Multiple-Input Single-Output Voltage-Mode Multifunction Filter Based On Vdddas

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Abstract. *In recent years, the voltage differencing differential difference amplifier (VDDDA) has been used in various analog signal processing circuit designs. A second-order multifunction filter with multiple-inputs and single-output (MISO) voltage mode using VDDDA as active elements is proposed in this paper. The structure of the proposed filter comprises two VDDDAs, two grounded capacitors, and two resisters. The proposed filter has a cascadability feature in a voltage-mode system, producing voltage input and voltage output at high and low impedance ports, respectively. It can offer responses for all-pass (AP), band-reject (BR), band-pass (BP), low-pass (LP), and high-pass (HP) filters without additional inverting and double gain amplifiers, as well as the matching conditions. Choosing the appropriate input signals provides these five filter responses in the same circuit topology. With two VDDDAs, the bias currents can be utilized to electronically tune the natural frequency (ω_0) independently from the quality factor (Q). Experimental results using available commercial ICs have supported the theoretical expectations and confirmed the practical operation of the proposed multifunction biquad filter.*

Keywords

Multifunction filter, VDDDA, voltage-mode circuit, MISO, electronical controllability, LM13700, AD830.

1. Introduction.

A filter is an electrical network that is designed to pass or reject an electrical signal in a certain way when it is connected to its input terminals [1]. Active filters, in particular, are versatile, low-cost configurations that are simple to design and tune. Communications, electronic music, medical electronics, seismology, instrumentation, and many other fields use active filters in important ways [2]. A multiple-input, single-output (MISO) multifunction biquad filter is one of the most popular categories of analog filters [3]. In the same circuit topology, it can offer various filter responses. Based on suitable input signals, the MISO filter's various output transfer functions can be chosen. The most common way to control the input signal at the filter's input nodes is to turn on or off the input signals. This digital selection can be done by a microcontroller or microprocessor [4].

The voltage differencing differential difference amplifier (VDDDA) [5] combines the functions of both the transconductance amplifier (TA) and the unity-gain voltage differential difference amplifier (DDA). It is an immensely useful and flexible active building block (ABB) for designing a voltage-mode active filter. Where the TA is at the VDDDA input stage, the filtering parameters of the VDDDA-based filter, such as the passband voltage gain, bandwidth, cut-off frequency, quality factor, and phase response, may be tuned via the transconductance (gm). With a DDA at the VDDDA output stage, it is also very useful for building voltage-mode filters without the need for extra or external voltage summation or voltage difference circuits. Moreover, certain VDDDA-based voltage-mode filters

Tab. 1: Some results with accuracy.

Ref.	Filter sort	No. Of ABB	No. Of R+C	High input impedance	Low output impedance	Availability of LP,HP,BP,BR, and AP responses	No need for matching condition	No need of additional circuits for selecting the filtering responses	Independent control of ω_0 and Q	Electronic control
[4]	MISO	1	2+2	No	No	Yes	Yes	No	No	Yes
[6]	MIMO	3	1+2	Yes	Yes	Yes	No	Yes	Yes	Yes
[7]	MIMO	1	1+2	Yes	No	No	No	Yes	Yes	Yes
[8]	MISO	1	1+2	No	No	Yes	Yes	No	No	Yes
[9]	MISO	2	0+2	Yes	Yes	Yes	Yes	Yes	No	Yes
[10]	MISO	3	1+2	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[11]	MISO	1	1+2	No	No	Yes	No	No	No	Yes
[12]	MISO	2	1+2	Yes	Yes	Yes	No	No	No*	Yes
[13]	MISO	1	2+2	Yes	No	Yes	Yes	No	No	Yes
[14]	SIMO	2	2+2	Yes	No	No	Yes	Yes	Yes	Yes
[15]	SIMO	3	1+2	Yes	No	Yes	Yes	Yes	Yes	Yes
[16]	SIMO	2	0+1	No	No	No	Yes	Yes	No	Yes
[17]	SIMO	3	1+2	Yes	No	Yes	Yes	Yes	Yes	Yes
[18]	MISO	2	3+2	No	Yes	Yes	Yes	Yes	Yes	No
[19]	MIMO	3	4+2	No	Yes	No	Yes	Yes	No*	No
[20]	MIMO	3	5+2	No	Yes	No	Yes	Yes	No*	No
[21]	MIMO	2	3+2	No	Yes	No	Yes	Yes	No*	No
[22]	SIMO	3	2+2	Yes	Yes	No	Yes	Yes	No	No
[23]	MIMO	3	1+2	Yes	No	Yes	Yes	Yes	No	Yes
[24]	MIMO	3	0+2	Yes	No	Yes	Yes	Yes	No	Yes
[25]	MIMO	2	0+2	Yes	No	Yes	Yes	No	No	Yes
[26]	SIMO	3	1+2	Yes	Yes	No	Yes	Yes	No*	Yes
This work	MISO	2	2+2	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*The multifunction filters provide only the orthogonal control of ω_0 and Q (Q is tuned without affecting the ω_0).

can be connected without the use of additional buffer devices [12].

