VM UNIVERSAL BIQUAD FILTER AND VARIOUS EXISTING SIMO FILTERS USING DIFFERENT ABBS

Ref	ABB	No. of ABB	No. of Commercial ICs	Use of grounded capacitors	Filtering functions	No. of low output impedance	Electronic tune both f_0 and Q	Independent tune of f_0 and Q	Experimental Results
[6]	EXCCTA (Fig. 3b)	2	NA	√	LP, BP, HP, BR, AP	2	√	√	X
[7]	FDCCII	1	NA	X	LP, BP, HP, BR	1	X	X	X
[8]	FDCCII	2	NA	√	LP, BP, HP, BR, AP	0	X	X	X
[9]	FDCCII	1	NA	√	LP, BP, HP, BR, AP	0	X	X	X
[10]	FDCCII	1	NA	√	LP, BP, HP, BR	0	X	X	X
[11]	I-CB & VCII	4	NA	X	LP, BP, HP	3	X	X	X
[12]	OTA	6	NA	√	LP, BP, HP, BR, AP	0	√	X	X
[13]	OTA	8	4	√	LP, BP, HP, BR, AP	0	√	X	√
[14]	OTA	7	NA	√	LP, BP, HP, BR	0	√	X	X
[15]	VDCC (Fig. 3b)	1	3	√	HP, BP	0	√	X	√
[16]	CCII	4	NA	√	LP, BP, HP	0	X	X	X
[17]	CCII	4	4	√	LP, BP, HP, BR, AP	0	X	X	√
[18]	ICCII	2	NA	√	LP, BP, HP	0	X	X	X
[19]	DVCC	2	NA	√	LP, BP, HP, BR, AP	0	X	X	X
[20]	DVCC	1	NA	X	LP, BP, HP, BR	0	X	X	X
[21]	VDTA	3	NA	√	LP, BP, HP	0	√	√	X
[22]	VDTA	1	NA	X	LP, BP, HP	0	√	X	X
[23]	VDTA	2	NA	√	LP, BP	0	√	X	X
[24]	VDTA	2	NA	√	LP, BP, HP, BR, AP	0	√	√	X
[25]	DDCCTA	2	NA	√	LP, BP, HP, BR, AP	0	√	√	X
[26]	DDCC	3	6	√	LP, BP, HP, BR, AP	0	X	X	√
[27]	DDCC	3	NA	√	LP, BP, HP, BR, AP	2	X	X	X
[28]	DDCC	1	NA	√	LP, BP, HP, BR	0	X	X	X
[29]	CFA	3	3	√	LP, BP, BR	3	X	X	√
[30]	CFOA	3	3	√	LP, BP, BR	3	X	√	√
[31]	VDDDA	3	6	√	LP, BP, HP, BR, AP	2	√	√	√
[32]	VDDDA	3	6	√	LP, BP, HP, BR, AP	3	√	√	√
[33]	VD-DIBA (Fig. 5)	2	4	√	LP, HP, BP, BR	2	X	√	√
[34]	VD-DIBA	2	4	√	LP, BP, HP	1	√	X	√
[36]	LT1228	3	3	√	LP, BP, HP	2	√	√	√
[37]	LT1228 (1st proposed)	2	2	√	LP, BP, HP	2	X	√	√
	LT1228 (2nd proposed)	2	2	√	LP, BP, HP	2	X	√	√
[38]	LT1228 (1st proposed)	2	2	√	LP, BP, HP	2	√	X	√
	LT1228 (2nd proposed)	2	2	√	LP, BP, HP	2	√	X	√
Proposed	LT1228	3	3	√	LP, HP, BP, BR	2	√	√	√

The LM13700 and the AD830, two commercially available ICs, are used to realize VDDDA and VD-DIBA in [31]– [34]

DC bias current, which can be easily handled by a microprocessor or microcontroller. This device's input voltage terminals all have high impedance, and its CFA is the best buffer for the transconductance amplifier's output. Moreover, the LT1228 IC provides a wide tuning range for the transconductor. LT1228 is ideal for using to design analog voltage-mode circuits with electronic controllability owing to these characteristics [35]. Therefore, numerous studies have been conducted on commercially available IC LT1228-based analog filters [36–38], inductance simulators [39], capacitance multipliers [40], sinusoidal oscillators [41], and triangular/square wave generators [42].

