High-Input-Impedance Four-Input Single-Output Voltage-Mode Biquadratic Filter with Only VDTAs and Grounded Capacitors

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***Abstract*— This paper presents a voltage-mode universal biquadratic filter with voltage differencing transconductance amplifiers (VDTAs) as active components. The proposed filter comprises four inputs and a single output and can perform all five general biquadratic filter functions, namely lowpass, bandpass, highpass, bandstop, and allpass responses, without modifying the circuit architecture. It also offers the advantages of resistorless implementation with only two grounded capacitors, orthogonal adjustment of the natural angular frequency and the quality factor, as well as the absence of any constraint related to the values of input signals. Moreover, because the circuit contains all of the high input impedance levels, it may be cascaded without the requirement of additional buffers. The suggested filter's functioning has been validated by simulations using the PSPICE application.**

***Index Terms*-universal filter, Voltage Differencing Transconductance Amplifier (VDTA), biquadratic filter, voltage-mode circuit, electronically tunable.**

I. Introduction

Universal filters are analog active filters that can perform all five typical filter functions such as lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS), and allpass (AP) from the same topology [1]. They are a very valuable circuit function block that is frequently employed in communication and measurement systems such as phase-locked loop FM stereo demodulators, touch-tone telephones, and cross-over networks used in three-way high-fidelity loudspeakers [2]. The following benefits must be offered by a voltage-mode universal biquadratic filter topology: (i) high input impedance; (ii) all grounded passive components; (iii) no additional conditioning of input and/or output signals; and (iv) orthogonal tuning of natural angular frequency (ω_o) and quality factor (Q). A plethora of fascinating multiple-input single-output (MISO) voltage-mode universal biquad solutions with diverse active element types, such as those described in [3-26], have been proposed. However, these MISO solutions come with some of the following problems:

(i) there are non-grounded passive components in the topology [3-6, 8-9, 11-16, 19-23, 25-26];

(ii) there are no high-impedance inputs [5-6, 8-9, 11-13, 15-16, 18, 20-23, 25-26];

(iii) they have external passive resistors [3, 5-9, 11-14, 16, 19-22, 24-26];

(iv) additional input and/or output signal conditioning is required [4, 6, 8-9, 11-13, 15-17, 20-23, 25-26];

(v) the critical parameters ω_o and Q are inseparable [3-7, 10-17, 19, 22, 26];

(vi) they are not electronically tunable [3, 5-9, 12-14, 20, 22];

(vii) they employ various types of active elements [4, 20].

Because of the resistorless filter topologies accessible, the voltage differencing transconductance amplifier (VDTA) is an interesting active component for the implementation of universal biquadratic filters [28-32]. The VDTA is a voltage-controlled current source combining active devices. It functions as a multiple-output transconductor with differential input voltage control, resulting in two distinct transconductances: first transconductance (g_{mF}) and second transconductance (g_{mS}) [33-34]. Because of its ability to regulate these transconductances individually via external bias currents, it is an alternative device for circuit designers to other active components. Furthermore, a VDTA's ability to function as a voltage or current-mode device adds to its versatility.

The primary goal of this work is to present a circuit configuration for the creation of a universal voltage-mode biquadratic filter based on VDTAs and solely grounded capacitors. The proposed circuit, which has four inputs and a single output (FISO), can perform the LP, BP, HP, BS, and AP filter functions concurrently. It possesses a high input impedance and independent electronic control of the ω_o and Q parameters. In addition, no further conditioning of input or output signals is required by the circuit. The simulation results from the PSPICE program are used to demonstrate the behavior of the circuit.