The voltage-mode multifunction filters using a family of voltage differential difference amplifiers can be found in the open literature. These are based on VDDDA [4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17], AD830-based DDA [18, 19, 20, 21, 22], and a differential difference transconductance amplifier (DDTA) [23, 24, 25, 26]. The comparison and review of a proposed filter with the referenced single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), and MISO in voltage-mode filters are given in Table 1. It is found that filters in [4], [8], [11], [16], and [18, 19, 20, 21] cannot provide high input impedance at all input voltage nodes. Low output impedance is not obtained for all standard function responses [4], [7], [8], [11], [13, 14, 15, 16, 17], and [23, 24, 25]. Five different filter responses cannot be realized in the same circuit topology [7], [14], [16], [19, 20, 21, 22], and [26]. The voltage-mode filters in [6], [7], [11], and [12] need matching conditions, and in [4], [8], [11, 12, 13], and [25] they need additional circuits for selecting the filtering responses. The parameters ω_0 and Q of the filters in [4], [8, 9, 11, 12, 13, 16], and [19, 20, 21, 22, 23, 24, 25, 26] cannot be independently adjusted. the parameters ω_0 in [18, 19, 20, 21, 22] cannot be electronically controlled. It is also found that with two VDDDAs, the independent control of the parameters ω_0 and Q is not achieved. The two VDDDA-based MISO multifunction filters in [12] only control ω_0 and Q orthogonally (Q is tuned without affecting ω_0).

This paper introduces a voltage-mode multifunction filter based on VDDDAs that has multiple-inputs and a single-output voltage. Two grounded capacitors, two resistors, and two VDDDAs are used in the proposed multifunction filter. Without matching requirements, it can provide all typical filter responses, such as HP, LP, BP, BR, and AP. It features high input impedance and low output impedance for all functions, with no need for additional circuits for selecting the filtering responses. The parameters ω_0 and Q can be independent, where ω_0 can be electronically tuned using bias current and Q can be adjusted via a grounded resistor. The results of the experiment supports the viability of the proposed circuit.

2. Proposed Filter

2.1. VDDDA

A voltage differencing differential difference amplifier (VDDDA) as a voltage-mode active device is used in the proposal filter. Fig. 1(a) denotes the VDDDA's symbol. Fig. 1(b) is the equivalent circuit of the VDDDA. It comprises a transconductance amplifier (TA) and a differential difference amplifier (DDA). The ter-

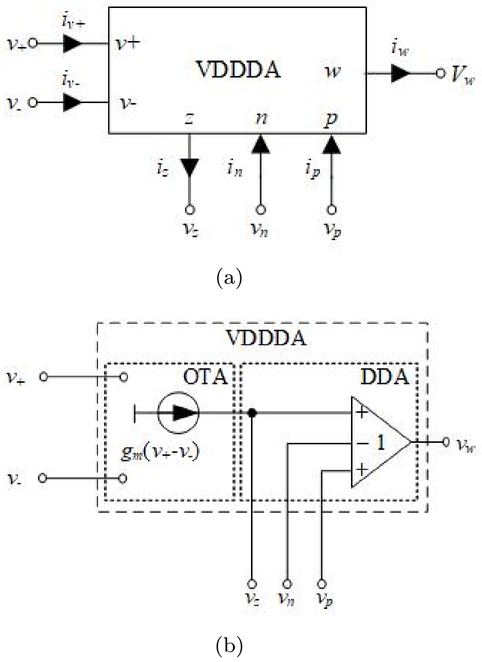

Fig. 1: The VDDDA's symbol and equivalent circuit.

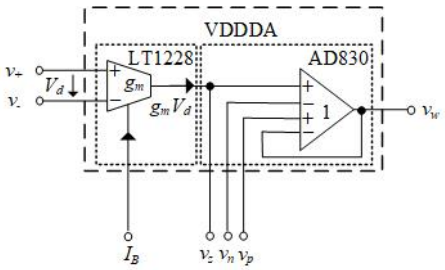

Fig. 2: The VDDDA's symbol and equivalent circuit.

minal relation of the ideal VDDDA can be characterized by the following set of equations [5].

$$\begin{aligned} i_z &= g_m\left(v_+ - v_-\right) \\ v_w &= v_z - v_n + v_p. \end{aligned} \tag{1}$$

According to the equivalent circuit and symbol of the VDDDA in Fig. 1, v_+, v_-, n, and p are high-impedance voltage input terminals, z is a high-impedance current output terminal, and w is a low-impedance voltage output terminal. By using bias current (I_B), the transconductance of VDDDA is electronically tuned.

For the real experiment, the VDDDA comprises commercially available ICs [9], as illustrated in Fig. 2. LT1228 is an OTA, and AD830 is a DDA. The bias current of the LT1228 can be used to control the value g_m. The relationship between g_m and I_B is given by

$$g_m = 10 I_B. \tag{2}$$

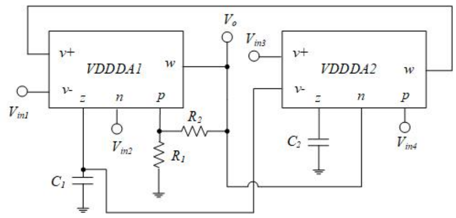

Fig. 3: The proposed multifunction filter using VDDDAs.

Tab. 2: Some results with accuracy.

Output response	V_{in1}	V_{in2}	V_{in3}	V_{in4}
Non-inverting low-pass	GND	GND	V_{in}	GND
Inverting high-pass	GND	V_{in}	V_{in}	GND
Non-inverting band-pass	GND	GND	GND	V_{in}
Inverting band-pass	V_{in}	GND	GND	GND
Inverting band-reject	GND	V_{in}	GND	GND
Inverting all-pass	GND	V_{in}	GND	V_{in}