The literature review has reported several single-input, multiple-output active biquad filters using different ABBs [6–34]. They have many beneficial characteristics, but they still have some disadvantages, as follows: The filters proposed in [7, 11, 20, 22] use floating capacitors; the filters implemented in [7-11, 16-20, 26-30, 33, 37] are not electronically tuned between ω_0 and Q; the universal filters realized in [7-20, 22, 23, 26-29, 34, 38] provide non-interactive control between ω_0 and Q; and the filtering structures in [6-12, 14, 16, 18-25, 27, 28] do not use commercially available ICs. Because the filter proposed in this paper uses LT1228 as an ABB, the review of LT1228-based SIMO universal filters [36–38] will be carefully discussed. A LT1228-based single-input and three-output (SITO) second-order active filter was reported in [36]. The circuit was realized from three LT1228s, four resistors, and two grounded capacitors. It can be provided only three filtering responses: LP, HP, and BP. The center frequency of this filter is electronically controlled and does not influence the quality factor. The HP and BP responses have low output impedances. A SITO voltage-mode multifunction biquad filter with two LT1228s and passive components (five resistors and two grounded capacitors) was proposed in [37]. This work describes two proposed filters that can provide independent adjusting features for ω_0 and Q. However, they cannot be electronically controlled by both ω_0 and Q. The low impedance features can be provided at the HP and BP voltage output nodes for the first proposed active filter, whereas the low impedance features can be provided at the LP and BP voltage output nodes for the second proposed active filter. In [38], the universal SITO biquad filters employing two LT1228s cannot offer independent controllability of ω_0 and Q, but they can only be electronically adjusted. The proposed filter is compared with other filters that use different ABBs in Table I.

This study introduces a one-input voltage and four-output voltage biquad filter using three LT1228s. This contribution is divided into five major sections. Firstly, Section I describes the introduction, and Section II shows the review of LT1228, the principle for synthesizing the filter, the proposed filter, and a non-ideal study. The related illustrations of the PSpice simulation and experimental laboratory results of the proposed LT1228-based biquad filter are explained in Sections III and IV, respectively. The conclusion is finally described in Section V.

II. Proposed Universal Biquad Filter

A. Principle Operation of LT1228

In analog circuit design, the commercially available active device LT1228 has been used a lot in the past few years. It consists of an OTA and a CFA combined into one chip. The electronic control properties of the LT1228 can be obtained by adjusting the external DC bias current (I_B). Figs. 1(a) and (b) depict the circuit symbol and equivalent circuit for LT1228, respectively. Fig. 1(c) depicts the internal pin diagram of the LT1228, which has eight terminals. High impedances are present in the V_+ and V_- input voltage terminals, as well as in the y output current terminal. The x and w output voltage terminals have low impedance. The following equation is the form of the LT1228's electrical terminal matrix:

$$\begin{pmatrix} I_{V+} \\ I_{V-} \\ I_y \\ V_x \\ V_w \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_T & 0 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_y \\ I_x \\ I_w \end{pmatrix} \quad (1)$$

where R_T is the transresistance gain. The R_T value is infinite for an ideal. The external I_B is used to electronically tune the transconductance, g_m: $g_m=I_B/3.87V_T$ [35]. V_T is the thermal voltage. The microcontroller or microcomputer can be applied for this electronic control.

B. Synthesis of a proposed VM Universal Biquad Filter

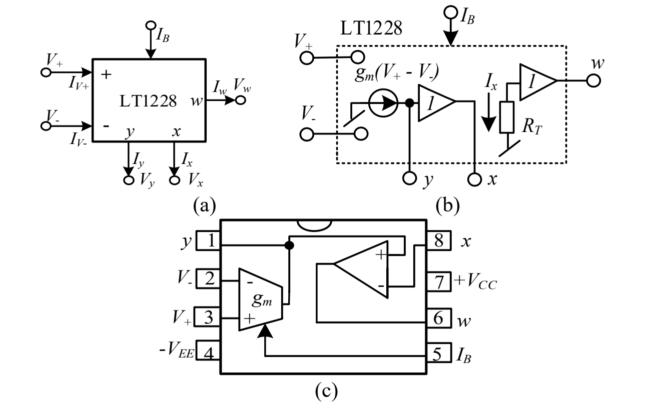


Fig. 1. (a) LT1228's scheme symbol [36] (b) equivalent circuit representation [36] (c) internal pin diagram [35].

Fig. 2 depicts the basic block diagram for synthesizing the proposed filter. It consists of four voltage summing circuits, two voltage-mode lossless integrators with two variables (a and b) representing the time constants of both lossless integrators, three double-gain voltage amplifiers, and one variable-gain voltage amplifier. The input voltage port of represents V_{in}, whereas the output voltage ports of this second-order filter are assigned to V_{BP}, V_{BR}, V_{LP}, and V_{HP}. It is found that the filter simultaneously provides four filtering responses: an LP, HP, BP, and BR.

