

Implementation of Filter Structures in VLF Band for Remote Sensing Systems Using MCFOA

Fadile Şen^{1, 2}, Ali Kırçay³ and Buket Sonbaş Cobb⁴

ABSTRACT

This paper presents analogue current-mode filter circuits for the very low frequency (VLF) band (3–30 kHz), intended for remote sensing applications. The proposed designs include first-order low-pass, high-pass, and all-pass filters, together with a single-input, three-output universal filter providing simultaneous low-pass, high-pass, and all-pass responses. Each structure employs a single modified current feedback operational amplifier (MCFOA) and only four grounded passive components, enabling a simple and compact implementation. Designed at a cut-off frequency of 10 kHz, the filters achieve a total harmonic distortion (THD) of $\leq 1.5\%$, a dynamic range (DR) greater than 60 dB, and power consumption below 1 mW with a 2.5 V single supply. Frequency and gain can be adjusted through passive component selection. Moreover, the use of a 100 pF capacitance supports VLSI and low-voltage/low-power implementations. The proposed circuits are verified through PSpice simulations.

Keywords: *Very low frequency (VLF), Modified Current Feedback Operational Amplifier (MCFOA), Current-mode filters.*

1. INTRODUCTION

The Very Low Frequency (VLF) band, ranging from 3 kHz to 30 kHz, is widely used in remote sensing systems due to its ability to transmit low-frequency signals with wavelengths between 10 and 100 kilometers. These signals, originating from both artificial and natural sources, are particularly useful for stable, secure, and long-distance communication. VLF waves have the unique capability to penetrate seawater, making them ideal for underwater communications and underground analysis, depending on frequency and water salinity [1]. Man-made VLF signals are primarily employed for military submarine communications, global positioning systems (GPS), time information transmission, and navigation systems of ships and aircraft. VLF is also used in military and amateur radio communications, as it experiences minimal signal degradation over long

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distances and maintains stable phase characteristics. Various receivers are designed to capture VLF signals. Typically, a VLF receiver system (see **Figure 1**) includes an analogue front end, an antenna, a low-noise amplifier, a high-pass filter, and an anti-aliasing low-pass filter [1]. The antenna captures radiofrequency waves, while the low-noise amplifier enhances the signal and increases its dynamic range before digitization. The high-pass filter removes unwanted harmonics from the VLF signals, and the low-pass filter prevents aliasing during the analogue-to-digital conversion process.

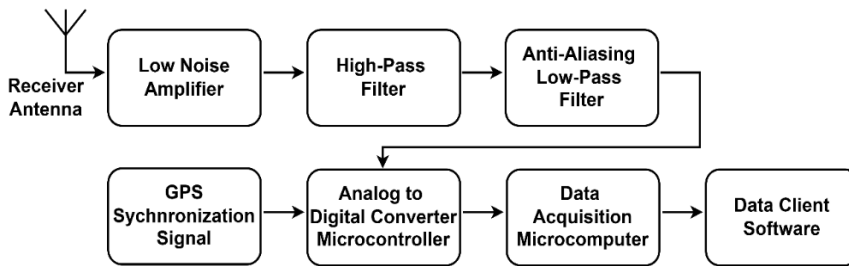


Figure 1. Block diagram of the VLF receiver system [3].

Recent advancements in linear analogue circuits have led to more efficient designs, especially in applications such as filters, converters, multipliers, signal generators, and oscillators. Linear analogue circuits are widely used in the frequency range of 3 kHz to 30 kHz, particularly in signal processing, communication systems, and other electronic applications. These circuits form the basis for various components like analogue-to-digital converters (ADCs), digital-to-analogue converters (DACs), and other filtering and signal processing elements [2]. The development of first-generation current conveyors in 1968 [3] was followed by second-generation current conveyors (CCII) in 1970 [4]. The third-generation current conveyor was introduced by Fabre in 1995 [5], and in 1996, he presented the second-generation current-controlled current conveyor [6]. Since then, numerous filter and oscillator circuits related to CCII have emerged [7]–[11]. The CCII element has also become a foundational building block for current feedback operational amplifiers (CFOA) and modified current feedback operational amplifiers (MCFOA) [12]–[16]. Following the introduction of the CFOA, several analogue filters and oscillator circuits have been implemented using this element. Yuce et al. (2019) introduced two first-order all-pass filter circuits that feature adjustable gain and low output impedance [13]. However, the circuit designed by Yuce et al. does not possess infinite input impedance. This design was subsequently improved by Senani et al. (2021), providing fewer components and achieving infinite input impedance [14]. More recently, Senani et al. (2022) presented six new all-pass filter circuits utilizing the CFOA element [15]. By making simple modifications to these circuits, five universal filter circuits were created, each implemented as voltage-mode

(VM) controlled filters using two CFOA elements [13]–[15]. The filter designs from the studies mentioned above typically employ grounded capacitors and a few resistors as floating components [13]–[15].

The MCFOA structure, generally designed as a VM operand, was developed by Yuce and Minaei in 2008 to meet the demand for active elements, incorporating the CCII element as its fundamental building block [16]. The current-voltage coupling design of the MCFOA differs from conventional CFOAs (see **Section 2**). While the established Y-terminal current value of a CFOA is zero, the MCFOA generates a Y-terminal current by copying the current flowing through the W-terminal in the opposite direction. This makes the MCFOA structure simpler and more convenient to design in current-mode (CM) compared to the CFOA structure. The literature presents very few analogue filter circuit designs using the MCFOA structure [16]–[22]. Herencsar et al. (2009) introduced a second-order universal filter topology based on this structure [18], designed as a VM operand. The output values of this universal filter are adjusted by varying the input voltage values, with passive elements functioning as floating filter components. The MCFOA structure in this filter is based on a bipolar array transistor (BJT) and includes high-value DC sources, specifically bias currents of 200 μA . In another study, Herencsar et al. (2012) combined voltage gain control with the MCFOA to create a new active block structure known as the voltage gain controlled modified current feedback amplifier (VGC-MCFOA) [19]. This structure enabled the design of a first-order all-pass filter circuit, with the VGC-MCFOA based on a BJT infrastructure and a large, complex structure that incorporates multiple high-value DC sources, including base control currents of 100 μA and bias currents of 400 μA . The first-order all-pass filter was designed using the VGC-MCFOA, operating in CM and transimpedance-mode (TIM) by applying two input currents, resulting in a cut-off frequency of 29.96 kHz. The same research team also developed another first-order all-pass filter circuit using the VGC-MCFOA, which was realized in CM, VM, transimpedance-mode, and trans-admittance-mode (TAM) [20]. In another study by the authors utilizing MCFOA, CM fractional-order low-pass and high-pass shelving filters were designed for practical applications [23]. These filters were derived from basic first-order low-pass and high-pass filter topologies. In 2018, CUI conducted a study on filter circuits designed in both VM and CM, utilizing the MCFOA structure [17]. This study included separate implementations of VM second-order low-pass, high-pass, band-pass, and band-stop filter circuits, along with transformations of these circuits into CM. A summary of these studies is provided in **Table 1** for comparison. The findings indicate a growing trend in the popularity of active CFOA and MCFOA elements in recent research.