2.2. Proposed filter

According to Fig. 3, the proposed filter is constructed using VDDDA as the active component. It has two grounded capacitors (C_1 and C_2), two resistors (R_1 and R_2), and two voltage-amplifying components (VDDDA1 and VDDDA2). One output voltage node and four high-impedance input voltage nodes make up the proposed circuit. Without requiring both active and passive element matching conditions, it can provide HP, LP, BP, BR, and AP responses in the same topology. It should be noted that R_1 should be shorted ($R_1 = 0$) for an AP response. The following gives the equation for the proposed filter's output voltage:

$$V_o = \left(\frac{R_1+R_2}{R_2}\right)\frac{\left(\begin{array}{l} -s^2 V_{in2} + \dfrac{g_{m1}}{C_1} s V_{in4} - \dfrac{g_{m1}}{C_1} s V_{in1} \\ + \dfrac{g_{m1}g_{m2}}{C_1C_2} V_{in3} - \dfrac{g_{m1}g_{m2}}{C_1C_2} V_{in2} \end{array}\right)}{s^2 + \left(\frac{R_1+R_2}{R_2}\right)\frac{g_{m1}}{C_1}s + \frac{g_{m1}g_{m2}}{C_1C_2}}. \tag{3}$$

It is obvious from Eq. (3) that the proposed filter may achieve all standard second-order filter responses in the same circuit topology by selecting the proper input terminals according to Table 2, where the gain of the BP function is unity, and the gain of the other functions is $(R_1 + R_2)/R_2$.

From Eqs. (2) and Eqs. (3), the parameters ω_0 and Q are given by:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} = 10\sqrt{\frac{I_{B1}I_{B2}}{C_1C_2}}, \tag{4}$$

and

$$Q = \left(\frac{R_2}{R_1+R_2}\right)\sqrt{\frac{g_{m1}C_1}{g_{m2}C_2}} = \left(\frac{R_2}{R_1+R_2}\right)\sqrt{\frac{I_{B1}C_1}{I_{B2}C_2}}. \tag{5}$$

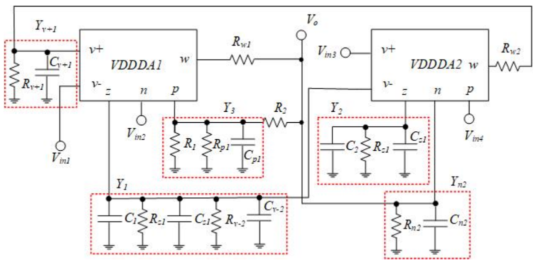

Fig. 4: The proposed multifunction filter with parasitic impedances.

From Eqs. (4) and (5), if $C_1 = C_2 = C$ and the bias currents, I_{B1} and I_{B2} are simultaneously tuned ($I_{B1} = I_{B2} = I_B$), the parameter ω_0 and Q can be rewritten as

$$\omega_0 = \frac{g_m}{C} = \frac{10 I_B}{C}, \tag{6}$$

and

$$Q = \frac{R_2}{R_1 + R_2}. \tag{7}$$

From Eqs. (6) and (7), it is discovered that the parameter ω_0 can be adjusted linearly and electronically by bias current (I_B). Moreover, both the ω_0 and Q can be independently tuned. The Q can be controlled without disturbing ω_0 by the resistors, R_1 and R_2.

2.3. Circuit sensitivities

From Eqs. (4) and (5), the active and passive sensitivities of the parameters ω_0 and Q of a proposed filter are given by

$$S_{I_{B1}}^{\omega_0} = S_{I_{B2}}^{\omega_0} = S_{I_{B1}}^{Q} = S_{C_1}^{Q} = \frac{1}{2}, \tag{8}$$

$$S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = S_{I_{B2}}^{Q} = S_{C_2}^{Q} = -\frac{1}{2}, \tag{9}$$

$$S_{R_1}^{Q} = -\frac{R_1}{R_1 + R_2}, S_{R_2}^{Q} = \frac{R_1}{R_1 + R_2}. \tag{10}$$

2.4. Analysis of non-ideal cases

For the sake of practicality, it is important to consider the non-ideal characteristics of the VDDDA that affect the circuit's performance. Firstly, taking into account the voltage tracking error from the voltage and current terminals of VDDDA, the terminal relationships in Eq. (1) can be rewritten as

$$v_W = \beta_z v_z - \beta_n v_n + \beta_p v_p, \tag{11}$$

Where β_z, β_n, and β_p are the voltage transfer gain errors from the z, n, and p terminals to the w terminal

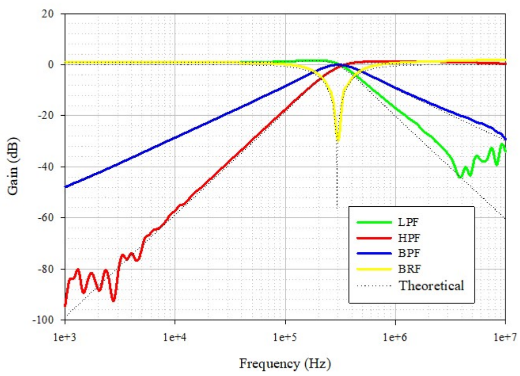

Fig. 5: Experimental gain responses of LP, HP, BR, and BP functions.

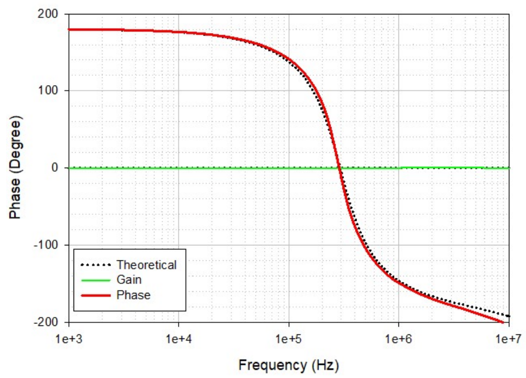

Fig. 6: Experimental gain and phase responses of AP functions.