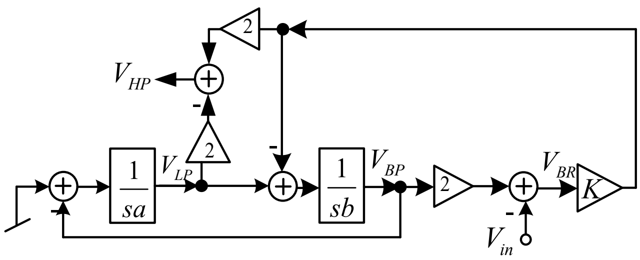


Fig. 2. Functional block diagram for synthesizing the proposed biquad filter.

Routine analysis of the simplified functional block diagram depicted in Fig. 2, the mathematical voltage transfer equations for LP and HP filtering responses are as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{-\dfrac{K}{ab}}{s^2 + s\dfrac{2K}{b} + \dfrac{1}{ab}} \quad (2)$$

$$\frac{V_{HP}}{V_{in}} = \frac{-2Ks^2}{s^2 + s\dfrac{2K}{b} + \dfrac{1}{ab}} \quad (3)$$

The voltage gains for the LP and HP responses obtained from the block diagram depicted in Fig. 2 are K and $2K$, respectively, as shown in (2) and (3). The mathematical transfer equations for BP and BR functions are as follows:

$$\frac{V_{BP}}{V_{in}} = \frac{s\frac{K}{b}}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{4}$$

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{1}{ab}\right)}{s^2 + s\frac{2K}{b} + \frac{1}{ab}} \tag{5}$$

The BP and BR functions have voltage gains of one and half, respectively, as shown in (4) and (5). The ω_0 and Q equations are expressed as follows by examining (2) to (5):

$$\omega_0 = \sqrt{\frac{1}{ab}} \text{ and } Q = \frac{1}{2K}\sqrt{\frac{b}{a}} \tag{6}$$

It is possible to simultaneously adjust two variables, a, and b, of the lossless integrator circuits, in which the center frequency can be tuned in (6), without influencing the quality factor. By changing the voltage gain (K), the quality factor can be changed without effect on the center frequency. As a result, the center frequency and quality factor can be controlled independently. In addition, simultaneous tuning of the variables a and b allows for linear control of the center frequency.

C. Synthesis of a proposed VM Universal Biquad Filter

Based on the simplified block diagram depicted in Fig. 2, the proposed filter is synthesized using the LT1228 IC as the main active element. With this synthesis, it results in the proposed voltage-mode universal biquad filter with one input and four outputs depicted in Fig. 3. It has three function blocks in this synthesis. The first block is an OTA-C inverting voltage-mode lossless integrator and a voltage gain amplifier. The second block is an OTA-C voltage differential voltage-mode lossless integrator and a voltage gain amplifier. The third block is a non-inverting OTA-R amplifier and a voltage gain amplifier. As a result, the LT1228 is appropriate for use in this design because it utilizes both an OTA and CFA in the LT1228. The first voltage inverting lossless integrator is obtained from $LT1228_1$ with grounded capacitor C_1, while the voltage gain amplifier can be achieved from $LT1228_1$ with resistors R_2 and R_1. The second voltage differential lossless integrator is built using the $LT1228_2$ and a grounded capacitor C_2. The $LT1228_2$ with resistors R_4 and R_3 is used to implement the voltage gain amplifier. The non-inverting amplifier can be constructed from $LT1228_3$ with a grounded resistor R_5, whereas the voltage gain amplifier is built from $LT1228_3$ with resistors R_7 and R_6. The single input voltage node, V_{in} does not provide high impedance because the input node is connected in series with R_3. The output voltage of the V_{HP} and V_{BR} nodes, on the other hand, is obtained at the w terminals of the $LT1228_3$, which has an ideally low impedance. The V_{HP} and V_{BR} nodes can be directly connected to external loads in other voltage-mode circuits using this advantage feature, eliminating the need for an additional buffer. In a real application, the output resistances (Z_{oHP} and Z_{oBR}) of the proposed filter are around $Z_{oHP} \cong R_{w3} // R_7$ and $Z_{oBR} \cong R_{w2} // R_4$.