Table 1. Comparative properties of first-order filters created with CFOA and MCFOA.

Ref.	CFOA / MCF OA	Mode of operation	Types of functions realized	Capacitor (Grounded capacitor)	Resistor (Grounded resistor)	Tunability of pole frequency	Tunability of gain	Power consumption	Total harmonic distortion (THD; %)
[13]	2 CFOA	VM	+AP	1(1)	5(3)	NO	YES	0.26 W	1.5
	3 CFOA		+AP	1(1)	6(4)			0.39 W	1.66
[14]	2 CFOA	VM	+AP	1(1)	3(2)	YES	YES	NA	1.09
	2 CFOA		+AP	1(1)	4(2)				1.90
[15]	2 CFOA	VM	- LPF, +HPF, +APF	1(1)	3(2)	YES	NO	NA	NA
					4(3)				
[22]	1 CFOA	VM, TAM, CM	+LPF, +HPF, +APF	1(1)	3(1)	YES	YES	NA	NA
		TIM							
[19]	1 VGC-MCFOA	CM, VM, TAM, TIM	+AP	1(1)	3(1)	YES	YES	23.1 mW	1.59
[20]	1 VGC-MCFOA	CM, TIM	+AP	1(1)	3(3)	YES	YES	NA	1.59
Section 3.1	1MCF OA	CM	+LP +HP +AP	1(1)	3(3)	YES	YES	<1mW	≤ 1

Section	1MCF OA	CM	Universal	1(1)	3(3)	YES	YES	<1mW	≤ 1
			(+LP +HP +AP)						
3.2									

NA: Not Available

In this study, analogue filters were designed using the MCFOA structure for application in the VLF band and the filter stages of VLF receiver systems (see **Figure 1**). Initially, CM, first-order low-pass (LP), high-pass (HP), and all-pass (AP) filter circuits were developed. Following this, a CM first-order single-input, three-output universal filter was created to generate LP, HP, and AP outputs simultaneously. The CM design offers advantages such as wide bandwidth, low power consumption, high linearity, wide dynamic range, and simplified circuit structures, making it ideal for integrated systems. Each filter circuit employs only four grounded passive elements and one MCFOA, making these circuits well-suited for very large-scale integration (VLSI) due to their compact size, low power consumption, and cost-efficiency. The total power consumption of these filters was measured at less than 1 mW using a 2.5 V single supply. Grounded passive components, especially capacitors, were used to enhance convenience in the design process. The cut-off frequencies of the filters were recorded at 10 kHz, confirming their suitability for the VLF band and VLF receiver filter stages. The circuits demonstrated a wide dynamic range (greater than 60 dB) and total harmonic distortion (THD) below 1.5%. Additionally, the cut-off frequency and gain could be tuned by modifying the values of passive elements and DC sources (see **Section 2**) within the MCFOA structure.

As summarized in Table 1, previously reported CFOA- and MCFOA-based filter designs generally require multiple active elements, include floating passive components, or operate mainly in VM configurations. In contrast, the proposed filter structures are realized in CM using a single MCFOA and only grounded passive elements, resulting in a more compact and integration-friendly design. Furthermore, while most existing studies focus on individual filter responses, the proposed configuration provides a single-input, three-output universal filter capable of simultaneously generating LP, HP, and AP responses. These distinguishing features clearly demonstrate the novelty and practical significance of the proposed work.

The rest of the paper is organized as follows: Section 2 presents the block structure, equations, and circuit configuration of the MCFOA element. Section 3 introduces the filter circuits designed with the MCFOA. Section 4 provides PSpice simulation results of the filter circuits, while Section 5 discusses the results.

2. Materials and Methods

2.1. Modified Current Feedback Operational Amplifier (MCFOA)

The MCFOA, an active building block, was introduced in a paper by Yuce and Minaei [16]. The schematic symbol of the MCFOA is shown in Figure 2.

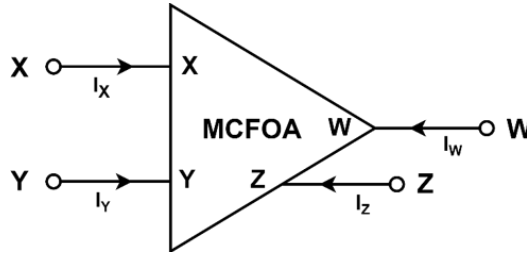


Figure 2. Schematic representation of the MCFOA [16].

The MCFOA structure, formed by a combination of the positive-type CCII (CCII+) and negative-type CCII (CCII-), was introduced to the literature by Sedra and Smith [17]. The MCFOA structure utilizing this combination of CCII+ and CCII- is shown in Figure 3. The current and voltage relationships between the independent terminals of the MCFOA (as shown in **Figure 2**) are provided in Equation 1.

$$\begin{aligned} I_Z &= \alpha_1 I_X, & I_Y &= -\alpha_2 I_W \\ V_X &= \beta_1 V_Y, & V_W &= \beta_2 V_Z \end{aligned} \quad (1)$$

I_X , I_Y , I_Z and I_W represent the currents at the independent terminals of the MCFOA, while V_X , V_Y , V_Z and V_W represent the voltages at the respective terminals. For simplicity, the parameter vector of the MCFOA is expressed as $[P] = [\alpha_1 \quad -\alpha_2 \quad \beta_1 \quad \beta_2]$.

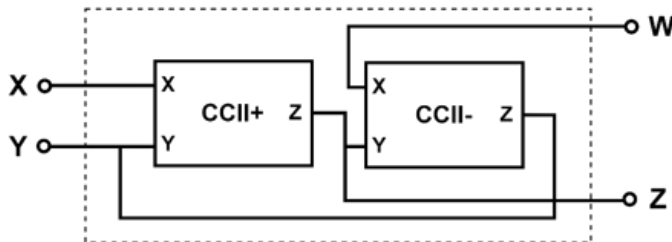


Figure 3. MCFOA structure using two CCII [17].