II. Circuit Description

The VDTA active element has been used for the realization of the proposed FISO voltage-mode universal biquadratic filter. The port relation of the ideal VDTA,

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depicted in Fig. 1, can be characterized by the matrix given below.

$$\begin{bmatrix} i_z \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} g_{mF} & -g_{mF} & 0 \\ 0 & 0 & g_{mS} \\ 0 & 0 & -g_{mS} \end{bmatrix} \begin{bmatrix} v_p \\ v_n \\ v_z \end{bmatrix} \quad (1)$$

In the above expression, g_{mF} and g_{mS} denote the first and second small-signal transconductance parameters, respectively. It should be noted that the transconductances g_{mF} and g_{mS} may be electrically adjusted using external DC control voltages or currents.

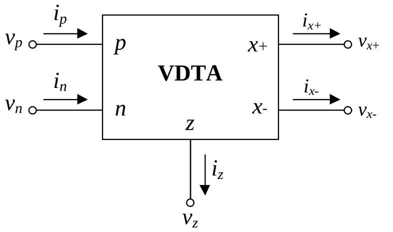

Fig. 1. Symbol of the VDTA

Fig. 2 depicts the proposed voltage-mode universal biquadratic filter. It consists of two VDTAs and two grounded capacitors. Using solely grounded capacitors is helpful for general integrated circuit implementation [35]-[36]. For the ideal case, the circuit analysis in Fig. 2 provides the following output voltage function:

$$v_{out} = \frac{s^2 v_{in4} + s\left(\frac{g_{mF2}g_{mS2}}{g_{mF3}C_2}\right)(v_{in3} - v_{in2}) + \left(\frac{g_{mF1}g_{mS1}g_{mS2}}{g_{mF3}C_1C_2}\right)v_{in1}}{D(s)} \quad (2)$$

where $$D(s) = s^2 + s\left(\frac{g_{mS2}g_{mS3}}{g_{mF3}C_2}\right) + \left(\frac{g_{mF1}g_{mS1}g_{mS2}}{g_{mF3}C_1C_2}\right) \quad (3)$$

and $g_{mF2} = g_{mS3}$. Here, g_{mFi} and g_{mSi}, i = 1, 2, 3, are the transconductance parameters g_{mF} and g_{mS} of the i-th VDTA.

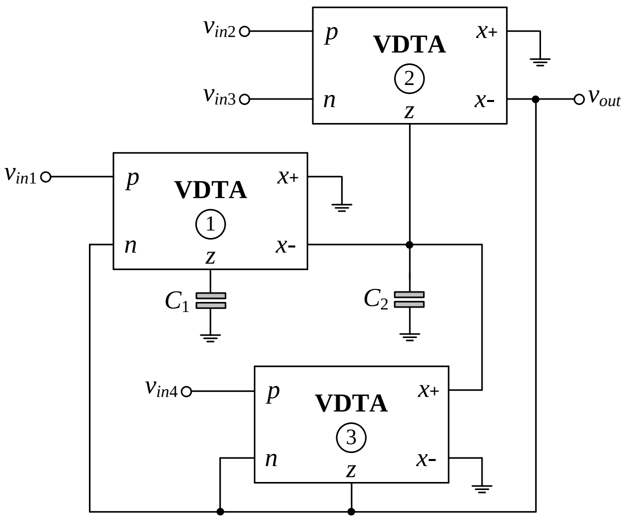

Fig. 2. Proposed VDTA-based universal biquadratic filter

According to (2) and (3), the proposed circuit can realize all basically five biquadratic filtering functions under the following conditions:

(i) to obtain an LP filter, set v_{in} (input voltage) = v_{in1} and $v_{in2} = v_{in3} = v_{in4} = 0$ (ground potential);

(ii) to obtain a BP filter, set $v_{in} = v_{in3}$ and $v_{in1} = v_{in2} = v_{in4} = 0$;

(iii) to obtain an HP filter, set $v_{in} = v_{in4}$ and $v_{in1} = v_{in2} = v_{in3} = 0$;

(iv) to obtain a BS filter, set $v_{in} = v_{in1} = v_{in4}$ and $v_{in2} = v_{in3} = 0$;

(v) to obtain an AP filter, set $v_{in} = v_{in1} = v_{in2} = v_{in4}$ and $v_{in3} = 0$.