of VDDDA, respectively. Thus, the voltage-tracking error transfer functions can be expressed as

$$V_O^* = \frac{\left(\frac{R_1+R_2}{R_2+R_1(1-\beta_{p1})}\right)\begin{bmatrix} -\beta_{n1}V_{in2}s^2 - \beta_{z1}\frac{g_{m1}}{C_1}sV_{in1} \\ +\beta_{p2}\beta_{z1}\frac{g_{m1}}{C_1}sV_{in4} \\ +\beta_{z2}\beta_{z1}\frac{g_{m1}g_{m2}}{C_1C_2}V_{in3} \\ -\beta_{n1}\beta_{z2}\frac{g_{m1}g_{m2}}{C_1C_2}V_{in2} \end{bmatrix}}{\begin{bmatrix} s^2 + \left(\frac{(R_1+R_2)\,\beta_{n2}\beta_{z1}\frac{g_{m1}}{C_1}s}{R_2 + R_1(1-\beta_{p1})}\right) \\ +\beta_{z2}\frac{g_{m1}g_{m2}}{C_1C_2} \end{bmatrix}}. \tag{12}$$

From Eq. (12), the non-ideal parameters filter is given by:

$$\omega_0^* = \sqrt{\beta_{z2}\frac{g_{m1}g_{m2}}{C_1C_2}}, \tag{13}$$

$$Q^* = \left[\frac{1}{\beta_{n2}\beta_{z1}} - \frac{\beta_{p1}}{\beta_{n2}\beta_{z1}}\left(\frac{R_1}{R_1+R_2}\right)\right]\sqrt{\frac{\beta_{z2}g_{m2}C_1}{g_{m1}C_2}}. \tag{14}$$

It can be seen from Eq. (12) that parameters β_z, β_n and β_p affect gain and filter responses. Also, the voltage tracking errors have a slight effect on the ω_z and Q. as illustrated in Eq. (13) to (14).

Secondly, this section considers the VDDDA's parasitic impedance effect. The high-impedance terminals v_+, v_-, z, n, and p of VDDDA have a parallel parasitic resistance and a parasitic capacitance. The low-impedance terminal w has a parasitic series resistance (R_w), as illustrated in Fig. 4, the non-ideal transfer functions will be expressed as where $Y_{n2} = sC_{n2} + G_{n2}$, $Y_{v+1} = sC_{v+1} + Gv + 1$, $Y_1 = sC_{T1} + G_{T1}$, $Y_2 = sC_{T2} + G_{T2}$, $Y_3 = sC_{p1} + G_{p1} + G_1$, $C_{T1} = C_1 + C_{z1} + C_{v-2}$, $C_{T2} = C_2 + C_{z2}$, $C_{T3} = C_{p1}$, $G_{T1} = G_{z1} + G_{v-2}$, and $G_{T2} = G_{z2}$. If the operational frequency (f_{op}) of the proposed biquad filter is much less than $1/[2\pi C_{p1}(R_1//R_2)]$ and R_{p1} is much more than R_1, then Y_3 is approximately equal to $Y3 \cong 1/R_1$. Also, if the operational frequency is much less than $1/[2\pi C_{v+1}(R_{v+1}//R_{w2})]$ and $1/[2\pi C_{n2}(R_{n2}//R_{w1})]$, then the admittances Y_{n2} and Y_{v+1} are neglected. Thus, the voltage transfer functions in (15) can be rewritten as

$$V_O^{***} = \frac{\left(\frac{R_1+R_2}{R_2}\right)\left[\begin{array}{l} -V_{in2}\left(s^2 + s\frac{G_{T2}}{C_{T2}} + s\frac{G_{T1}}{C_{T1}} + \frac{G_{T1}G_{T2}}{C_{T1}C_{T2}}\right) \\ + \left(\frac{g_{m1}}{C_{T1}}s + \frac{G_{T2}g_{m1}}{C_{T1}C_{T2}}\right)V_{in4} \\ - \left(\frac{s}{C_{T1}} + \frac{G_{T2}}{C_{T1}C_{T2}}\right)g_{m1}V_{in1} \\ + \frac{g_{m1}g_{m2}}{C_{T1}C_{T2}}V_{in3} - \frac{g_{m1}g_{m2}}{C_{T1}C_{T2}}V_{in2} \end{array}\right]}{\left\{\begin{array}{l} s^2 + \left[\left(\frac{R_2}{R_1+R_2}\right)\frac{g_{m1}}{C_{T1}} + \frac{G_{T2}}{C_{T2}} + \frac{G_{T1}}{C_{T1}}\right]s \\ + \frac{g_{m1}g_{m2}}{C_{T1}C_{T2}} + \left(\frac{R_2}{R_1+R_2}\right) \\ \times \frac{G_{T2}g_{m1}}{C_{T1}C_{T2}} + \frac{G_{T1}G_{T2}}{C_{T1}C_{T2}} \end{array}\right\}}. \tag{16}$$

From Eq. (16), the non-ideal filter parameters are given as

$$\omega_0^{***} = \sqrt{\frac{g_{m1}g_{m2}}{C_{T1}C_{T2}} + \left(\frac{R_2}{R_1+R_2}\right)\frac{G_{T2}g_{m1}}{C_{T1}C_{T2}} + \frac{G_{T1}G_{T2}}{C_{T1}C_{T2}}}, \tag{17}$$

$$Q^{***} = \frac{\sqrt{\frac{g_{m1}g_{m2}}{C_{T1}C_{T2}} + \left(\frac{R_2}{R_1+R_2}\right)\frac{G_{T2}g_{m1}}{C_{T1}C_{T2}} + \frac{G_{T1}G_{T2}}{C_{T1}C_{T2}}}}{\left[\left(\frac{R_2}{R_1+R_2}\right)\frac{g_{m1}}{C_{T1}} + \frac{G_{T2}}{C_{T2}} + \frac{G_{T1}}{C_{T1}}\right]} \tag{18}$$

The parasitic impedances of VDDDA have an impact on the voltage gain, ω_0, Q, and the filter response, as can be observed from Eq. (18). In a while, C_1 and C_2 can absorb the parameters C_{z1} and C_{z2} at ports Z_1 and Z_2.