The frequency-independent non-ideality current gains α_1 and α_2 , defined in Equation 1, are also expressed as the frequency-independent non-ideality voltage gains β_1 and β_2 . Ideally, these current and voltage gains are assumed to be equal to one. The relationships of current and voltage in the MCFOA, as stated in Equation 1, indicate a fundamental difference between the MCFOA and the traditional CFOA. In the traditional CFOA, the Y-terminal current is zero, but this is not the case for the MCFOA. In the MCFOA, the Y-terminal current is generated by copying the current flowing through the W-terminal in the opposite direction [18], [19]. In this study, DO-CCCII are employed instead of CCII to create the MCFOA. The internal structure of the DO-CCCII is depicted in Figure 4. This structure consists of NPN and PNP bipolar array transistors, powered by two low-value DC voltage sources ($+V_{EE} = -V_{CC} = +2.5$ V) and a single low-value DC current source ($I_0 = 13$ μ A).

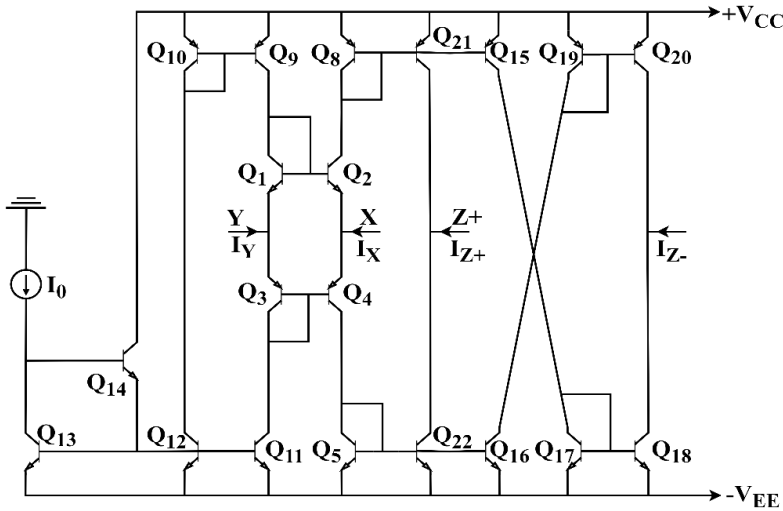


Figure 4. The Internal structure of DO-CCCII with BJT transistors [10].

2.2 Circuit Structures Using MCFOA

In this study, first-order CM filter circuits were designed using the MCFOA structure, incorporating a minimal number of grounded passive elements. The design of these filters utilized the ideal frequency response of the MCFOA structure. Specifically, the transfer functions ($H(s)$) of the filter circuits were derived based on the relationships $I_Z = I_X$, $I_Y = -I_W$, $V_X = V_Y$, and $V_Z = V_W$.

2.2.1. First-Order Filters Using the MCFOA

Initially, CM first-order LP, HP, and AP filter circuits were developed as distinct topologies, each employing only grounded passive elements and a single MCFOA. The LP filter circuit is depicted in Figure 5, the HP filter circuit in Figure 6, and the AP filter circuit in Figure 7.

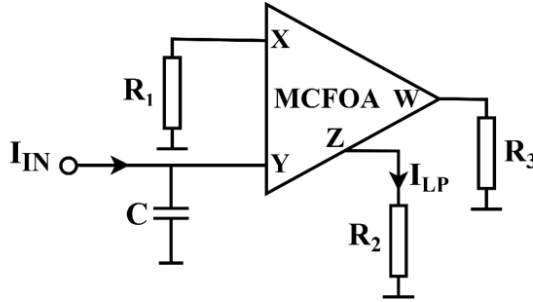


Figure 5. LP filter circuit design with MCFOA.

The transfer function of the LP filter circuit given in Figure 5 is given in Equation 2:

$$H_{LP}(s) = \frac{I_{LP}}{I_{IN}} = \frac{\frac{1}{CR_1}}{s + \frac{R_2}{CR_1R_3}} \quad (2)$$

Here, I_{IN} denotes the input current. The cut-off frequency (ω_0) and gain (α_0) of the filter are derived from the transfer function presented in Equation 2 and are detailed in Equation 3.

$$\omega_0 = \frac{R_2}{CR_1R_3}, \quad \alpha_0 = \frac{R_3}{R_2} \quad (3)$$

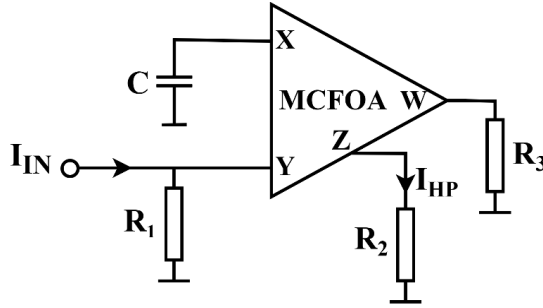


Figure 6. HP filter circuit design with MCFOA.

The transfer function of the HP filter circuit given in Figure 6 is given in Equation 4.

$$H_{HP}(s) = \frac{I_{HP}}{I_{IN}} = -\frac{\frac{R_3}{R_2}s}{s + \frac{R_3}{CR_1R_2}} \quad (4)$$

The cut-off frequency (ω_0) and gain (α_0) of the HP filter circuit, based on the transfer function presented in Equation 4, are described in Equation 5.

$$\omega_0 = \frac{R_3}{CR_1R_2}, \quad \alpha_0 = \frac{R_3}{R_2} \quad (5)$$

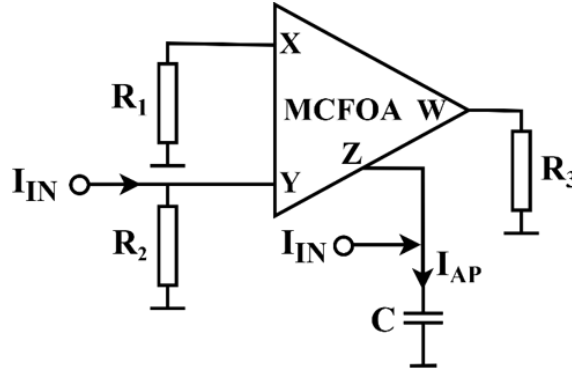


Figure 7. AP filter circuit design with MCFOA.