The preceding shows that the five filter functions are accomplished by selecting the proper input signals with no requirement for inverting the output signals. Furthermore, all realized filter functions have the same sign; therefore no additional inversion stages are required at the filter's output. Another essential characteristic is the availability of voltage inputs with high impedance, allowing for voltage-mode cascadability.

The important filter characteristics, namely ω_o and Q, for all responses are given by

$$\omega_o = 2\pi f_o = \sqrt{\frac{g_{mF1}g_{mS1}g_{mS2}}{g_{mF3}C_1C_2}} \quad , \quad (4)$$

and $$Q = \left(\frac{1}{g_{mS3}}\right)\sqrt{\frac{g_{mF1}g_{mS1}g_{mF3}C_2}{g_{mS2}C_1}} \quad . \quad (5)$$

The above-mentioned analysis proves that the filter characteristics ω_o and Q can be orthogonally tuned and electrically modified through the VDTA transconductance gains (i.e., the bias currents of the VDTAs). Under the assumptions of $g_{mi} = g_{mFi} = g_{mSi}$, the ω_o and Q parameters simplify to, respectively,

$$\omega_o = g_{m1}\sqrt{\frac{g_{m2}}{g_{m3}C_1C_2}} \quad , \quad (6)$$

and $$Q = \left(\frac{g_{m1}}{g_{m3}}\right)\sqrt{\frac{C_2}{C_1}} \quad . \quad (7)$$

When the values of C_1 and C_2 are known in advance, the ω_o-value can be determined using g_{m1}. The transconductance gain g_{m3} can also be used to adjust the parameters Q without altering the ω_o-value.

III. Non-ideality Analysis

Given the VDTA's non-ideality, its terminal relationship may be expressed as:

$$\begin{bmatrix} i_z \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} \beta_F g_{mF} & -\beta_F g_{mF} & 0 \\ 0 & 0 & \beta_{SP} g_{mS} \\ 0 & 0 & -\beta_{SN} g_{mS} \end{bmatrix} \begin{bmatrix} v_p \\ v_n \\ v_z \end{bmatrix}, \quad (8)$$

where β_F, β_{SP}, and β_{SN} are the parasitic transconductance gains for the VDTA's input and output stages, respectively.

When these parasitic transconductance gains are taken into account, the denominator in (3) becomes

$$D(s) = s^2 + s\left(\frac{\beta_{SN2}\beta_{SP3}g_{mS2}g_{mS3}}{\beta_{F3}g_{mF3}C_2}\right) + \left(\frac{\beta_{F1}\beta_{SN1}\beta_{SN2}g_{mF1}g_{mS1}g_{mS2}}{\beta_{F3}g_{mF3}C_1C_2}\right).$$

(9)

In (9), β_{Fi}, β_{SPi}, and β_{SNi} are the parameters β_F, β_{SP}, and β_{SN} of the *i*-th VDTA. In this case, the filter characteristics ω_o and Q are obtained as:

$$\omega_o = \sqrt{\frac{\beta_{F1}\beta_{SN1}\beta_{SN2}g_{mF1}g_{mS1}g_{mS2}}{\beta_{F3}g_{mF3}C_1C_2}}\ , \qquad (10)$$

and $$Q = \left(\frac{1}{\beta_{SP3}g_{mS3}}\right)\sqrt{\frac{\beta_{F1}\beta_{SN1}\beta_{F3}g_{mF1}g_{mS1}g_{mF3}C_2}{\beta_{SN2}g_{mS2}C_1}}\ . \qquad (11)$$

The active and passive sensitivities of the parameters ω_o and Q to circuit components are determined as provided in Table I. It reveals that the sensitivity performance is low.