If $R_1 = R_2 = R_3 = R_4 = R_6 = R_7 = R$, the voltage transfer functions of the LT1228-based universal biquad filter depicted in Fig. 3 is described as follows:

$$\frac{V_{LP}}{V_{in}} = \frac{-K\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\frac{2Kg_{m2}}{C_2} + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{7}$$

$$\frac{V_{HP}}{V_{in}} = \frac{-2Ks^2}{s^2 + s\frac{2Kg_{m2}}{C_2} + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{8}$$

$$\frac{V_{BP}}{V_{in}} = \frac{Ks\frac{g_{m2}}{C_2}}{s^2 + s\frac{2Kg_{m2}}{C_2} + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{9}$$

$$\frac{V_{BR}}{V_{in}} = \frac{-\left(s^2 + \frac{g_{m1}g_{m2}}{C_1C_2}\right)}{s^2 + s\frac{2Kg_{m2}}{C_2} + \frac{g_{m1}g_{m2}}{C_1C_2}} \tag{10}$$

where $K = g_{m3}R_5$. In (7), K is the voltage gain for LP filtering functijon, and $2K$ in (8) is the voltage gain for the HP filtering function. The voltage gain for the BP filtering function is half of that in (9). The unity voltage gain for the BR filtering function is verified as depicted in (10).
The equations of ω_0 and Q can be described as

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad \text{and} \quad Q = \frac{1}{2g_{m3}R}\sqrt{\frac{C_2g_{m1}}{C_1g_{m2}}} \tag{11}$$

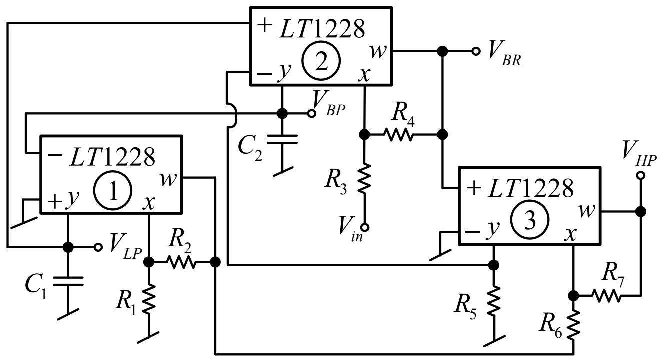


Fig. 3. Proposed universal biquad filter using three LT1228s.

The orthogonal control feature of Q can be done by adjusting the R_5 or g_{m3} values in (11), without affecting the value of ω_0. It is better with electronic tuning Q via g_{m3}. By simultaneously controlling the bias currents ($I_{B1} = I_{B2} = I_B$) and choosing $C_1 = C_2 = C$, the ω_0 and Q in (11) become

$$\omega_0 = \frac{g_m}{C} \quad \text{and} \quad Q = \frac{1}{2g_{m3}R_5} \tag{12}$$

In (12), the values of ω_0 and Q are set electronically and independently of each other. In addition, ω_0 is both linearly and electronically tuned. However, tuning Q by g_{m3} and R_5 affects the voltage gains of the LP and HP functions. In addition, the allpass (AP) response is not obtained from this structure. Another drawback of the proposed LT1228-based universal biquad filter is that it lacks a high input impedance at the voltage input node. This circuit requires more resistors to construct many voltage gain amplifiers. The proposed biquad filter sensitivity values of ω_0 and Q for all the components are described in (13).

$$S_{g_{m1}}^{\omega_0} = S_{g_{m2}}^{\omega_0} = \frac{1}{2}; S_{C_1}^{\omega_0} = S_{C_1}^{\omega_0} = -\frac{1}{2}; S_{g_{m1}}^{Q} = S_{C_2}^{Q} = \frac{1}{2};$$
$$S_{g_{m2}}^{Q} = S_{C_1}^{Q} = -\frac{1}{2}; S_{g_{m3}}^{Q} = -1; S_{R_5}^{Q} = -1 \tag{13}$$

D. Nonideal Consideration

The non-ideal effects of the LT1228 are discussed in detail in this section. This might influence the operation of the proposed filter in practical applications. The parasitic resistance and capacitance R_-, C_-, R_+, and C_+ at the input voltage terminals are investigated in parallel because the V_- and V_+ terminals possess high impedance. The R_y and C_y are also found in parallel at the y terminal, which has a high impedance. The x terminal has a low impedance; therefore, the parasitic resistance, R_x appears connection in series at this terminal. The parasitic resistance, R_w is found connection in series at the terminal w, which has a low impedance. The internal transresistance gains R_T and C_T are investigated in parallel. According to the datasheet for LT1228 [35], the lower values of the feedback resistors R_2, R_4, and R_7, which are placed among the w and x terminals, provide a higher bandwidth (operational frequency) than a higher value. If R_w and R_x are very small, $R_T >> R_2$, R_4, and R_7, the parasitic elements from the R_y, C_y, R_+, C_+, R_-, and C_- terminals have the highest impact on the operational frequency of the proposed filter. When all these parasitic elements are considered, the following mathematical equations of the voltage transfer function are obtained.

