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One input voltage and three output voltage universal biquad filters with orthogonal tune of frequency and bandwidth

May Phu Pwint Wai, Amornchai Chaichana, Winai Jaikla, Surapong Siripongdee, Peerawut Suwanjan
Department of Engineering Education, Faculty of Industrial Education and Technology,
King Mongkut's Institute of Technology Ladkrabang, Bangkok

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ABSTRACT

This research paper contributes the one input three output voltage mode universal biquad filters with linear and electronic control of the natural frequency (ω_0), using two commercially available ICs, LT1228s as active device with two grounded capacitors, five resistors. The presented universal biquad filters can simultaneously provide three voltage-mode filtering functions, low-pass (LP), high-pass (HP) and band-pass (BP) without changing the circuit architecture. Furthermore, the first presented biquad filter provides low impedance at HP, BP voltage output nodes and LP, BP output voltage nodes are low impedance for the second proposed filter which is easy cascade ability with other voltage mode circuits without the employment of buffer circuits. The quality factor (Q) of both proposed filters is orthogonally adjusted from the passband voltage gain and ω_0. The proposed filters are simulated and experimented with commercially accessible ICs, LT1228. The simulated and experimental results demonstrate the filtering performances.

Corresponding Author:

Amornchai Chaichana
Department of Engineering Education, Faculty of Industrial Education and Technology
King Mongkut's Institute of Technology
Ladkrabang, Bangkok, 10520, Thailand
Email: amornchai.ch@kmitl.ac.th

1. INTRODUCTION

The analog filters or some likeness thereof are basic to the operation of the most engineering circuits. It is hence considering a logical concern for anybody handled with electronic circuit design to be able to create filter circuits fit for meeting a given arrangement of specifications. They are emphasized signals in the specified frequency band (wanted signal) while reject other the signals outside that band (unwanted signal). They are broadly utilized for their significant prerequisites in electrical and electronic engineering application and extremely famous in utilizing for a circuit framework of analog signal processing system. Numerous fields utilize filter circuits, for example, communication, instrumentation, measurement, sound system, and control systems [1]. Particularly, several function filters which are called universal filters or multifunction filters have been extensively studied and have become an interesting research topic. The analog biquad filter with single-input multiple-output (SIMO) category is the most renowned filtering circuit which provides numerous output responses in the same circuit topology. Moreover, SIMO filtering scheme does not want other circuits to get the wanted filtering responses for example the input signal selection. With SIMO feature, the single input is employed and provides simultaneously multiple filtering output responses.

Thus, SIMO type filters are more beneficial in comparison with other type filters for the applications which require simultaneously several filtering responses such as in 3-way crossover network [2-5].

The operational transconductance amplifier (OTA) is active building block which has received great attention to employ for synthesis of analog signal processing systems [6]. With electronic adjustability of transconductance gain, the parameters of the OTA based circuits are electronically controllable. Varied commercial OTA ICs are accessible for instance CA3080 [7] and LM13700 [8], and LT1228 [9]. For specific work with real practical test, the use of commercially available OTA is still cheaper and more appropriate compared to the chip fabrication [10]. The LT1228 from Linear Technology Inc is the intriguing one. This active device consists of OTA and current feedback amplifier (CFA). The LT1228's CFA has high input impedance and so it is a superb buffer for the output of the transconductance amplifier maintains its wide bandwidth over a large vary of voltage gains creating it simple to interface the transconductance amplifier output to different electronic circuitry. It is intended to drive low impedance loads, such as cables, with better linearity at high frequencies. Moreover, the external dc bias current, I_B can control electronically to its transconductance g_m. Therefore, the LT1228 based circuits are controlled by computer in trendy circuit vogue.

Several SIMO second order voltage mode universal filters using different analog active function blocks have been published in the literature [11-47]. However, these reposed filters have some inconveniences as it has been observed that the active building blocks are not implemented from the commercially available IC [13-31, 36-43]; all capacitors are not grounded [14, 18, 29, 42], the natural frequency is not electronically tuned [14-34, 36], absence of orthogonal tune of the ω_0 and Q [13-16, 18-24, 29, 30, 35, 36, 40, 41, 43, 46, 47], the passband voltage gain is not constant during tuning the natural frequency and quality factor [14, 17, 18, 20, 25, 26, 28, 29, 32-34, 36, 38, 39, 42].

This current paper's commitment is to propose two universal second order filters with one input voltage and three output voltages. The presented filters are constructed from two LT1228s with five resistors and two grounded capacitors. Three voltage mode filtering functions, HP, LP and BP with constant passband gain during tuning the ω_0 and Q are obtained. The ω_0 is electronically adjusted. The Q or bandwidth is controlled by means of setting the value of the feedback resistors while no disturbing the ω_0. The exhibition of the proposed filters is approved through utilizing P spice program and trial.

2. PROPOSED UNIVERSAL FILTERS

2.1. Principle of the used commercially available active element

The active element used in this design is LT1228, commercially available IC from Linear Technology Inc. The LT1228 symbolic diagram with eight terminals is illustrated in Figure 1(a). The y terminal is output current which has high impedance and the V_+ and V_- terminals are inverting and non-inverting input voltages that also have high impedance. The x and w terminals are voltage output which have low impedance. Terminal relationships of LT1228 can be shown in hybrid matrix form given in (1).

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

where R_T is the internal trans resistance gain and it is infinity in an ideal case. The LT1228's g_m is controlled electronically via external DC bias current (I_B) as (2):

$$g_m = I_B / 3.87V_T \tag{2}$$

where V_T is thermal voltage. As defined in (1), the LT1228 characteristics can be represented as equivalent scheme in Figure 1(b). The pin connection of LT1228 is illustrated in Figure 1(c).