TABLE I
INCREMENTAL SENSITIVITIES OF THE ω_o AND Q PARAMETERS.

x	$S_x^{\omega_o}$	S_x^Q
g_{mF1}	0.5	0.5
g_{mS1}	0.5	0.5
g_{mF2}	0	0
g_{mS2}	0.5	-0.5
g_{mF3}	-0.5	0.5
g_{mS3}	0	-1
β_{F1}	0.5	0.5
β_{SP1}	0	0
β_{SN1}	0.5	0.5
β_{F2}	0	0
β_{SP2}	0	0
β_{SN2}	0.5	-0.5
β_{F3}	-0.5	0.5
β_{SP3}	0	-1
β_{SN3}	0	0
C_1	-0.5	-0.5
C_2	-0.5	0.5

IV. DESIGN EXAMPLE AND SIMULATION RESULTS

The CMOS realization of the VDTA in Fig.3 was used for simulations of the proposed VDTA-based universal biquadratic filter in PSPICE using TSMC 0.18-µm CMOS technology [33-34]. The supplied DC bias voltages were +V = -V = 1V. Table II lists the transistor dimensions of the CMOS VDTA in Fig.3. In all subsequent simulations, the capacitor values were set to $C_1 = C_2 = 100$ pF.

TABLE II
TRANSISTOR ASPECT RATIOS (W/L) OF THE VDTA IN FIG.3.

Transistors	W/L (µm/µm)
M_1 - M_2 , M_5 - M_6	20/0.18
M_3 - M_4 , M_7 - M_8	27/0.18
M_9 - M_{18}	5/0.18

As a design example, the filter realization with f_o = 2.22 MHz and Q = 1 has been considered. To obtain the filter characteristic above, the following settings were used: $g_{mFi} = g_{mSi} \cong 1.40$ mAV^{-1} ($I_{BFi} = I_{BSi} = 150$ µA). Figs. 4-8 show the ideal and simulated frequency response characteristics, as well as the related phase plots, for the five types of filters. The simulation results demonstrate that the f_o of operation is 2.16 MHz for all filter designs, which is close to the predicted value. It is also observed that the overall power consumption of the circuit is roughly 1.8 mW for the specified component values, which is a really low value.

For the same given component values, the simulated time-domain responses for all filter configurations are also shown in Figs.9-13 when a sinusoid with an amplitude of 50 mV (peak) at 2.22 MHz was applied to the filter. Table III shows the relationship between the total harmonic distortion (THD) of the BP filter output and the amplitude of the applied sinusoidal signal at 2.22 MHz operation frequency. It should be noted that the percentage of THD is modest and maintained within the acceptable range of 5% [37] until the significant input signal of 200 mV (peak) is applied.