$$\frac{V_{LP}}{V_{in}} = \frac{-\dfrac{K^* g_{m1} g_{m1}}{C_1^* C_2^*}}{D^*(s)} \tag{14}$$

$$\frac{V_{HP}}{V_{in}} = \frac{-2K^*\left[s^2 + \left(\dfrac{G_{y1}^* C_2^* + G_{y2}^* C_1^*}{C_1^* C_2^*}\right)s + \dfrac{G_{y1}^* G_{y2}^*}{C_1^* C_2^*}\right]}{D^*(s)} \tag{15}$$

$$\frac{V_{BP}}{V_{in}} = \frac{\dfrac{K^* g_{m2}(G_{y1}^* + sC_1^*)}{C_1^* C_2^*}}{D^*(s)} \tag{16}$$

$$\frac{V_{BR}}{V_{in}} = \frac{-\left[s^2 + \dfrac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right)}{C_1^* C_2^*}s + \dfrac{G_{y1}^* G_{y2}^* + g_{m1} g_{m2}}{C_1^* C_2^*}\right]}{D^*(s)} \tag{17}$$

$$D^*(s) = \left\{ s^2 + \left[\frac{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right) + 2K^* g_{m2} C_1^*}{C_1^* C_2^*}\right]s + \frac{G_{y1}^* G_{y2}^* + 2K^* g_{m2} G_{y1}^* + g_{m1} g_{m2}}{C_1^* C_2^*} \right\} \tag{18}$$

where, $C_1^* = C_1 + C_{y1} + C_{+2}$, $C_2^* = C_2 + C_{y2} + C_{-1}$, $K^* = \dfrac{g_{m3}}{G_{y3}^* + sC_{y3}^*}$, $G_{y1}^* = \dfrac{1}{R_{y1}} + \dfrac{1}{R_{+2}}$, $G_{y2}^* = \dfrac{1}{R_{y2}} + \dfrac{1}{R_{-1}}$, and $G_{y3}^* = \dfrac{1}{R_{y3}} + \dfrac{1}{R_{-2}} + \dfrac{1}{R_5}$. If the C_{y3}^* is a little effect on this filter, K^* will be approximately as $K^* \approx g_{m3} / G_{y3}^*$. From (14) through (18), the non-ideal center frequency and quality factor of the proposed LT1228-based universal second-order filter become:

$$\omega_0 = \sqrt{\frac{G_{y1}^* G_{y2}^* + 2K^* g_{m2} G_{y1}^* + g_{m1} g_{m2}}{C_1^* C_2^*}} \tag{19}$$

$$Q = \frac{\sqrt{\left(G_{y1}^* G_{y2}^* + 2K^* g_{m2} G_{y1}^* + g_{m1} g_{m2}\right) C_1^* C_2^*}}{\left(G_{y1}^* C_2^* + G_{y2}^* C_1^*\right) + 2K^* g_{m2} C_1^*} \tag{20}$$

It has been shown that the parasitic resistance and capacitance of LT1228 influence how well the filter operates in terms of the operating frequency range, the pass-band gain, the center frequency, and the quality factor.

III. Simulation Results

The proposed one-input and four-output versatile second-order active filter was simulated employing PSpice program. The power supply voltage used in the test is ±5V. To get a center frequency (f_0) value of approximately 100kHz and Q = 1.57, the bias currents, $I_{B1} = I_{B2}$ = 204.4µA, I_{B3} = 100.4µA, all resistors, $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = R_7$ = 1kΩ, and the capacitors, C_1 = 1nF, C_2 = 10nF have been selected. The gain responses of the proposed biquad filter are depicted in Figure 4. This figure demonstrates that the proposed LT1228-based second-order active filter can simultaneously give LP, HP, BP, and BR filtering responses. By tuning the bias current I_{B3}, which is defined by the three values of 50µA, 100µA, and 150µA, the quality factor can be adjusted with no effect on the center frequency, as shown in Fig. 5. The simulated quality factors can be obtained by varying I_{B3} with values of 0.81, 1.57, and 3.08, respectively.