2.2. First proposed voltage-mode universal biquad filter using two LT1228s

The proposed biquad filters in Figure 2 are synthesized from two loop integrators. Figure 2(a) illustrates the first proposed universal voltage-mode second order filter comprised of two LT1228s, two grounded capacitors and five resistors. The first lossless integrator is constructed from the capacitor C_1 and first LT1228 while, the second lossless integrator is realized from capacitor C_2 and second LT1228. The resistors R_1, R_2, R_3 and first LT1228 are constructed as voltage summing circuit. Finally, the resistors R_4, R_5 and second LT1228 are constructed as voltage amplifier. The input voltage (V_{in}) is applied at the voltage summing circuit while, the high-pass (HP) filtering voltage node (V_{HP1}) is at the output of the voltage summing, the low-pass (LP) filtering voltage node (V_{LP1}) is at the output of first integrator and the band-pass (BP) filtering voltage node (V_{BP1}) is at the output of voltage amplifier. With this scheme, three second order filtering functions are simultaneously given without changing the filtering construction. Moreover, it is found that the low output impedance at output voltage nodes V_{HP1} and V_{BP1} responses is achieved.

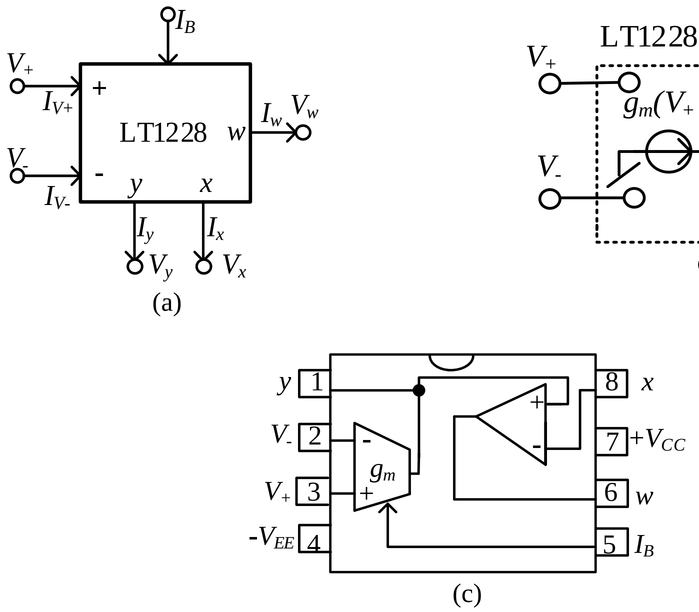


Figure 1. LT1228, (a) Symbolic diagram, (b) Representation, (c) Pin connection

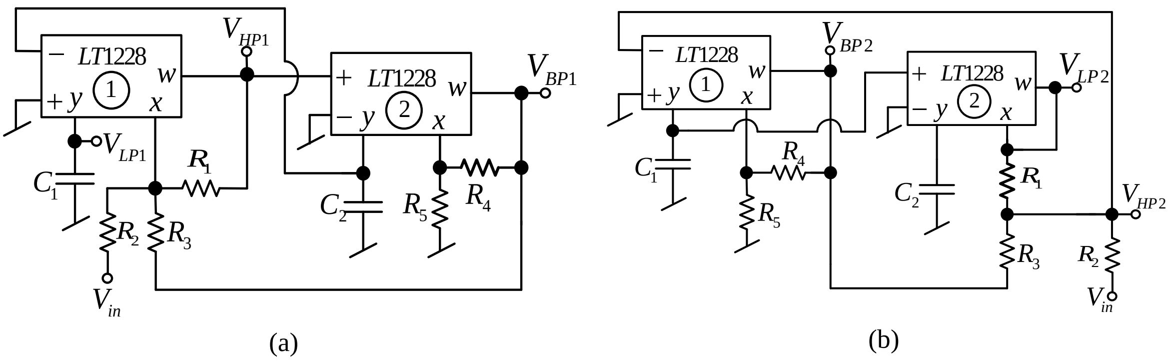


Figure 2. The proposed universal filters, (a) First filter, (b) Second filter

If $R_1 = R_2 = R_3$, the voltage transfer functions (TF) are expressed as (3):

$$\frac{V_{HP1}}{V_{in}} = \frac{-s^2}{s^2 + \frac{Kg_{m2}}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2}};\ \frac{V_{LP1}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + \frac{Kg_{m2}}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2}};\ \frac{V_{BP1}}{V_{in}} = \frac{-\frac{sKg_{m2}}{C_2}}{s^2 + \frac{Kg_{m2}}{C_2}s + \frac{3g_{m1}g_{m2}}{C_1C_2}} \quad (3)$$

where $K = 1 + (R_4/R_5)$. From (3), the unity passband voltage gain for high-pass and band-pass functions, the one-third passband voltage gain for low-pass function are obtained. Also from them, the high-pass and band-pass functions are inverting, while the low-pass function is non-inverting. The natural freqeuncy (ω_{01}) of the first filter as well as the quality factor (Q_1) are obtained as (4):

$$\omega_{01} = \sqrt{\frac{3g_{m1}g_{m2}}{C_1C_2}} \text{ and } Q_1 = \frac{1}{K}\sqrt{\frac{3g_{m1}C_2}{g_{m2}C_1}} \tag{4}$$

Substituting the transconductances g_{m1} and g_{m2} in function of I_{B1} and I_{B2} as appeared in (2) into (4), the ω_{01} and Q_1 of the first proposed circuit are as (5):

$$\omega_{01} = \frac{1}{3.87V_T}\sqrt{\frac{3I_{B1}I_{B2}}{C_1C_2}} \text{ and } Q_1 = \frac{R_5}{R_4+R_5}\sqrt{\frac{3I_{B1}C_2}{I_{B2}C_1}} \tag{5}$$