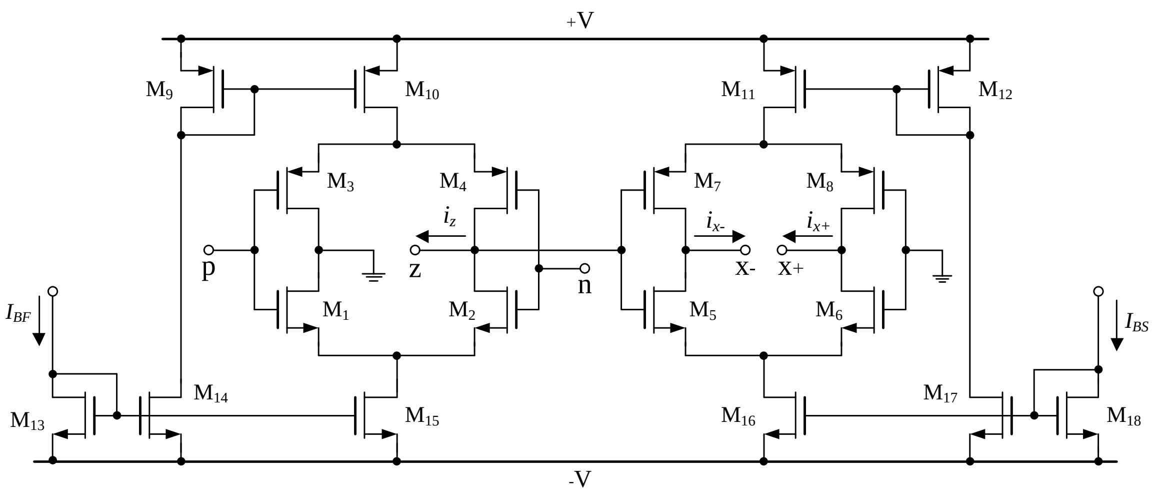

Fig. 3. CMOS realization of the VDTA

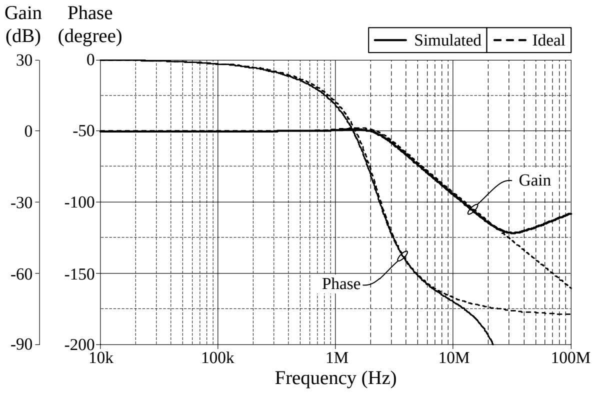

Fig. 4. Ideal and simulated frequency characteristics of the LP filter obtained from Fig.2.

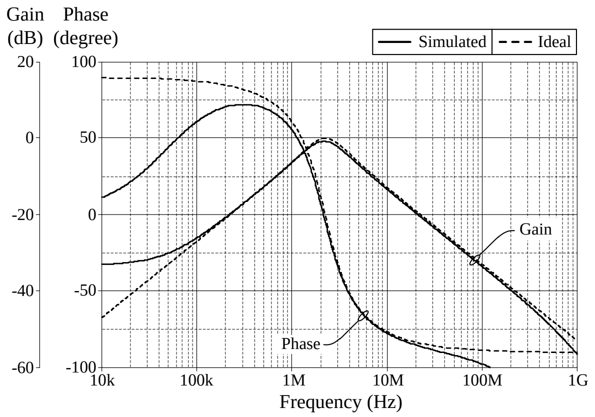

Fig. 5. Ideal and simulated frequency characteristics of the BP filter obtained from Fig.2.

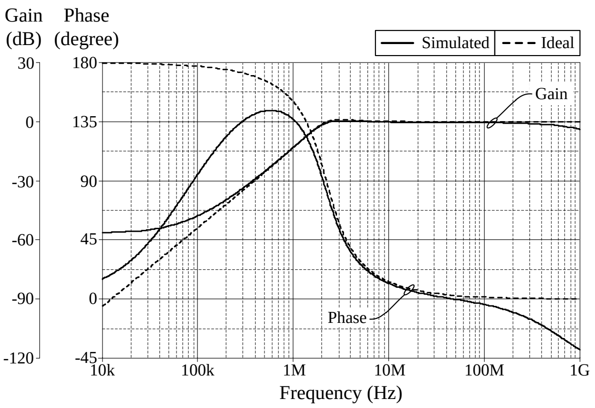

Fig. 6. Ideal and simulated frequency characteristics of the HP filter obtained from Fig.2.

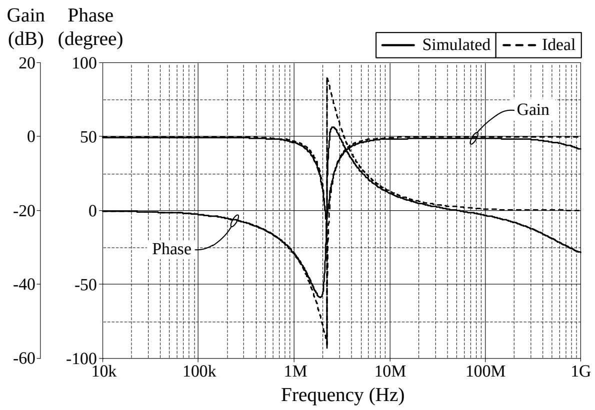

Fig. 7. Ideal and simulated frequency characteristics of the BS filter obtained from Fig.2.