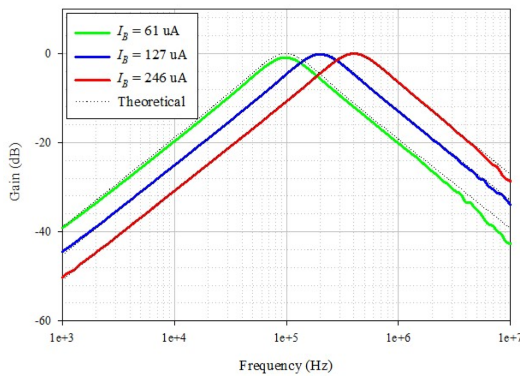

Fig. 7: Tuning of f_0 for BP filter via I_B.

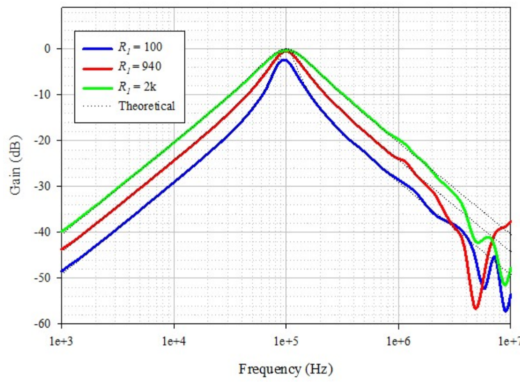

Fig. 8: Tuning of the quality factor for BP filter via R_1.

3. Experimental results

The proposed multiple-input single-output voltage-mode multifunction filter based on VDDDAs is experimentally tested. In Fig. 3, the VDDDA is implemented by using commercially available ICs LT1228 and AD830. To design all standard functions of the proposed filter with gain = 1.1 dB, Q = 0.9, and f_0 = 300 kHz. The circuit components are chosen as: $C_1 = C_2 = 1$ nF, $R_1 = 100\ \Omega$ for LP, HP, and BP functions. $R_2 = 1$ kΩ, $I_{B1} = I_{B2} = 185\ \mu$A and the supply voltage = $\pm$5V. The experimental and theoretical results of the frequency gain response for all filtering functions are illustrated in Fig. 5. The experimental f_0 is 299 kHz. So, the deviation between experimental and theoretical values is ~0.3%. It is found that the experimental LP response at high frequency is inconsistent with the theoretical response because of the effect of the parasitic impedances of VDDDA as studied in Eq. (15). The parasitic elements in VDDDA also affect the HP response at low frequency. The experimental

$$V_O = \frac{\begin{bmatrix} -V_{in2} + \frac{g_{m1}}{Y_1}\left(\frac{1}{1+Y_{v+1}R_{w2}}\right)V_{in4} - \frac{g_{m1}}{Y_1}V_{in1} \\ +\frac{g_{m1}g_{m2}}{Y_1Y_2}\left(\frac{1}{1+Y_{v+1}R_{w2}}\right)V_{in3} - \frac{g_{m1}g_{m2}}{Y_1Y_2}\left(\frac{1}{1+Y_{v+1}R_{w2}}\right)V_{in2} \end{bmatrix}}{\begin{Bmatrix} \frac{Y_3Y_{n2}+Y_3R_2+1+R_{w1}Y_{n2}\left(Y_3R_2+1\right)}{Y_3Y_{n2}+Y_3R_2+1} - \left(\frac{1}{1+R_2Y_3}\right) + \frac{g_{m1}}{Y_1}\left(\frac{1}{1+Y_{v+1}R_{w2}}\right) \\ +\frac{g_{m1}g_{m2}}{Y_1Y_2}\left(\frac{1}{1+Y_{v+1}R_{w2}}\right)\left[\frac{Y_3Y_{n2}+Y_3R_2+1+R_{w1}Y_{n2}\left(Y_3R_2+1\right)}{Y_3Y_{n2}+Y_3R_2+1} - \frac{1}{1+R_2Y_3}\right] \end{Bmatrix}}. \quad (15)$$

gain and phase responses of the AP function are depicted in Fig. 6. It is found that the phase shift begins at 180 degrees at low frequency and transitions to -180 degrees at high frequency. With this phenomenon, the proposed AP function can provide the leading phase shift from low frequency to natural frequency and the lagging phase shift from the natural frequency to high frequency. As stated above for an AP response, R_1 should be shorted ($R_1 = 0$).

Experimental results in Fig. 7 demonstrate that f_0 can be tuned without affecting Q, where I_B was changed to 61 μA, 127 μA, and 246 μA, while other elements were as follows: $C_1 = C2 = 1$ nF, $R_1 = 100$ kΩ, and $R_2 = 1$ kΩ. The experimental results show that f_0 obtained from these tuning I_B values are 97.9 kHz, 203 kHz, and 390 kHz. The deviations from experimental and theoretical values are 0.1%, 0.09%, and 0.5%, respectively. It is found that when f_0 is tuned by I_{B1}, it slightly affects the pass band gain due to the parasitic elements as analysed in Eq. (16). Experimental results in Fig. 8 demonstrate that Q can be tuned without affecting f_0, where R_1 was varied to 100Ω, 940Ω, and 2 kΩ, while other elements were as follows: $C_1 = 10$ nF, $C_2 = 1$ nF, $I_{B1} = I_{B2} = 202\mu$A, $R_2 = 1$ kΩ. The experimental results show that Q obtained from these tuning R_1 values are 2.87, 1.63, and 1.05. The deviations from experimental and theoretical values are 2.8%, 1.2%, and 0.9%, respectively. It is found that when Q is tuned by R_1, it slightly affects the pass band gain due to the parasitic elements as analysed in Eq. (16). The measured output and input sinusoidal waveforms of the LP, HP, BP, BR, and AP functions for three frequencies are depicted in Figs. 10, 11, 12, 13, and 14 respectively