From (5), it can be remarked that ω_{01} can be electronically controlled by I_{B1} and I_{B2}. Moreover, the Q_1 can be altered without affecting ω_0 by changing the value of R_5 (as stated in data sheet of LT1228 [10], R_4 should not be adjusted to keep the constant bandwidth.). Other advantages for tuning filter parameter can be achieved by simultaneously adjusting $I_{B1}=I_{B2}=I_B$ (this feature is easily implemented by using microcontroller or microcomputer) and setting $C_1=C_2=C$. Then filtering parameters in (5) becomes

$$\omega_{01} = \frac{I_B}{3.87V_TC}\sqrt{3} \text{ and } Q_1 = \frac{R_5}{R_4+R_5}\sqrt{3} \tag{6}$$

It can be remarked from (6) that ω_{01} and Q_1 are independently controlled. Moreover, the ω_{01}can be linearly and electronically adjusted. Also, the control of ω_{01} and Q_1 doesn't affect the passband voltage gain for all filtering responses.

2.3. Second proposed voltage-mode universal biquad filter using two LT1228s

The second proposed biquad filter is also synthesized from two loop integrators as explained above. Figure 2(b) illustrates the scheme of the second proposed filter. It is comprised of two LT1228s, five resistors, two grounded capacitors which is same to first proposed filter. The first lossless integrator is constructed from the capacitor C_1 and first LT1228 while, the second lossless integrator is realized from capacitor C_2 and second LT1228. The resistors R_1, R_2, R_3 and second LT1228 are constructed as voltage summing circuit. Finally, the resistors R_4, R_5 and first LT1228 are constructed as voltage amplifier. The input voltage (V_{in}) is applied at the voltage summing circuit while, the high-pass (HP) filtering voltage node (V_{HP2}) is at the output of the voltage summing, the low-pass (LP) filtering voltage node (V_{LP2}) is at the output of first integrator and the band-pass (BP) filtering voltage node (V_{BP2}) is at the output of voltage amplifier. With this scheme, three second order filtering functions are simultaneously given without changing the filtering scheme. Moreover, it is found that the low output impedance at output voltage nodes V_{LP2} and V_{BP2} responses is achieved. If $R_1 = R_2 = R_3$, the voltage transfer functions (TF) are expressed as (7).

$$\frac{V_{HP2}}{V_{in}} = \frac{\frac{s^2}{3}}{s^2+\frac{Kg_{m1}}{3C_1}s+\frac{g_{m1}g_{m2}}{3C_1C_2}}\ ;\ \frac{V_{LP2}}{V_{in}} = \frac{-\frac{g_{m1}g_{m2}}{3C_1C_2}}{s^2+\frac{Kg_{m1}}{3C_1}s+\frac{g_{m1}g_{m2}}{3C_1C_2}}\ ;\ \frac{V_{BP2}}{V_{in}} = \frac{-\frac{sKg_{m1}}{3C_1}}{s^2+\frac{Kg_{m1}}{3C_1}s+\frac{g_{m1}g_{m2}}{3C_1C_2}} \tag{7}$$

where $K = 1 + (R_4/R_5)$. From (7), the unity passband voltage gain for low-pass and band-pass functions, the one-third passband voltage gain for high-pass function are obtained. Also from them, the low-pass and band-pass functions are inverting, while the high-pass function is non-inverting. The natural freqeuncy (ω_{02}) of the second filter as well as the quality factor (Q_2) are obtained as (8).

$$\omega_{02} = \sqrt{\frac{g_{m1}g_{m2}}{3C_1C_2}} \text{ and } Q_2 = \frac{1}{K}\sqrt{\frac{3g_{m2}C_1}{g_{m1}C_2}} \tag{8}$$

Substituting the transconductances g_{m1} and g_{m2} in function of the bias currents, I_{B1} and I_{B2} as appeared into (2) into (8), the ω_{02} and Q_2 of the second proposed circuit are as (9).

$$\omega_{02} = \frac{1}{3.87V_T}\sqrt{\frac{I_{B1}I_{B2}}{3C_1C_2}} \text{ and } Q_2 = \frac{R_5}{R_4+R_5}\sqrt{\frac{3I_{B2}C_1}{I_{B1}C_2}} \tag{9}$$

From (9), it is found that ω_{02} can be electronically controlled by I_{B1} and I_{B2}. Moreover, the Q_2 can be altered without affecting ω_0 by changing the value of R_5. Other advantage for tuning filter parameter can be achieved by simultaneously adjusting $I_{B1} = I_{B2} = I_B$ (this feature is easily implemented by using microcontroller or microcomputer) and setting $C_1 = C_2 = C$. Then filtering parameters in (9) becomes;

$$\omega_{02} = \frac{I_B}{3.87V_TC}\sqrt{\frac{1}{3}} \text{ and } Q_2 = \frac{R_5}{R_4+R_5}\sqrt{3} \tag{10}$$

It can be noted from (10) that ω_{02} and Q_2 are independently tuned. Moreover, the ω_{02} is linearly and electronically tuned. Also, the control of ω_{02} and Q_2 does not affect the passband gain for all filtering responses.