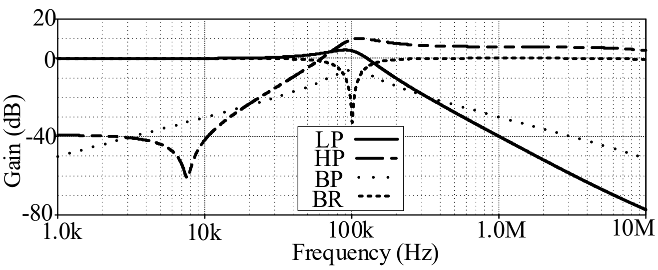


Fig. 4. Simulated magnitude response.

Additionally, the Q can be tuned by setting the different R_5 values (where R_5 is assigned to 0.5kΩ, 1kΩ, and 1.5kΩ) without affecting the f_0, as illustrated in Fig. 6. The simulated quality factors can be obtained by varying R_5 with values of 1.05, 1.57, and 3.08, respectively. As shown in Fig. 7, f_0 can be adjusted without changing Q. It can be obtained by simultaneously varying the bias currents (I_{B1} = I_{B2} = I_B are set to 123.5µA, 185.5µA, 371µA) and the different center frequencies are situated at 61.1kHz, 90.9kHz, and 179.9kHz, respectively. The test of the natural response for the BP filter function is illustrated in Fig. 8 where the sine wave input voltage signal was applied to 50mV$_{p-p}$ and f_0 =100kHz. The THD value of the BP function is steady straight up at 3% below 30mV$_{p-p}$ and then it gradually increases to 5.89%, as described in Fig. 9.

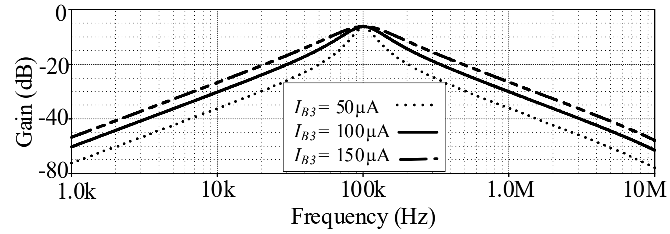


Fig. 5. Simulated frequency magnitude response of BP function for different I_{B3} values.

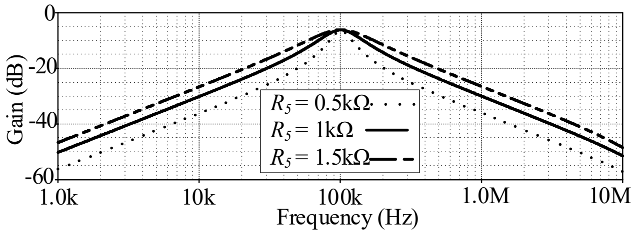


Fig. 6. Simulated magnitude BP function for various R_5 values.

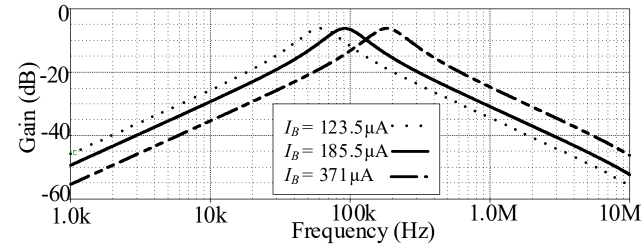


Fig. 7. Simulated magnitude BP response for various I_B values ($I_{B1} = I_{B2} = I_B$).

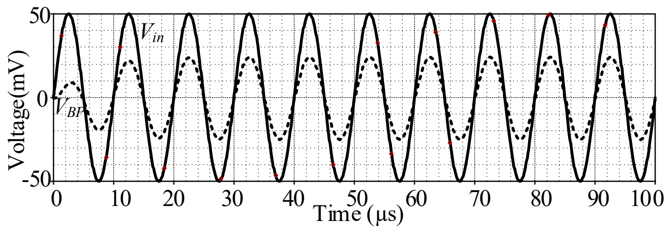
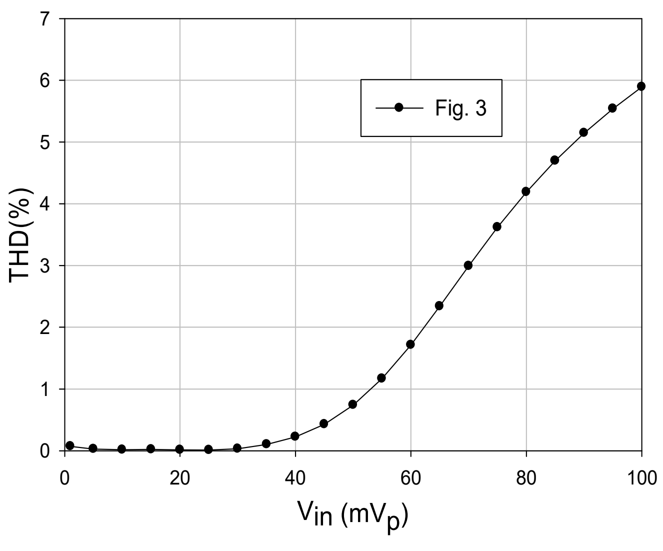


Fig. 8. BP filtering natural response.