4. Conclusion

This study describes a voltage-mode multifunction filter based on VDDDAs that has multiple-input and a single-output voltage node. Two VDDDAs, two grounded capacitors, and two resistors are used in the proposed filter. It can acquire all standard filter responses such as HP, LP, BP, BR, and AP without requiring matching conditions. The proposed filter can perform all functions with a high input impedance and a low output impedance. The ω_0 and Q can be independently tuned. The parameters ω_0 can be electronically and linearly controlled by bias current (I_B) without disturbing Q. Moreover, the Q is not electronically tuned (Q is controlled by a resistor (R_1)) without disturbing ω_0. The experimental results show strong performance and support the theoretical hypothesis.

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Author Contributions

Conceptual framework, P.H., W.J., and P.S.; Simulation, P.H., and W.J.; Experimental, P.H, and W.J.; Formal analysis and writing-original draft preparation, P.H., W.J., S.S., and A.C.; Verified the analytical methods, P.H.; All authors have discussed the results and contributed to the final manuscript.

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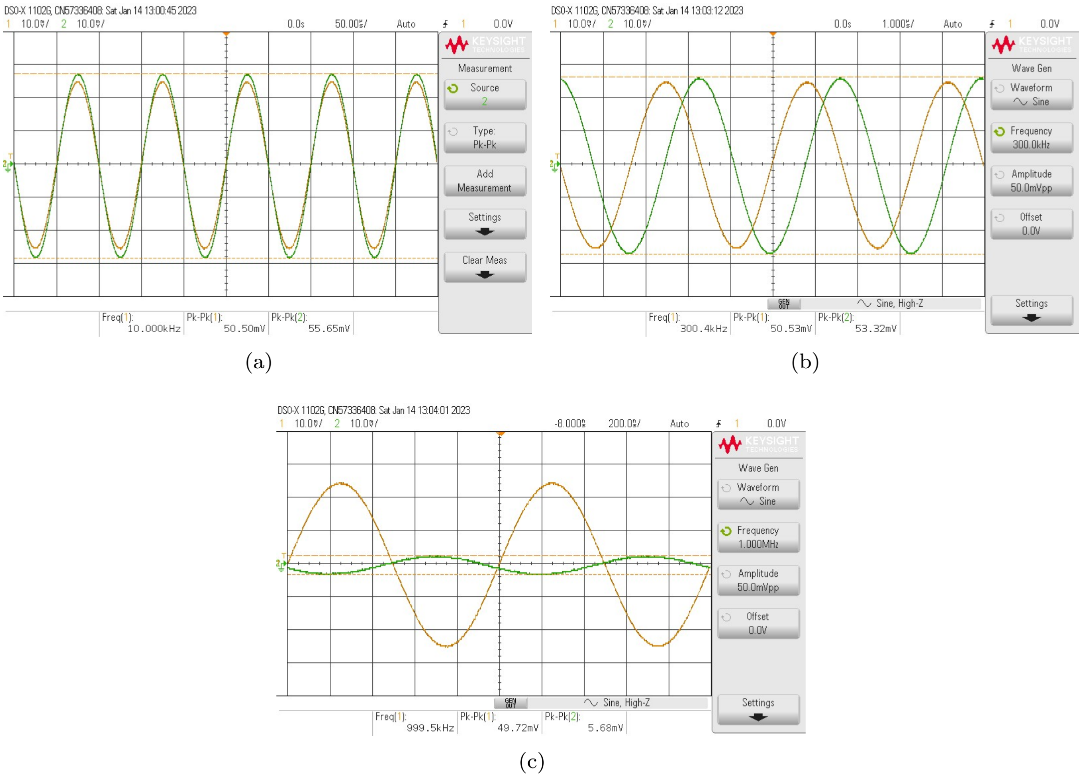


Fig. 9: Measured waveforms of non-inverting V_{LP} and V_{in} (a) $f = 10$ kHz, (b) $f = 300$kHz and (c) $f = 1$MHz.