3. PARASITIC EFFECTS

In a genuine application, the impacts of parasitic components in LT1228 are not ignorable that it might influence the performance of the proposed filters. So, the parasitic elements appeared at all terminals of LT1228 will be considered. These parasitic elements are as follows: R_- and C_- appear in parallel at V_- terminal to ground; R_+ and C_+ appear in parallel at V_+ terminal to ground; R_y and C_y appear in parallel at y terminal to ground; R_x appears in seires at x terminal; R_w appears in seires at w terminal and the internal transresistance gain is considered as $R_T//C_T$. As stated in data sheet of LT1228 [10], the feedback resistors (R_1, R_4 in first filter and R_4 in second filter) from w to x terminal in summing and amplifier circuits should be low to reduce the effect of C_T and R_T and to get higher operating frequency. Also, if the operational frequency of the proposed filters is expected lower than 10 MHz, the most effect stems from R_-, C_-, R_+, C_+, R_y and C_y (the effect of R_x, R_w, R_T and C_T is ignore). In consideration of these parasitic elements, the three voltage transfer functions (V_{HP1}, V_{LP1} and V_{BP1}) of the first presented biquad filter realized in Figure 2(a) are obtained as (11).

$$\frac{V_{HP1}^*}{V_{in}} = \frac{-s^2 - \left(\frac{G_{y1}C_1^* + G_{y2}C_1^*}{C_1^*C_2^*}\right)s - \frac{G_{y1}G_2^*}{C_1^*C_2^*}}{D^*(s)};\ \frac{V_{LP1}^*}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1^*C_2^*}}{D^*(s)};\ \frac{V_{BP1}^*}{V_{in}} = \frac{-\frac{Kg_{m2}G_{y1}}{C_1^*C_2^*} - \frac{g_{m2}K}{C_2^*}s}{D^*(s)} \tag{11}$$

where

$$D^*(s) = s^2 + \left(\frac{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*}{C_1^*C_2^*}\right)s + \frac{G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}}{C_1^*C_2^*} \tag{12}$$

$C_1^* = C_1 + C_{y1}$, $C_2^* = C_2 + C_{y2} + C_{-1}$, $G_{y1} = \frac{1}{R_{y1}}$ and $G_2^* = \frac{1}{R_{y2}} + \frac{1}{R_{-1}}$. From (12), the non-ideal natural freqeuncy and quality factor of the first proposed filter become;

$$\omega_{01}^* = \sqrt{\frac{G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}}{C_1^*C_2^*}} \text{ and } Q_1^* = \frac{\sqrt{C_1^*C_2^*\left(G_{y1}G_2^* + 3g_{m1}g_{m2} + Kg_{m2}G_{y1}\right)}}{G_{y1}C_2^* + G_2^*C_1^* + Kg_{m2}C_1^*} \tag{13}$$

In consideration of these parasitic elements, the three voltage transfer functions (V_{HP2}, V_{LP2} and V_{BP2}) of the second presented biquad filter realized in Figure 2(b) are obtained as (14).

$$\frac{V_{HP2}^*}{V_{in}} = \frac{\frac{s^2}{3} + \left(\frac{G_1^{**}C_2^{**} + G_{y2}C_1^{**}}{3C_1^{**}C_2^{**}}\right)s + \frac{G_1^{**}G_{y2}}{3C_1^{**}C_2^{**}}}{D^{**}(s)};\ \frac{V_{LP2}^*}{V_{in}} = \frac{\frac{-g_{m1}g_{m2}}{3C_1^{**}C_2^{**}}}{D^{**}(s)};\ \frac{V_{BP2}^*}{V_{in}} = \frac{-\frac{Kg_{m1}G_{y2}}{3C_1^{**}C_2^{**}} - \frac{Kg_{m1}}{3C_1^{**}}s}{D^{**}(s)} \tag{14}$$

where

$$D^{**}(s) = s^2 + \left[\frac{3\left(G_1^{**}C_2^{**} + G_{y2}C_1^{**}\right) + Kg_{m1}C_2^{**}}{3C_1^{**}C_2^{**}}\right]s + \frac{3G_1^{**}G_{y2} + Kg_{m1}G_{y2} + g_{m1}g_{m2}}{3C_1^{**}C_2^{**}} \quad (15)$$

$C_1^{**} = C_1 + C_{y1} + C_{+2}$, $C_2^{**} = C_2 + C_{y2}$, $G_1^{**} = \frac{1}{R_{y1}} + \frac{1}{R_{+2}}$ and $G_{y2} = \frac{1}{R_{y2}}$. From (15), the non-ideal natural freqeuncy and quality factor of the second proposed filter become;

$$\omega_{02}^{*} = \sqrt{\frac{3G_1^{**}G_{y2} + Kg_{m1}G_{y2} + g_{m1}g_{m2}}{3C_1^{**}C_2^{**}}} \text{ and } Q_2^{*} = \frac{\sqrt{3C_1^{**}C_2^{**}(3G_1^{**}G_{y2} + g_{m1}g_{m2} + Kg_{m1}G_{y2})}}{3(G_1^{**}C_2^{**} + G_{y2}C_1^{**}) + Kg_{m1}C_2^{**}} \quad (16)$$

4. SIMULATION RESULTS

To confirm the theoretical ability of the filtering design, the functionality of the presented circuits illustrated in Figure 2 was tested by using PSPICE. The supply voltages were V_{CC}=-V_{EE}=5 V. For the first proposed filter, the bias current was set to I_{B1}=I_{B2}=123.5 µA. The values of passive component were selected as R_1=R_2=R_3=R_4=R_5=1 kΩ, C_1=1 nF and C_2=10 nF. Using above mentioned device values, the calculated natural frequency and quality factor from (5) is obtained as f_{01}=107.66 kHz, Q_1= 2.73. The simulation results are obtained as f_{01}=105.682 kHz, Q_1=2.82. The deviation of the theoretical and simulated f_{01} is 1.84%, Q_1 is 3.29%. There simulated filtering responses of the first presented versatile second order filter are illustrated in Figure 3. The high-pass filtering response with different values of resistor R(R_1=R_2=R_3=R) in simming circuit of the first presented biquad filter is illustrated in Figure 4. In this simulation, the values of R were set to 0.2 kΩ, 0.6 kΩ and 5 kΩ. It is found that with low value of the feedback resistor (R), the bandwidth of the proposed filter is higher than the bandwidth at high value of R as expected in section of parasitic effect.