The transfer function of the AP filter circuit given in Figure 7 is given in Equation 6.

$$H_{AP}(s) = \frac{I_{AP}}{I_{IN}} = \frac{s - \frac{R_2}{CR_1R_3}}{s + \frac{R_2}{CR_1R_3}} \quad (6)$$

Based on the transfer function of the AP filter circuit in Equation 6, the cut-off frequency (ω_0) and gain (α_0) of the filter are detailed in Equation 7.

$$\omega_0 = \frac{R_2}{CR_1R_3}, \quad \alpha_0 = \left(\frac{R_2}{R_1} - 1 \right) \quad (7)$$

2.2.2. Universal Filter Using the MCFOA

In this study, a second type of filter: a CM first-order, single-input, triple-output universal filter was designed. This filter generates LP, HP, and AP outputs simultaneously, utilizing only four grounded passive elements and one MCFOA. The circuit for the universal filter designed with the MCFOA is illustrated in Figure 8.

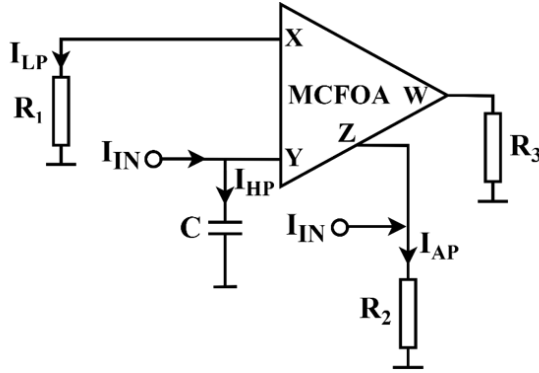


Figure 8. Universal filter circuit design with MCFOA.

Figure 8 illustrates that the output currents I_{LP} , I_{HP} , and I_{AP} are obtained simultaneously from an input current I_{IN} . The transfer functions of these filters were derived using Equation 1. The transfer function for the output current I_{LP} from the universal filter is provided in Equation 8.

$$H_{LP}(s) = \frac{I_{LP}}{I_{IN}} = \frac{\frac{1}{CR_1}}{s + \frac{R_2}{CR_1R_3}} \quad (8)$$

The transfer function for the output current of the HP I section in the universal filter is presented in Equation 9:

$$H_{HP}(s) = \frac{I_{HP}}{I_{IN}} = -\frac{s}{s + \frac{R_2}{CR_1R_3}} \quad (9)$$

The transfer function for the output current of the AP I section in the universal filter is shown in Equation 10:

$$H_{AP}(s) = \frac{I_{AP}}{I_{IN}} = \frac{s - \frac{1}{CR_1}}{s + \frac{R_2}{CR_1R_3}} \quad (10)$$

For a proper first-order all-pass filter response, the numerator and denominator of Equation (10) must have equal magnitudes. This requirement is satisfied when $R_2 = R_3$. Therefore, $R_2 = R_3$ should be regarded as a design condition required to obtain the all-pass response, rather than an independent gain parameter. The cut-off frequency of the universal filter is provided in Equation 11:

$$\omega_0 = \frac{R_2}{CR_1R_3} \quad (11)$$

The gain equations for the LP and HP outputs of the universal filter are given in Equation 12:

$$\begin{aligned} \alpha_{LP} &= \frac{R_3}{R_2} \\ \alpha_{HP} &= -1 \end{aligned} \quad (12)$$

It should be noted that the AP output requires the design condition $R_2 = R_3$ to achieve a proper first-order all-pass response.

Adjusting the passive resistance and capacitance values allows the cut-off frequency and the gains of the LP and HP outputs to be tuned. However, for the AP output, the condition $R_2 = R_3$ must be satisfied to obtain a proper first-order all-pass response. This flexibility also extends to the other filters described in Section 2.1.

3. Results and Discussion

This section presents the simulations of the filter circuits designed with the MCFOA (see Section 2). The simulations were conducted using the PSpice software.

3.1. First-Order Filters Using the MCFOA Simulation Results

In this study, first-order LP, HP, and AP filter circuits were implemented using the MCFOA active element, with the circuit representations shown in Figures 5, 6, and 7. To validate the theoretical findings, simulations of the designed filters were carried out using PSpice, revealing that the filters' cut-off frequency was set at 10 kHz. The MCFOA structure was built using two CCII elements, as illustrated in Figure 3. The DO-CCCII element was selected for this design due to its ability to receive inputs from both the Z+ and Z- terminals simultaneously, replacing the standard CCII in this configuration. The internal structure of the DO-CCCII, which utilizes BJT transistors, is shown in Figure 4. This structure incorporates PR100N (PNP) and NR100N (NPN) bipolar array transistors, with the parameters of these transistors detailed in Table 2.

Table 2. Model Parameters of Bipolar Array Transistors NR100N and PR100N.

<u>MODEL NR100N NPN</u>	
+IS=121E-018	BF=137.5 VAF=159.4 IKF=6.974E-3
+ISE=36E-16	NE=1.713 BR=0.7258 VAR=10.73
+IKR=2.198E-3	RE=1 RB=524.6 RBM=25 RC=50
+CJE=0.214E-12	VJE=0.5 MJE=0.28 CJC=0.983E-13
+VJC=0.5	MJC=0.3 XCJC=0.034 CJS=0.913E-12 +VJS=0.64
MJS=0.4	FC=0.5 TF=0.425E-9 TR=0.425E-8 +EG=1.206
XTB=1.538	XTI=2
<u>MODEL PR100N PNP</u>	
+IS=73.5E-018	BF=110 VAF=51.8 IKF=2.359E-3
+ISE=25.1E-16	NE=1.650 BR=0.4745 VAR=9.96
+IKR=6.478E-3	RE=3 RB=327 RBM=24.55 RC=50
+CJE=0.180E-12	VJE=0.5 MJE=0.28 CJC=0.164E-12
+VJC=0.8	MJC=0.4 XCJC=0.037 CJS=1.03E-12 +VJS=0.55
MJS=0.35	FC=0.5 TF=0.610E-9 TR=0.610E-8 +EG=1.206
XTB=1.866	XTI=1.7

The internal structure of the DO-CCCII incorporates a DC source with a current of $I_0=13 \mu\text{A}$ and DC voltage sources of $+V_{EE}=-V_{CC}=+2.5 \text{ V}$. For the LP and HP filter designs, the component values are set as follows: $R_1=150 \text{ k}\Omega$, $R_2=R_3=1 \text{ k}\Omega$, and $C=100 \text{ pF}$. In the AP filter design, the selected values are $R_1=1 \text{ k}\Omega$, $R_2=2 \text{ k}\Omega$, $R_3=300 \text{ k}\Omega$, and $C=100 \text{ pF}$. These values are chosen to ensure effective operation within the VLF band. The ideal frequency response data were derived from the filters' transfer functions, while the simulated data were obtained using PSpice and plotted in MATLAB. Figures 9, 11, and 13

display the ideal and simulated gain responses for the LP, HP, and AP filters, respectively. Figures 10, 12, and 14 present the corresponding ideal and simulated phase responses. The results show a close match between the simulation and ideal data, confirming the filters meet the design criteria for their intended applications.