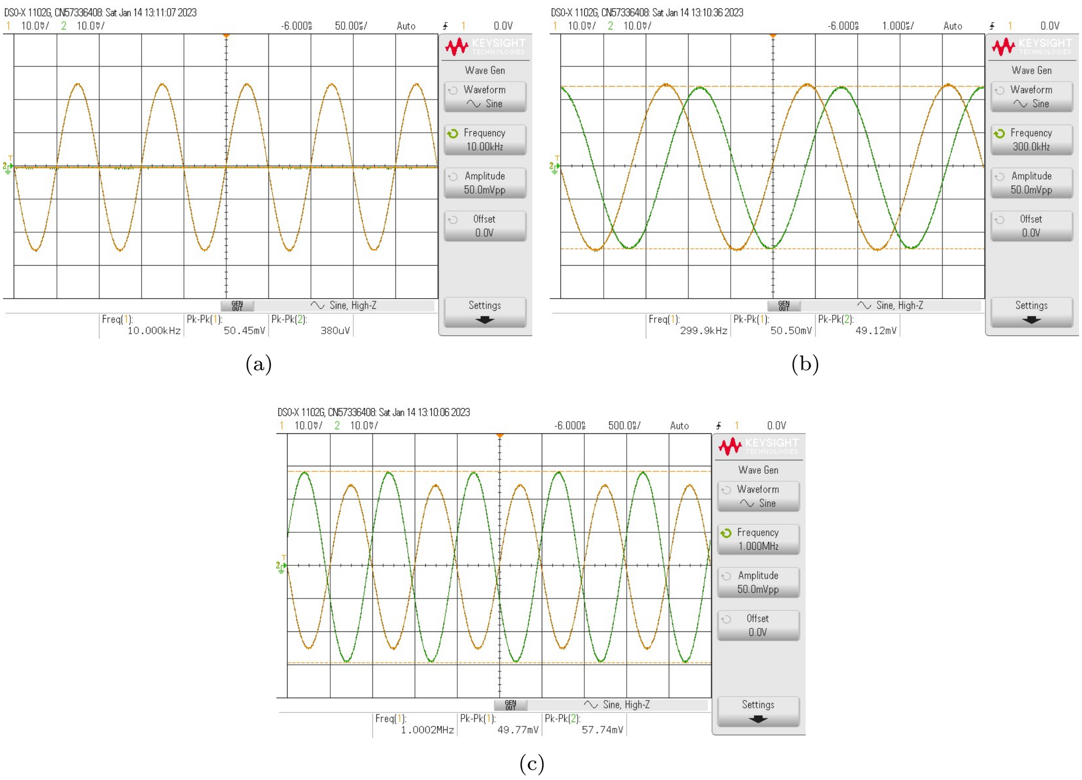
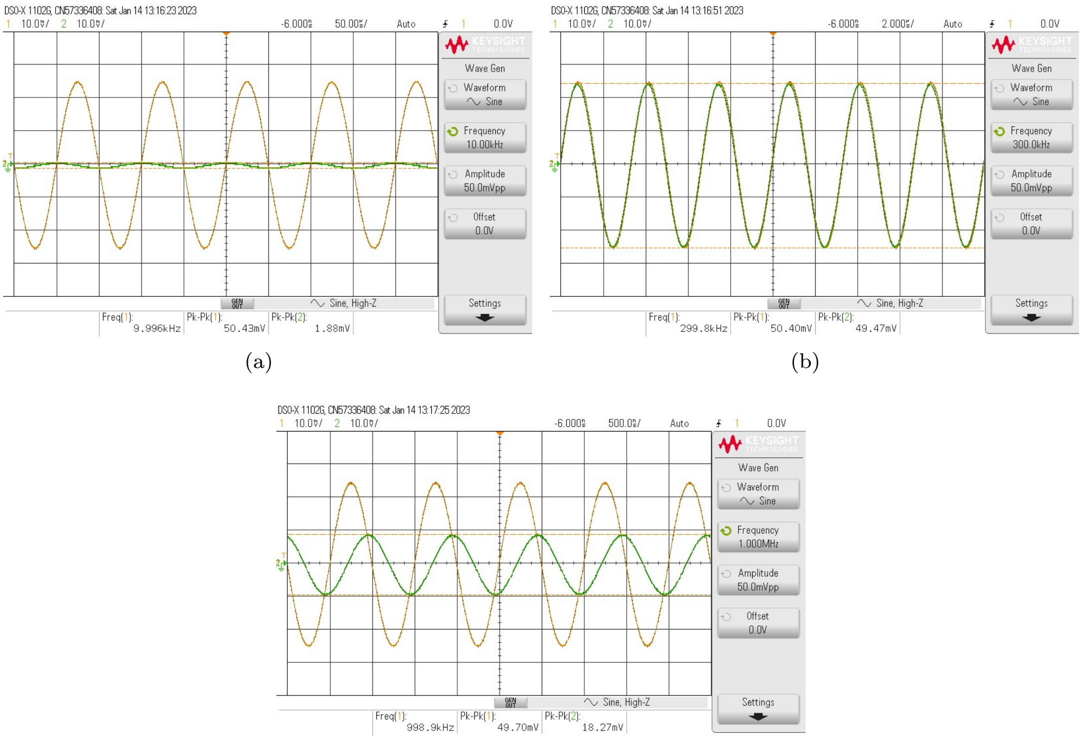


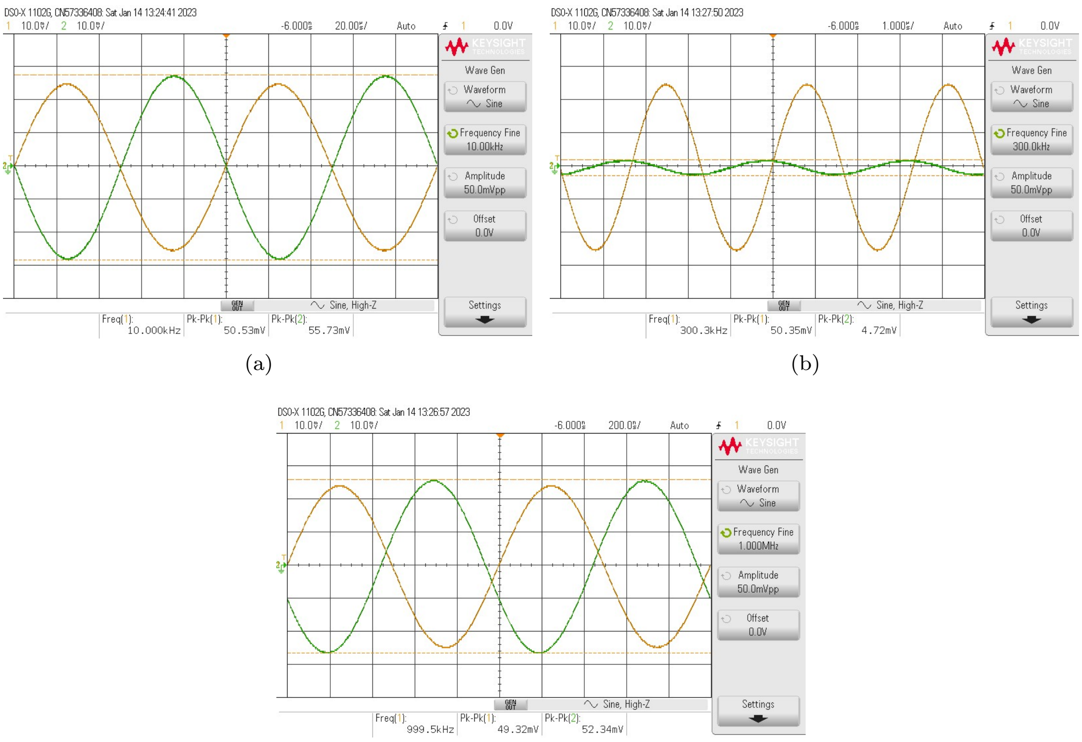
Fig. 10: Measured waveforms of inverting V_{HP} and V_{in} (a) $f = 10$kHz, (b) $f = 300$kHz and (c) $f = 1$MHz.