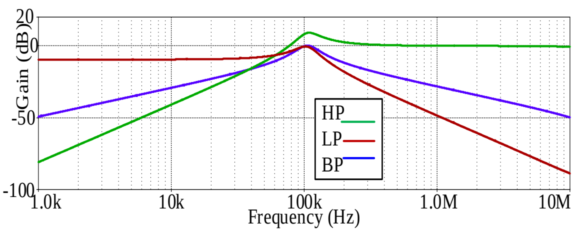


Figure 3. Th simulation of gain response of the presented versatile filter in Figure 2(a)

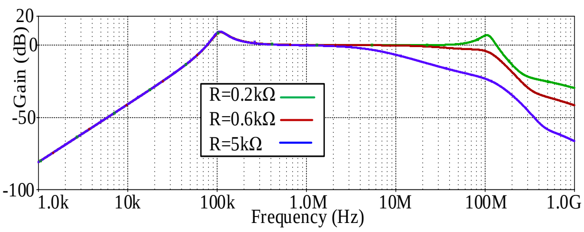


Figure 4. High-pass response of the filter in Figure 2(a) with different values of R(R_1=R_2=R_3=R)

Figure 5 confirms that Q_1 can be controlled by varying the value of resistance R_5 without affecting f_{o1} as expected in (7), where R_5 is assigned to 0.2 kΩ, 0.6 kΩ, 5 kΩ. The electronic tune of the natural frequency by simultaneously changing I_{B1} and I_{B2}(I_{B1}=I_{B2}=I_B) is shown in Figure 6 where value of I_B was set to 60 µA, 120 µA and 240 µA. The natural frequency tuned from these bias currents are located at 57.28 kHz, 102.80 kHz and 205.59 kHz. The result in Figure 6 indicates that the natural frequency can be linearly and electronically tuned by the I_B with constant value of the Q_1 as expected in (8). The second proposed filter was also simulated with the same voltage supplies and resistance values of the first filter. Other elements were set as follows: I_{B1}=I_{B2}=350 µA and C_1=10 nF, C_2=1 nF. Using these mentioned component values, the theoretical f_{02} and Q_2 from (13) are given as f_{02}=101.70 kHz, Q_2=2.73. The simulation results are obtained as f_{02}=99.77 kHz, Q_2=2.88. The deviation of the theoretical and simulated f_{02} is 1.89% and Q_2 is 5.49%. The simulated three filtering responses are shown in Figure 7. The result in Figure 8 confirms that Q_2 can be controlled by varying the value of resistance R_5 without affecting f_{02}, where R_5 is assigned to 0.2 kΩ, 0.6 kΩ, 5 kΩ. It is observed that Q_2 can be controlled without affecting the f_{02}. It is the fact that the BJT OTA has linear range when the input amplitude is below 50 mV. To prove the linearity of presented universal biquad filters, the plot of percent of total harmonic distortion (THD) versus input voltage amplitude for band-pass response is illustrated in Figure 9. Both presented filters were designed to achieve the natural frequency of 100 kHz. It can be seen from Figure 9 that the linearity of the second presented voltage-mode biquad filter is superior to the first presented biquad filter. It is seen from Figures 2(a) and 2(b) that the band-pass responses of both proposed filters are at the output of the lossless integrators which have the high-pass response as input voltage. The second presented filter's high-pass voltage gain is one third while the first presented filter's high-pass voltage gain is unity so this value of V_{HP1} causes the higher distortion than V_{HP2} at above 50 mV of the input voltage signal.

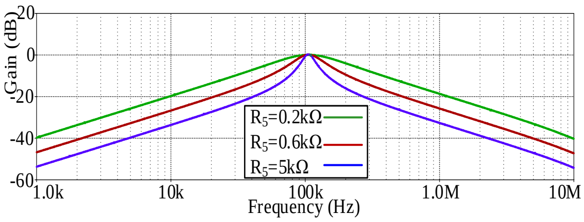


Figure 5. The BP gain response of the filter in Figure 2(a) with different values of R_5

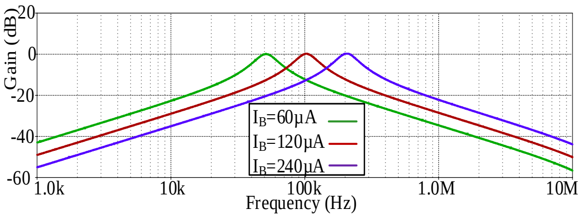


Figure 6. The BP gain response of the filter in Figure 2(a) with different values of $I_B(I_{B1}=I_{B2}=I_B)$

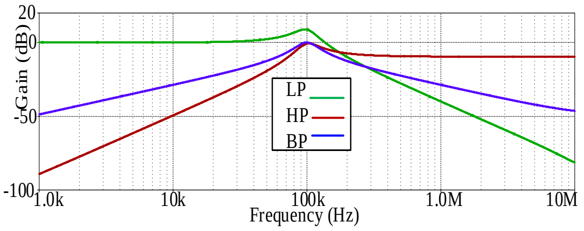


Figure 7. The simulation of gain response of the presented versatile filter in Figure 2(b)

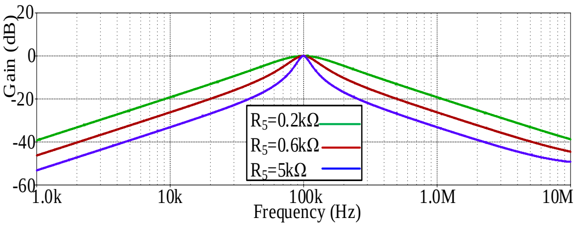


Figure 8. The gain response of the filter in Figure 2(b) with different values of R_5