The ideal and simulated gain responses of the LP filter circuit, shown in Figure 5, are presented in Figure 9, with the corresponding phase responses displayed in Figure 10.

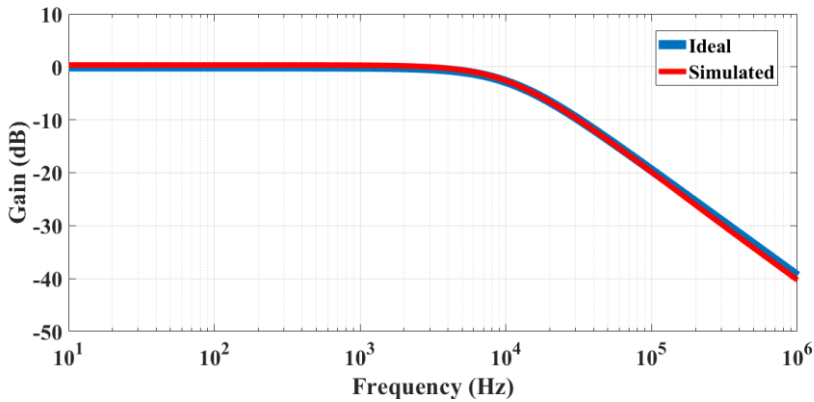


Figure 9. Gain response of the LP filter circuit.

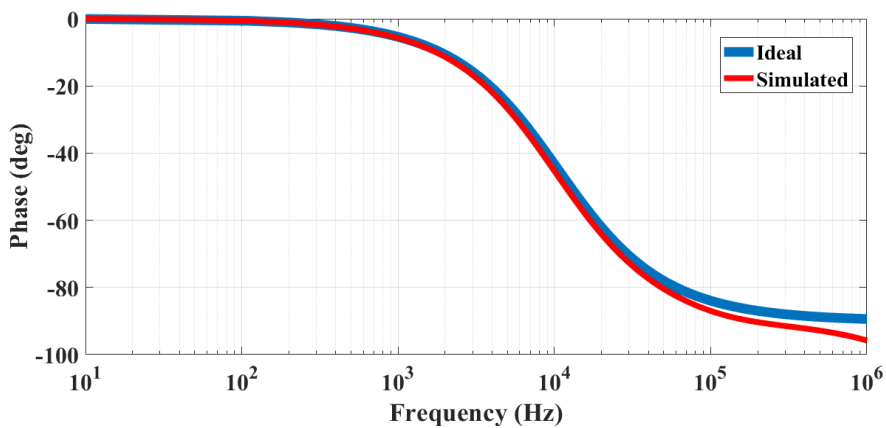


Figure 10. Phase response of LP filter circuit.

The ideal and simulated gain response of the HP filter circuit, shown in Figure 6, is presented in Figure 11, while Figure 12 displays the ideal and simulated phase response of the filter.

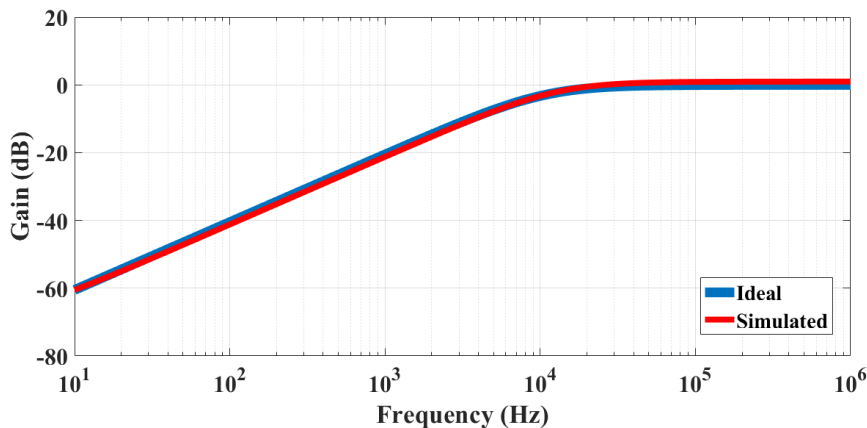


Figure 11. Gain response of the HP filter circuit.

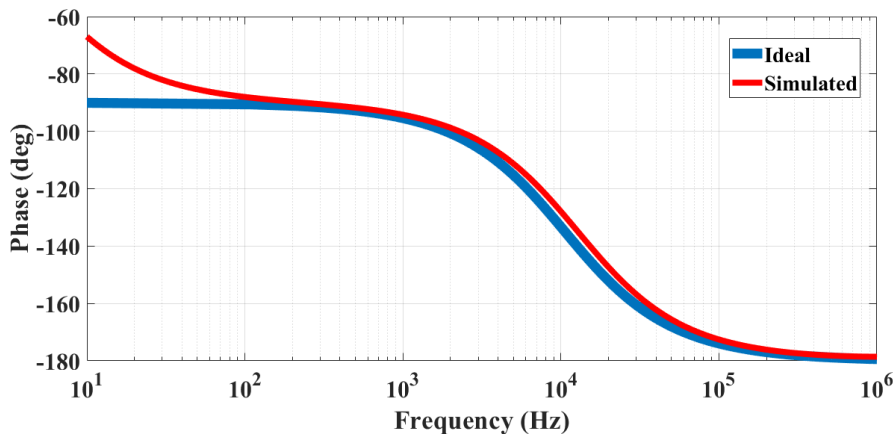


Figure 12. Phase response of HP filter circuit.

The ideal and simulated gain responses of the AP filter circuit, shown in Figure 7, are compared in Figure 13. Similarly, Figure 14 presents the ideal and simulated phase responses of the same filter.