IV. Experimental Results

In practice, experiments were also done to test the performance of the proposed LT1228-based universal filter shown in Fig. 3. The proposed circuit was supplied at ±5 V with a GW Instek GPS-3303 power supply. The passive elements: C_1 = 1nF, C_2 = 10nF, all resistors were 1kΩ, and bias currents $I_{B1} = I_{B2}$ = 204.4μA, and I_{B3} = 100.4μA were chosen for the experimental setup. Calculating f_0 and Q in (11) with the above active and passive component values yields f_0 = 100 kHz and Q = 1.58. The Keysight DSOX1102G oscilloscope with the sine wave input signal was used for the measurement. The measured theoretical and experimental magnitude responses of the proposed universal biquad filter for the LP, HP, BP, and BR filtering responses are compared and are illustrated in Fig. 10. The experimental center frequency is approximately 103.75kHz. The percent deviation for the center frequency is about 1.32%.

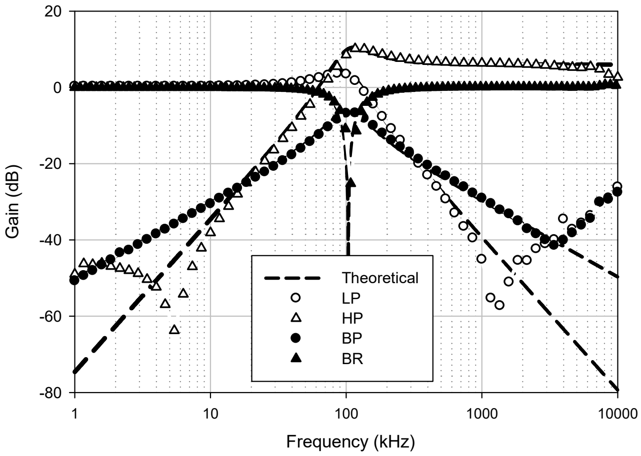


Fig. 10. Experimental magnitude response

By tuning the bias current I_{B3}, where it is defined as three values 50μA, 100μA, and 150μA, the Q can be adjusted with no effect on center frequency in Fig 11. The experimental result depicted in Fig. 11 confirms that the Q of the presented versatile filter is electronically controlled and does not influence the ω_0 as expected in (11). As shown in Fig. 12, the ω_0 can be tuned while keeping the Q constant by simultaneously varying the currents ($I_{B1} = I_{B2} = I_B$ are set to 123.5μA, 185.5μA, and 371μA). The resultant center frequencies are situated at 63.4kHz, 95.6kHz, and 185.8 kHz, respectively. The BP filtering response in the time domain with different frequencies (50kHz, 100kHz and 1MHz) is depicted in Fig. 13, where the sinewave signal amplitude applied at the input of the filter is 50mV_{p-p}.

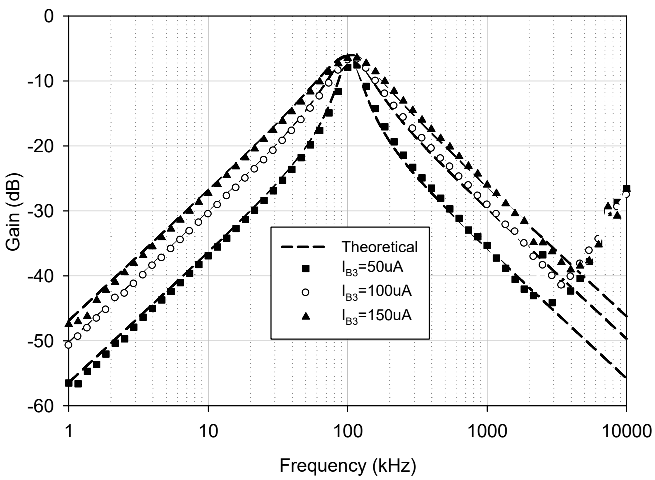


Fig. 11. BP experimental measurement for different I_{B3} values.