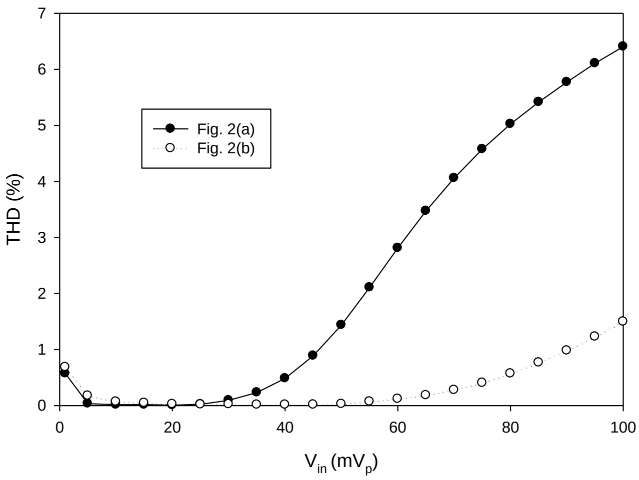
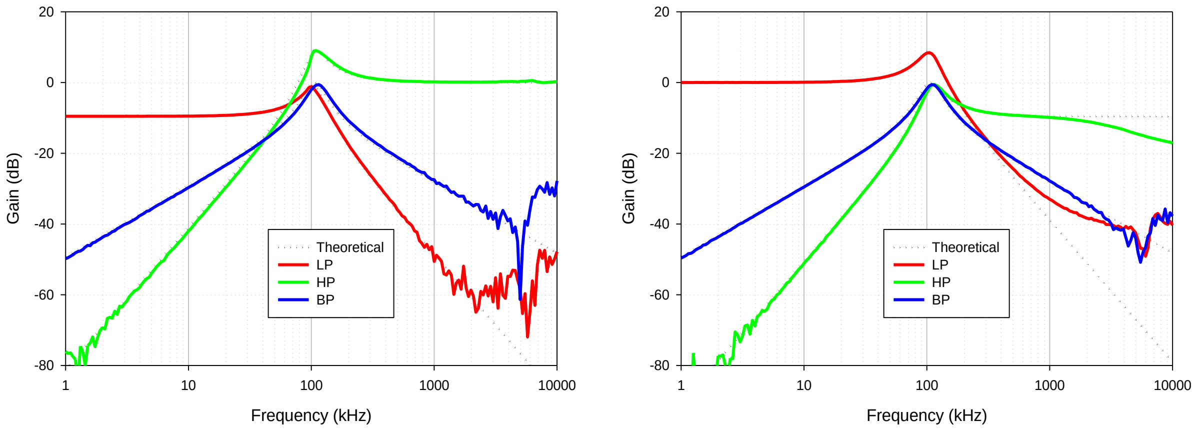


Figure 9. The percent THD against input magnitude

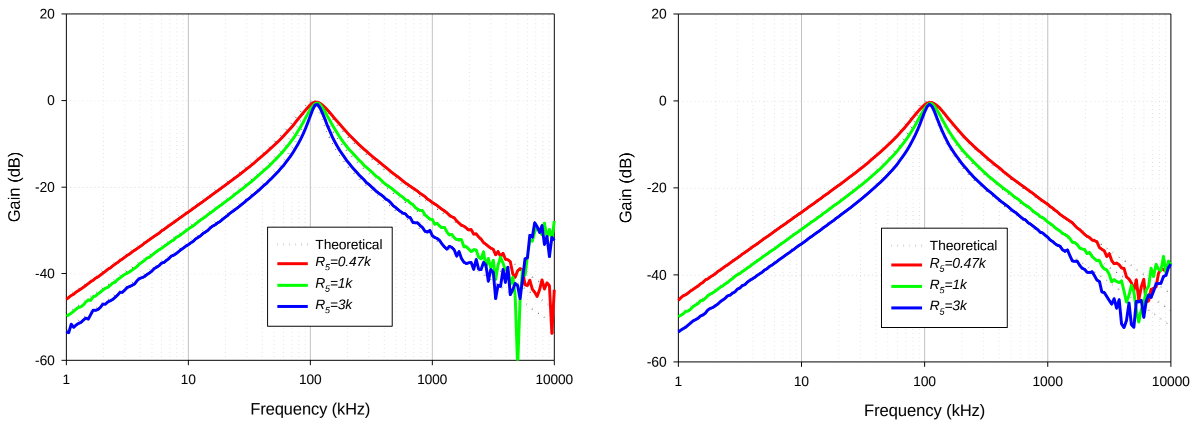
5. EXPERIMENTAL RESULTS

To assess the exhibitions of the presented universal filters in Figure 2, the experiments were also tested by utilizing two LT1228s. An experimental setup was made by taking V_{CC}=-V_{EE}=5 V using GW Instek GPS-3303 power supply, R_1=R_2=R_3=R_4=R_5=1 kΩ for both filters, C_1=1 nF, C_2=10 nF, I_{B1}=I_{B2}=123.5 µA for first presented filter and C_1=10 nF, C_2=1 nF, I_{B1}=I_{B2}=365 µA for second filter. The plot of experimental magnitude response (measured from Keysight DSOX1102G oscilloscope) of the first and second presented filters is shown in Figures 10(a) and 10(b), respectively. It is found that the experimental natural frequencies of the first and second proposed filters are f_{01}≅114 kHz and f_{02}≅109 kHz, respectively. Figure 11 confirms that Q_1 and Q_2 can be controlled by varying the value of resistance R_5 without affecting f_{o1} as expected in (5) and (9), where R_5 is assigned to 0.47 kΩ, 1 kΩ, 3 kΩ. The electronic tune of the natural frequency, f_{01} by simultaneously changing I_{B1} and I_{B2} ($I_{B1} = I_{B2} = I_B$) for the first presented universal biquad filter is illustrated in Figure 12(a) where value of I_B was set to 67 µA, 123.5 µA and 245 µA. The experimental natural frequency tuned from these bias currents are located at 60 kHz, 114 kHz and 230 kHz. For the second proposed filter, the electronic tune of the natural frequency, f_{02} by simultaneously changing I_{B1} and I_{B2}(I_{B1}=I_{B2}=I_B) is shown in Figure 12(b) where value of I_B was set to 184 µA, 365 µA and 722 µA. The experimental natural frequency tuned from these bias currents are located at 55 kHz, 114 kHz and 220 kHz. The result in Figure 12 indicates that the natural frequency of both proposed filters can be linearly and electronically tuned by the bias current without affecting the quality factor as expected in (6) and (10). The measurement of the band-pass response for the first presented versatile second order filter is illustrated in Figure 13, where the 50 mV$_{p-p}$ sine wave signals with frequencies, 10 kHz, 115 kHz and 1 MHz was input signal. The comparison of proposed universal biquad filter and other voltage-mode SIMO filtering configurations is shown in Table 1 (see in Appendix). It is found from Table 1 that with two commercially available ICs with grounded capacitors, the ω_0 of proposed filters can be electronically tuned. Also, both filters can provide orthogonal control ω_0 and Q. Additionally, the constant passband gain during tuning ω_0 and Q for all responses is achieved.