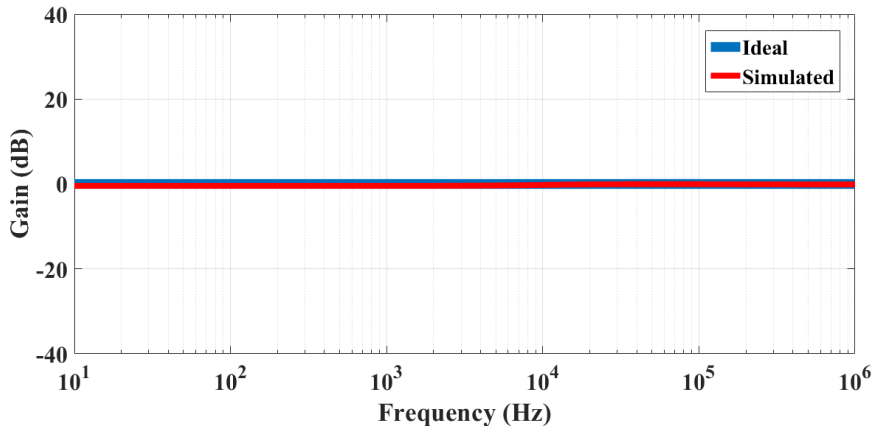


Figure 13. Gain response of AP filter circuit.

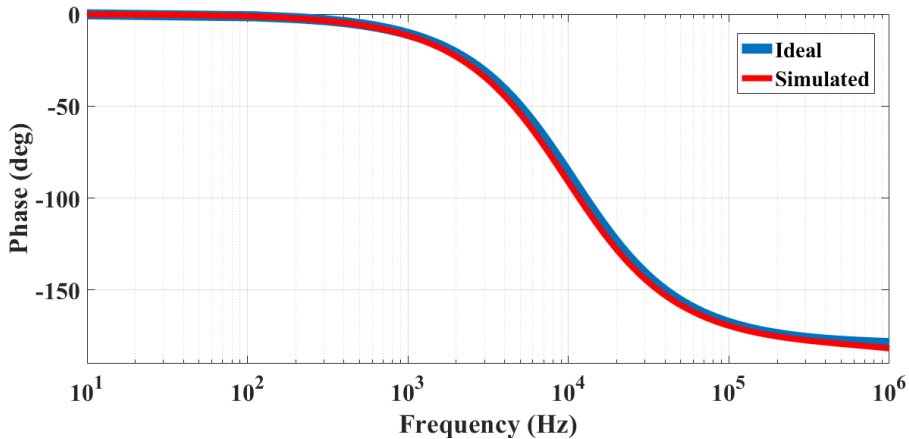


Figure 14. Phase response of AP filter circuit.

It has been shown that the cut-off frequency and gain of all the designed filter circuits can be adjusted by changing the values of the passive elements (R_1 , R_3 , and C) in the circuit. This tuning process is illustrated using the LP filter circuit in Figure 5. Equation 3 demonstrates that both the cut-off frequency and gain of the LP filter can be modified by varying these elements. Gain responses for different R_3 values, centered around the reference value of $R_3=1\text{ k}\Omega$, are simulated and plotted on the same axis for comparison in Figure 15.

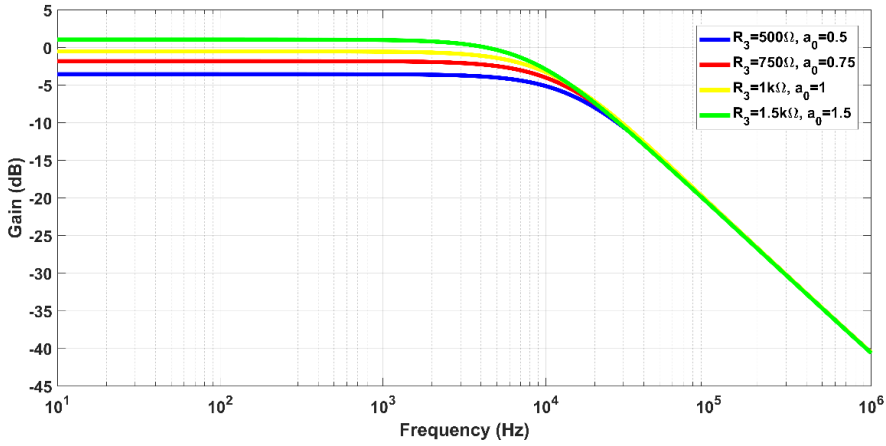


Figure 15. The gain response of the filter in Figure 5 shows that the value of the passive element R_3 varies between $500\text{ }\Omega$ and $1.5\text{ k}\Omega$, while the α_0 value ranges from 0.5 to 1.5.

Gain responses for the LP filter circuit, with different R_1 values centered around the reference value of $R_1=150\text{ k}\Omega$, are simulated and plotted on the same axis for comparison in Figure 16.

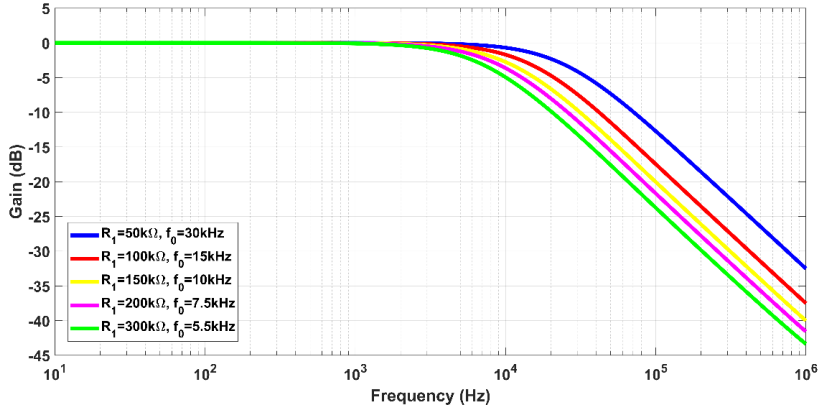


Figure 16. The gain response of the filter in Figure 5 indicates that the value of the passive element R_1 varies between 50 k Ω , and 300 k Ω , while the cut-off frequency f_0 ranges from 30 kHz to 5.5 kHz.

The LP filter circuit's response is simulated for various C values around the reference value of C=100 pF, and the results are plotted on the same axis for comparison in Figure 17.

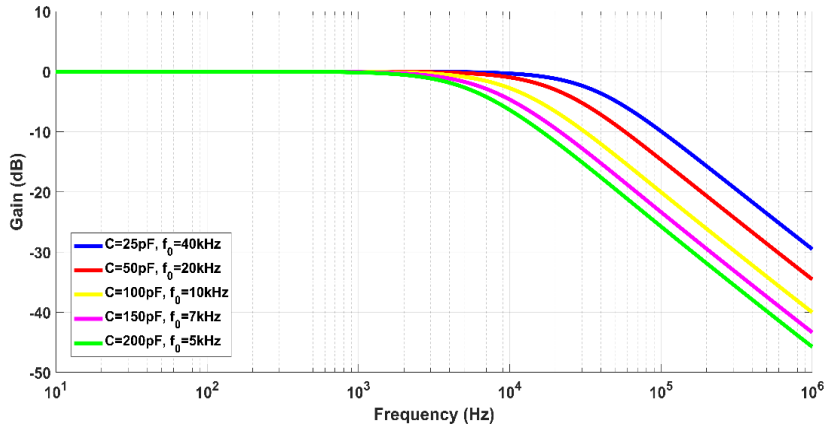


Figure 17. The gain response of the filter in Figure 5 shows that the capacitance (C) value varies between 25 pF and 200 pF, while the cut-off frequency (f_0) varies between 5 kHz and 40 kHz.