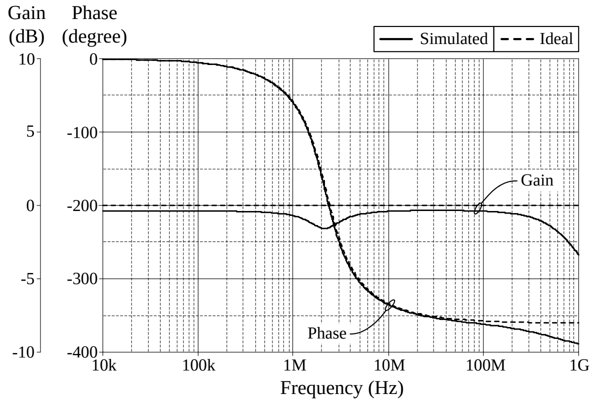

Fig. 8. Ideal and simulated frequency characteristics of the AP filter obtained from Fig.2.

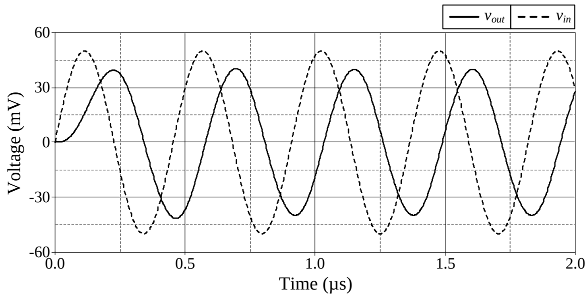

Fig. 9. Simulated time-domain responses of the LP filter of Fig.2.

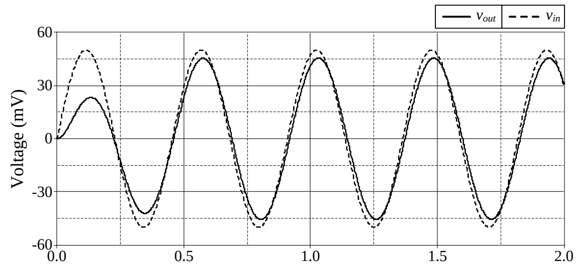

Fig. 10. Simulated time-domain responses of the BP filter of Fig.2.

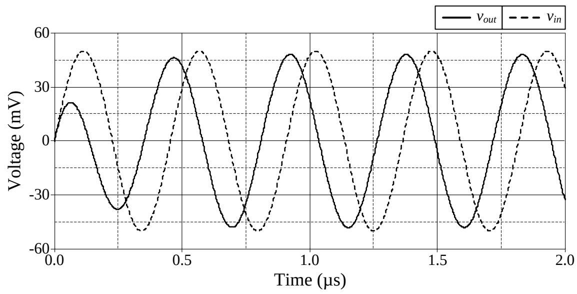

Fig. 11. Simulated time-domain responses of the HP filter of Fig.2.

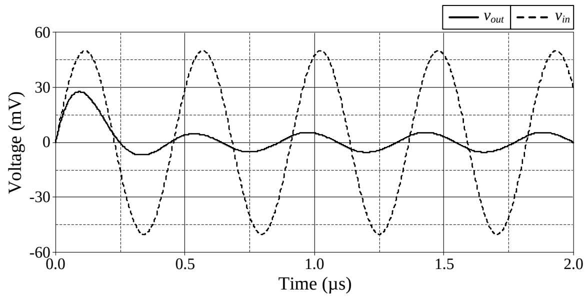

Fig. 12. Simulated time-domain responses of the BS filter of Fig.2.