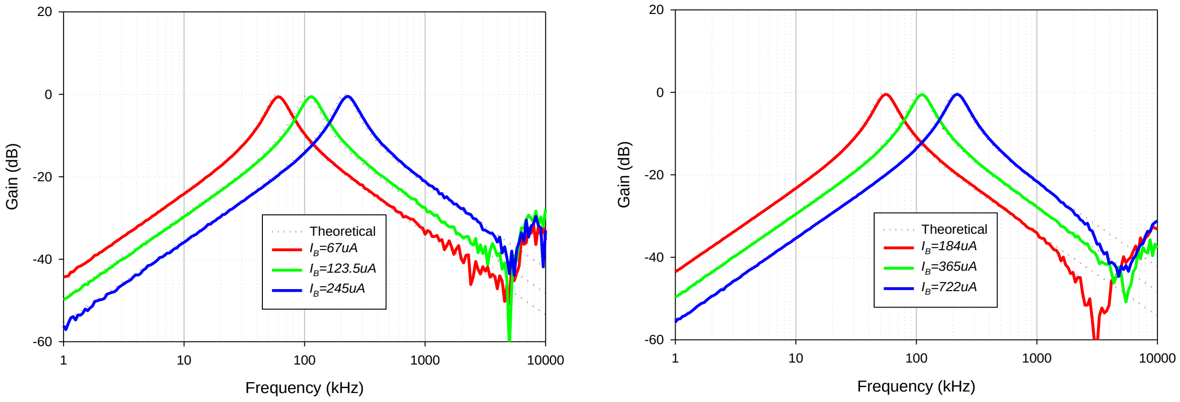
(a) (b)

Figure 10. The theoretical and experimental frequency response of the proposed filters; (a) Figure 2(a), (b) Figure 2(b)



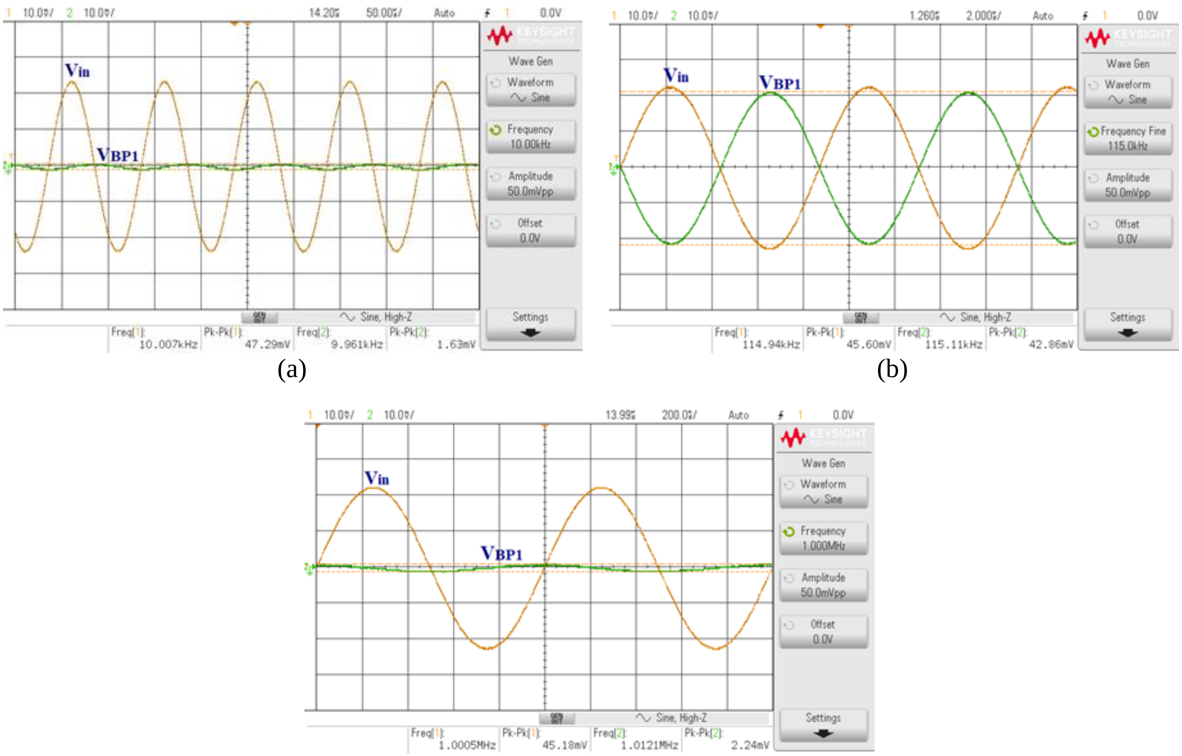
(a) (b)