The DC source I_0 is configured to 13 μA , establishing a cut-off frequency of 10 kHz. The input frequency is also set at 10 kHz for the LP, HP, AP and universal filters. During simulations, the THD (%) of the output signal was measured while varying the input current values. A sinusoidal signal with input currents ranging from 0.07 μA to 350 μA was applied to the filters, resulting in observed THD values of less than or equal to 1.5%. Figure 18 illustrates the THD values for the LP filter circuit corresponding to different input currents.

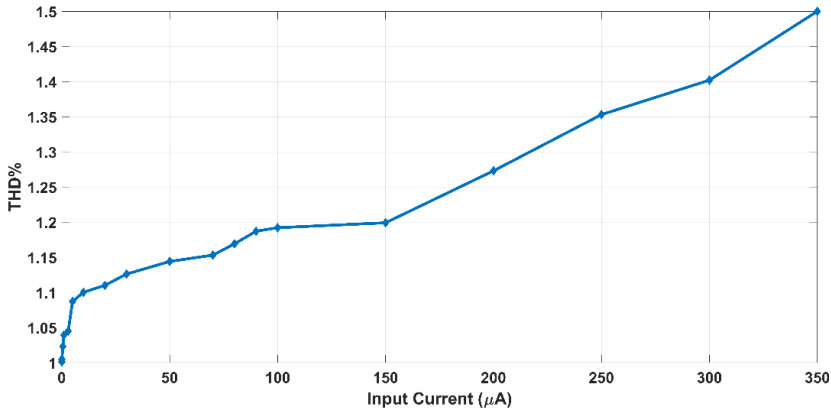


Figure 18. THD (%) of the LP filter.

In analog filter circuits, the dynamic range (DR) is defined as the ratio of the lowest input signal level to the highest input signal level at which the signal can be processed without distortion or noise. This is calculated using Equation 13. In this study, the dynamic range of the filter was assessed by applying a minimum input signal of 0.07 μA and a maximum input signal of 350 μA , resulting in a dynamic range that exceeded 60 dB. Furthermore, the total power loss of the filters was measured to be less than 1 mW when operated with a 2.5 V single supply, and the maximum noise value was found to be under 16 pA/ $\sqrt{\text{Hz}}$. Additionally, a time-domain analysis was conducted on the LP filter circuit, as illustrated in Figure 5. A sine wave input of 0 μA and 100 μA at a frequency of 10 kHz was applied to the circuit. The output response of the LP filter is depicted in Figure 19, showing that the phase difference between the signals closely aligns with the theoretical value.

$$\Delta R = 20 \log \left(\frac{I_{IN_{MAX}}}{I_{IN_{MIN}}} \right) \quad (13)$$

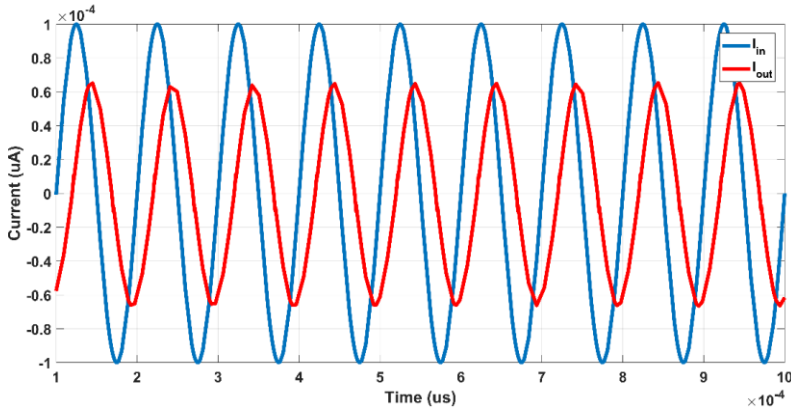


Figure 19. Time-domain response of the proposed LP filter circuit.

Parameter tolerance analysis for the proposed filters was conducted using Monte Carlo simulations in the PSpice program, performing 100 runs for the LP filter, shown in Figure 5. This analysis was implemented in two stages. First, the internal parameters of the BJT were varied to assess their impact on filter performance. Specifically, the saturation currents (I_S) were adjusted within a tolerance of 10%, current gains (β_F) were set with a tolerance of 20%, Early voltages (V_{AF}) were modified with a tolerance of 10%, and the internal resistance values (R_B , R_C , and R_E) were also varied within a 10% tolerance range. The gain response of the LP filter under these varying tolerance conditions is illustrated in Figure 20.

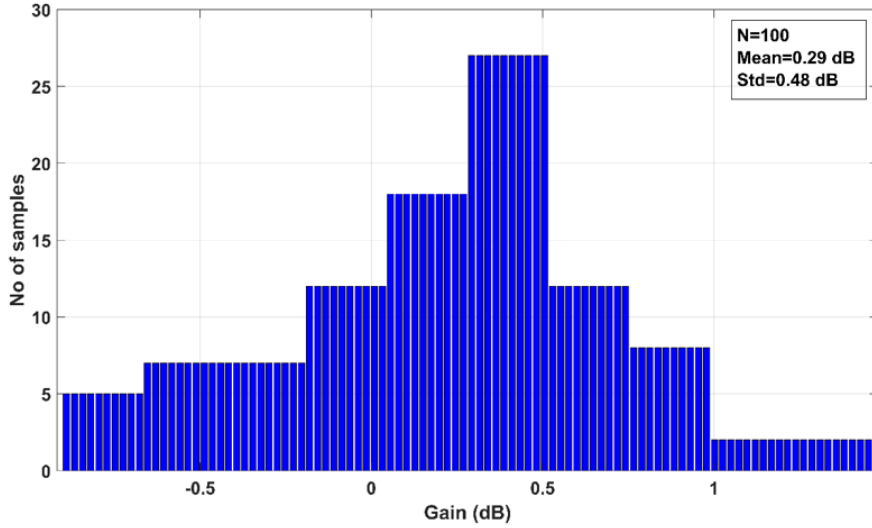


Figure 20. Gain response of the LP filter under BJT parameter variations (Monte Carlo-based tolerance analysis).