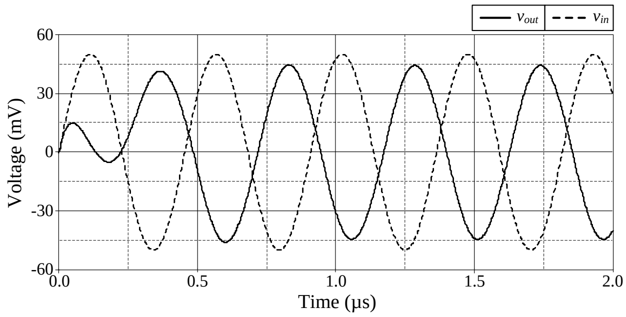

Fig. 13. Simulated time-domain responses of the AP filter of Fig.2.

TABLE III
DEPENDENCE OF BP OUTPUT HARMONIC DISTORTION ON APPLIED SIGNAL AMPLITUDE

Signal amplitude (mV_{peak})	THD (%)
5	0.018
10	0.017
20	0.032
50	0.080
80	0.241
100	0.674
120	1.285
140	1.996
160	2.736
180	3.461
200	4.143

The electronic tuning of the f_o without altering the value of the Q-factor is shown in Fig. 14. In Fig. 14, equal transconductances with $g_{mF3} = g_{mS3}$ = 1.40 mAV^{-1} and $g_m = g_{mF1} = g_{mS1} = g_{mF2} = g_{mS2}$ have different values of 1.14 mAV^{-1}, 1.61 mAV^{-1}, and 2.13 mAV^{-1}, resulting in Q = 1 for the BP filter and f_o = 1.81 MHz, 2.57 MHz, and 3.39 MHz, respectively. The simulated f_o are located at 1.80 MHz, 2.49 MHz, and 3.56 MHz, respectively, thereby resulting in frequency errors of 0.55%, 3.11%, and 5.01%.

Further, the modification of the Q-factor without influencing the f_o-value for the BP filter is given in Fig. 15. This design is for a constant f_o at 2.22 MHz with $g_{mF1} = g_{mS1} = g_{mF2} = g_{mS2} = g_{mF3}$ = 1.40 mAV^{-1}, and just modifying the value of g_{mS3} to 0.67 mAV^{-1}, 1.14 mAV^{-1}, and 2.42 mAV^{-1}, resulting in Q = 2.08, 1.22, and 0.58, respectively.

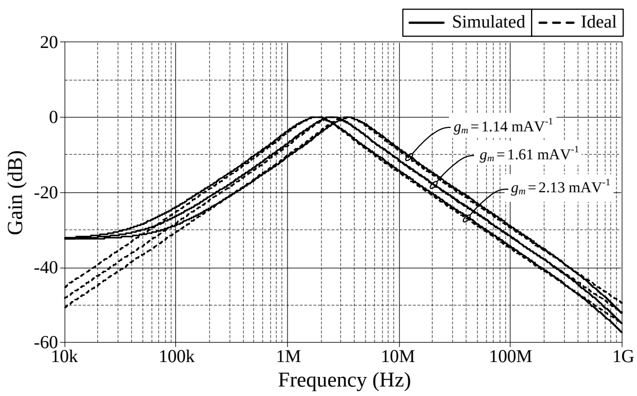

Fig. 14. Electronic Q tunability of BP response for the proposed filter.