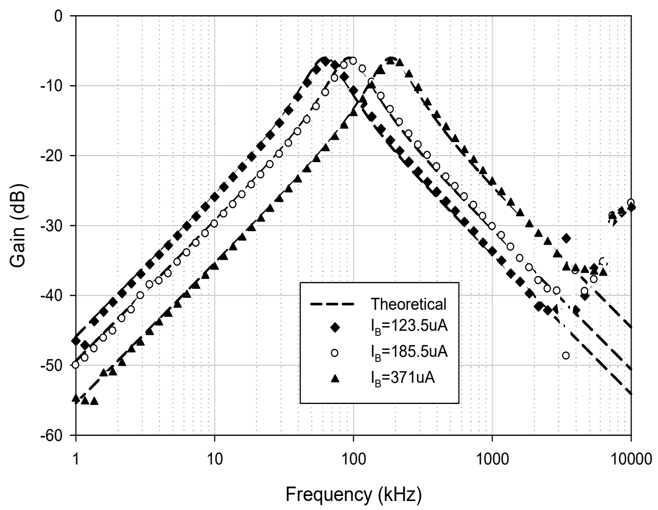
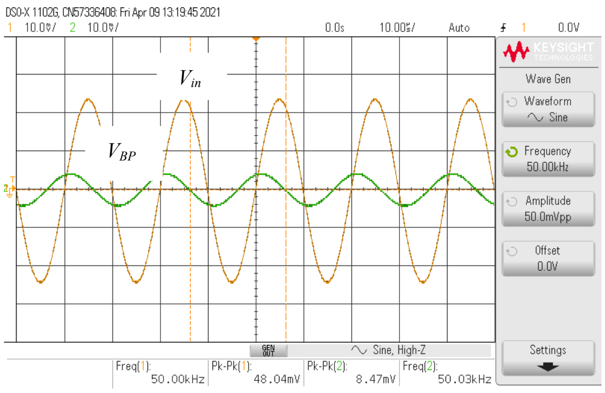
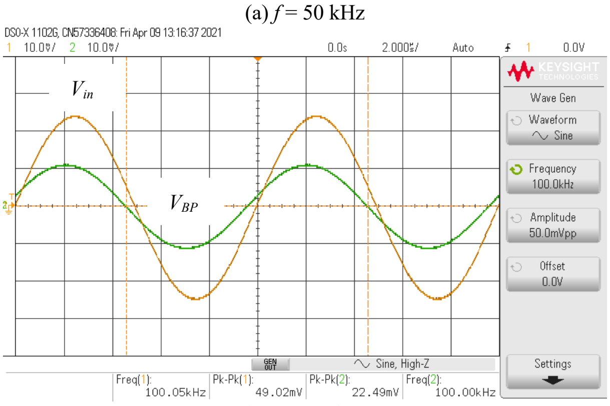


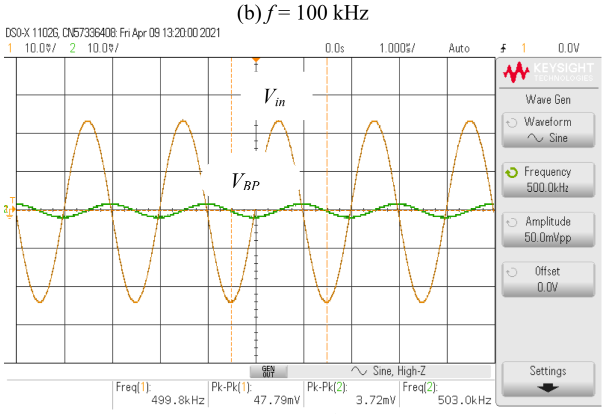
Fig. 12. BP experimental measurement for various I_B values.



(a) f = 50 kHz



(b) f = 100 kHz



(c) f = 500 kHz

Fig. 13. Measured BP filtering response in time domain.

V. Conclusion

In this research, the LT1228, which is a commercially available IC, is used to design a voltage-mode universal filter with one input and four outputs. The proposed filter consists of three LT1228s, seven resistors and two grounded capacitors. Without modifying the circuit construction, this filtering circuit can simultaneously provide the LP, HP, BP, and BR functions. By changing I_{B3}, the electronic and independent tuning of the Q can be done with no effect on the ω_0. In addition, the control of ω_0 is electronically and linearly tunable without being influenced in the Q by simultaneously changing I_{B1} and I_{B2}. The PSPICE software was used to verify the workability of the proposed filtering circuit, and laboratory experiments were also conducted using commercially available LT1228 ICs. The proposed filter can be used in various applications and low-cost measurements in the audio and acoustic frequency bands.

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