Figure 11. The experimental BP gain response of the proposed filters with different values of R_5; (a) Figure 2(a), (b) Figure 2(b)



(a) (b)

Figure 12. The experimental BP gain response of the proposed filters with different values of I_B, (a) Figure 2(a), (b) Figure 2(b)



(a) (b)

(c)

Figure 13. The measurement of the band-pass response for the first proposed filter, (a) f = 10kHz, (b) f = 115kHz, (c) f = 1MHz

6. CONCLUSION

In this article, the one input voltage and three output voltages universal biquad filters constructed two LT1228s, five resistors and two grounded capacitors. The proposed circuits are synthesized from two loop integrator topologies. They can simultaneously provide three voltage-mode biquad filtering transfer functions, LP, HP and BP. The availability of orthogonal adjustability of the quality factor and natural frequency is achieved. Also, the natrual frequency is electronically and linearly tuned. The effect of non-ideal properties of LT1228 on the performances of the presented filters are considered and studied. The performances of the presented filters have been investigated by simulation and experimental results using commercially available LT1228 with ±5 V supply voltages and the results confirm the theoretical propositions.

APPENDIX

Table 1. Comparison of proposed universal filter and other voltage-mode SIMO filtering configurations

Ref.	ABB	No. of ABB	No. of commercial ICs	Grounded C only	Filtering responses	No. of low Z_o nodes	Orthogonal control ω_0 and Q	Electronical tune of ω_0	Constant passband gain during tuning ω_0 and Q for all responses	Expermental result
[11]	VDDDA	3	6	Yes	LP, HP, BP, BR, AP	2	Yes	Yes	Yes	Yes
[12]	VDDDA	3	6	Yes	LP, HP, BP, BR, AP	3	Yes	Yes	Yes	Yes
[13]	VDDDA	2	-	Yes	LP, HP, BP	2	No	Yes	Yes	No
[14]	FDCCII	1	-	No	LP, HP, BP, BR	0	No	No	No	No
[15]	FDCCII	1	-	Yes	LP, HP, BP, BR, AP	0	No	No	Yes	No
[16]	FDCCII	1	-	Yes	LP, HP, BP, BR	0	No	No	Yes	No
[17]	FDCCII	1	-	Yes	LP, HP, BP, BR	0	Yes	No	No	No
[18]	I-CB & VCII	4	-	No	LP, HP, BP	3	No	No	No	No
[19]	DDCC	3	-	Yes	LP, HP, BP, BR, AP	1	No	No	Yes	No
[20]	DDCC	1	-	Yes	LP, HP, BP, BR	0	No	No	No	No
[21]	DDCC	2	-	Yes	LP, HP, BP, BR, AP	0	No	No	Yes	No
[22]	DDCC	3	-	Yes	LP, HP, BP, BR, AP	0	No	No	Yes	No
[23]	DDCC	3	-	Yes	LP, HP, BP	0	No	No	Yes	No
[24]	DDCC	3	-	Yes	LP, HP, BP, BR, AP	0	No	No	Yes	No
[25]	DDCC	2	-	Yes	LP, HP, BP, BR, AP	0	Yes	No	No	No
[26]	DDCC	2	-	Yes	LP, HP, BP	0	Yes	No	No	No
[27]	DDCC & DO-ICII	1+1	-	Yes	LP, HP, BP, BR	0	Yes	No	Yes	No
[28]	DVCC	2	-	Yes	LP, HP, BP, BR, AP	0	Yes	No	No	No
[29]	DVCC	1	-	No	LP, HP, BP, BR, AP	0	No	No	No	No
[30]	DVCC	3	-	Yes	LP, HP, BP, BR, AP	0	No	No	Yes	No
[31]	DVCC	3	-	Yes	LP, HP, BP, BR, AP	0	Yes	No	Yes	No
[32]	CCII	4	4	Yes	LP, HP, BP, BR, AP	0	Yes	No	No	Yes
[33]	CCII	4	4	Yes	LP, HP, BP, BR, AP	0	Yes	No	No	Yes
[34]	CCII	4	7	Yes	LP, HP, BP, BR, AP	0	Yes	No	No	Yes
[35]	VD-DIBA	2	4	Yes	LP, HP, BP	2	No	Yes	Yes	Yes
[36]	ICCII	2	-	Yes	LP, HP, BP	0	No	No	No	No
[37]	VDTA	2	-	Yes	LP, BP	0	Yes	Yes	Yes	No
[38]	VDTA	2	-	Yes	LP, HP, BP, BR, AP	0	Yes	Yes	No	No
[39]	DDCCTA	2	-	Yes	LP, HP, BP, BR, AP	0	Yes	Yes	No	No
[40]	DDCCTA	2	-	Yes	LP, HP, BP, BR, AP	0	No	Yes	Yes	No
[41]	DDCCTA	1	-	Yes	LP, HP, BP	0	No	Yes	Yes	No
[42]	CCCCTA	1	-	No	LP, HP, BP, BR	0	Yes	Yes	No	No
[43]	DDCC & OTA	1+1	-	Yes	LP, HP, BP	0	No	Yes	Yes	No
[44]	OTA	7	7	Yes	LP, HP, BP, BR	0	Yes	Yes	Yes	No
[45]	OTA	5	5	Yes	LP, HP, BP	0	Yes	Yes	Yes	No
[46]	OTA	8	8	Yes	LP, HP, BP, BR, AP	0	No	Yes	Yes	No
[47]	LT1228	2	2	Yes	LP, HP, BP	2	No	Yes	Yes	Yes
Figure 2(a)	LT1228	2	2	Yes	LP, HP, BP	2	Yes	Yes	Yes	Yes
Figure 2(b)	LT1228	2	2	Yes	LP, HP, BP	2	Yes	Yes	Yes	Yes

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