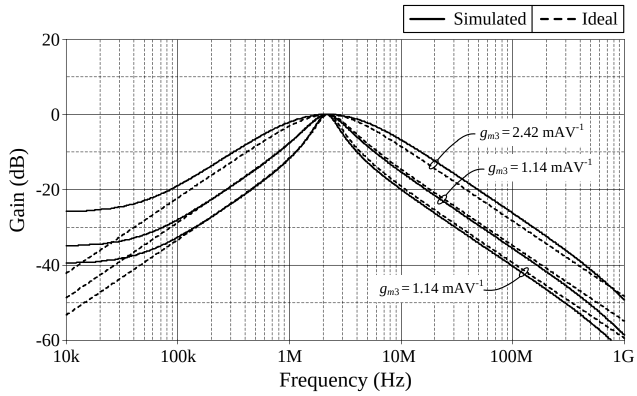

Fig. 15. Electronic f_o tunability of BP response for the proposed filter.

The sensitivity performance was investigated for 200 samples using Monte-Carlo statistical analysis, which considers both transconductance parameters (g_{mFi} and g_{mSi}) and capacitance values (C_1 and C_2) with a 5% deviation. The derived family histogram plots of f_o are provided in Figs. 16 and 17. The mean and standard deviation figures were [2.21955 MHz, 37.92 kHz] and [2.21945 MHz, 45.74 kHz], accordingly, indicating that the scheme has adequate sensitivity.

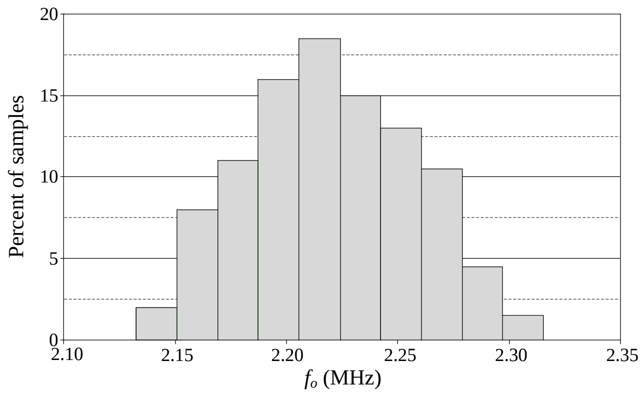

Fig. 16. Monte Carlo statistical analysis of BP response with 5% deviation in transconductances g_{mFi} and g_{mSi} (sample = 200, mean = 2.21955 MHz, median = 2.21703 MHz, minimum = 2.13252 MHz, maximum = 2.31543 MHz, sigma = 37.9206 kHz).

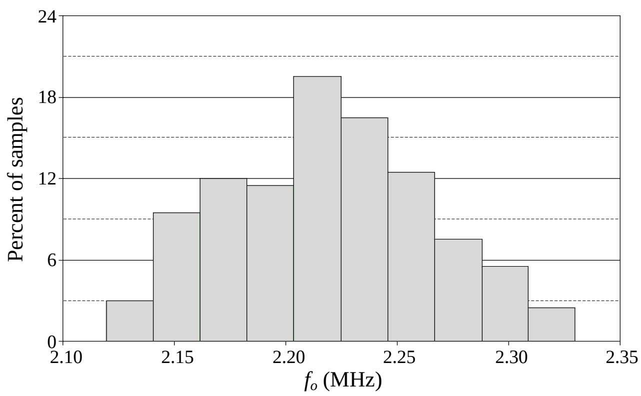

Fig. 17. Monte Carlo statistical analysis of BP response with 5% deviation in capacitances C_1 and C_2 (sample = 200, mean = 2.21945 MHz, median = 2.22201 MHz, minimum = 2.11940 MHz, maximum = 2.32989 MHz, sigma = 45.7446 kHz).

V. Conclusions

This paper described an electronically tunable voltage-mode universal biquadratic filter with four input and one output terminals that was created with three VDTAs and two grounded capacitors. The proposed circuit can realize LP, BP, HP, BS, and AP filter responses without any input signal constraints by appropriately setting the input signals. Its key characteristics, ω_o and Q, can be tuned electronically and separately using the transconductances of the VDTAs. This design also has the advantages of being resistor-free, having high input impedance, and employing only grounded capacitors. Simulation findings utilizing TSMC 0.18-μm CMOS technology verify the design's viability.

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