(a) (b)

(c)

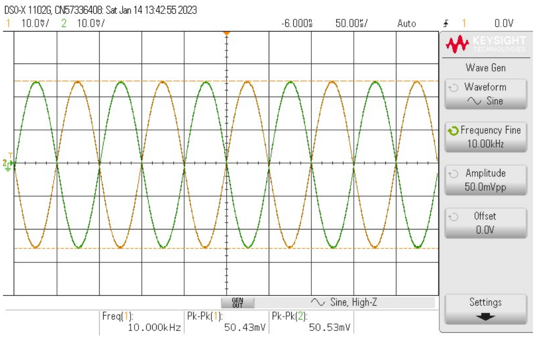
Fig. 11: Measured waveforms of non-inverting V_{BP} and V_{in} (a) $f = 10\text{kHz}$, (b) $f = 300\text{kHz}$ and (c) $f = 1\text{MHz}$.



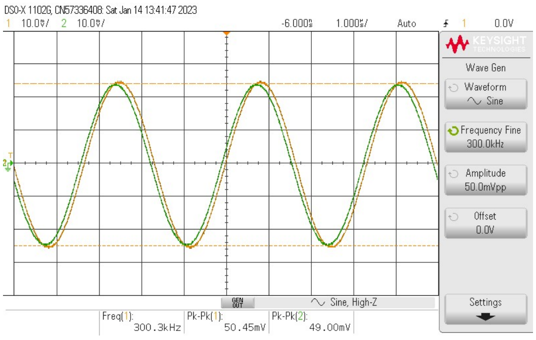
(a) (b)

(c)

Fig. 12: Measured waveforms of inverting V_{BP} and V_{in} (a) $f = 10\text{kHz}$, (b) $f = 300\text{kHz}$ and (c) $f = 1\text{MHz}$.



(a)



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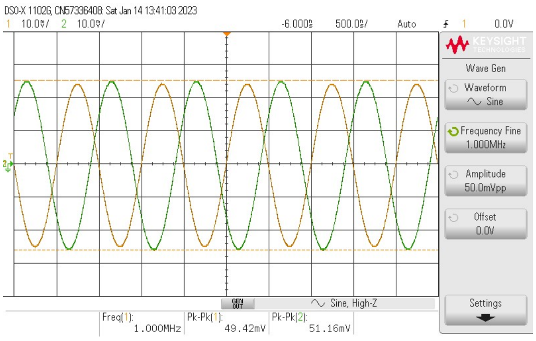
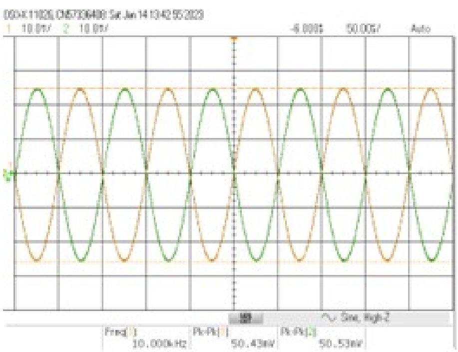
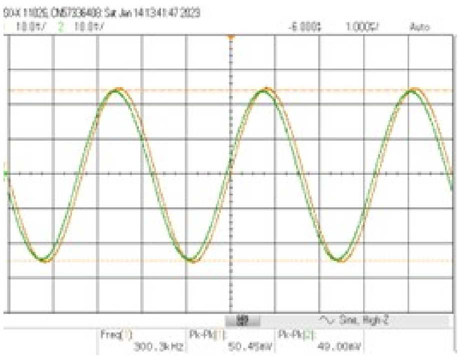


(c)

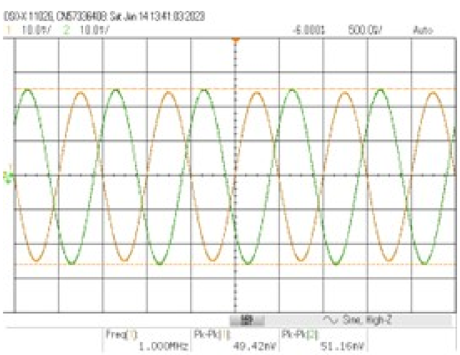
Fig. 13: Measured waveforms of inverting V_{BR} and V_{in} (a) $f = 10$kHz, (b) $f = 300$kHz and (c) $f = 1$MHz.



(a)



(b)



(c)

Fig. 14: Measured waveforms of inverting V_{AP} and V_{in} (a) $f = 10$kHz, (b) $f = 300$kHz and (c) $f = 1$MHz.

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