Next, the BJT parameters were restored to their original values, and a Monte Carlo analysis was performed, focusing solely on the tolerance values of the passive components in the circuit. The resistance values (R_1 , R_2 , and R_3) were assigned a tolerance of 10%, while the capacitance (C) was set with a tolerance of 20%. The resulting gain response of the LP filter under these varying tolerance conditions is presented in Figure 21.

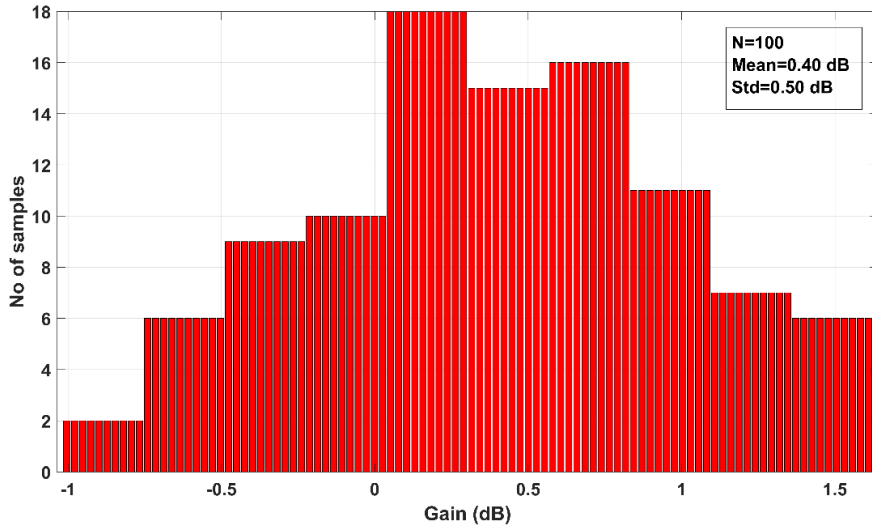


Figure 21. Gain response of the LP filter under passive component tolerances (Monte Carlo-based analysis).

3.2. Universal Filter Using the MCFOA Simulation Results

In this section of the study, a second-order universal filter circuit, as depicted in Figure 8, was implemented using the MCFOA structure. The values of the passive components in this filter circuit were set as follows: $R_1=150\text{ k}\Omega$, $R_2=R_3=1\text{ k}\Omega$, and $C=100\text{ pF}$. PSpice simulations were performed to validate the theoretical results, which indicated a cut-off frequency of 10 kHz. The simulated gain and phase responses of the universal filter are shown in Figures 22 and 23, respectively.

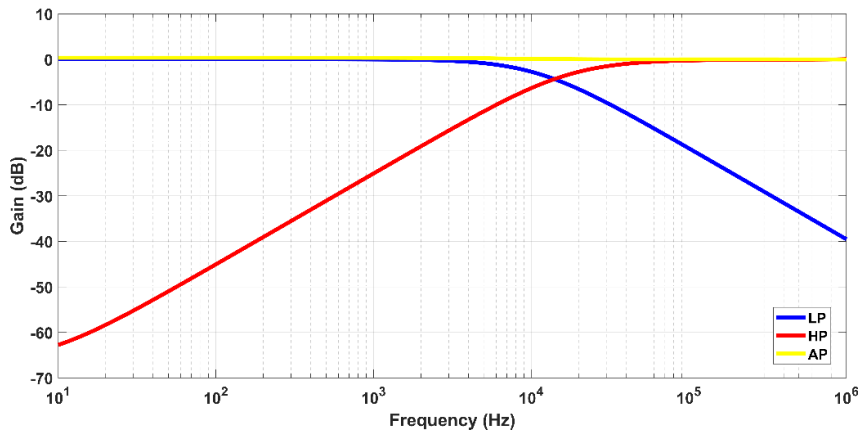


Figure 22. Gain response of the universal filter circuit.

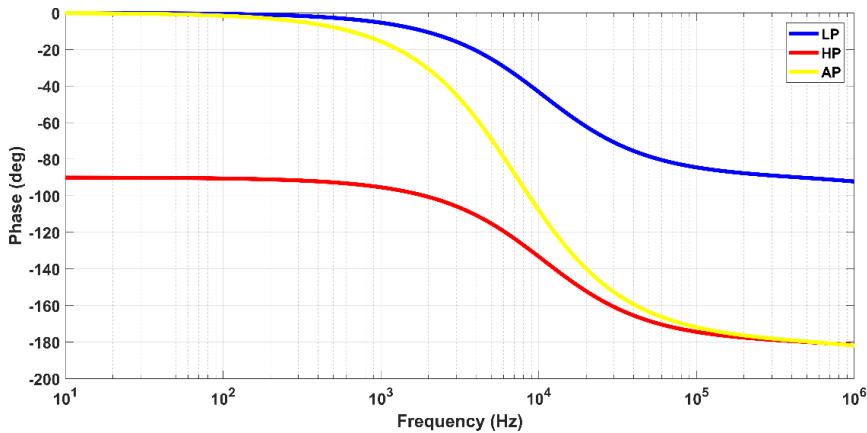


Figure 23. Phase response of the universal filter circuit.

The performance characteristics of the proposed filter circuits are summarized in Table 3. These designs employed the MCFOA active element. While minor differences were noted in the simulation results, both the simulated and theoretical findings suggest that the proposed filters are viable options.

Table 3. Performances and properties of the proposed filters.

Proposed Filters	
Classification	First order filters, CM
Synthesis method	MCFOA active element
Responses	LP, HP, AP, and Universal filter
Cut-off frequency	Tunable on the values of the passive elements
Configuration	BJT
Supply voltage	2.5 V
Dynamic range	>60 dB
THD (%)	≤ 1
Total power dissipation	<1mW
Noise	16 A/ $\sqrt{\text{Hz}}$

4. Conclusion

This study focuses on designing filters for operation in the Very Low Frequency (VLF) band, specifically for use in remote sensing systems. The research emphasizes first-order CM LP, HP, AP filters, as well as a universal filter circuit capable of outputting LP, HP, and AP filters simultaneously. These filters are constructed using a minimal number of grounded passive elements alongside an MCFOA active element, indicating the designs' straightforward implementation. The MCFOA active element, based on BJT technology, achieves a measured cut-off frequency of 10 kHz, demonstrating the appropriateness of the filter circuit structures for VLF and low-frequency applications. The cut-off frequency and gain of the filters can be adjusted by selecting appropriate passive component values in the circuits. With a grounded capacitor value of 100 pF, these filter circuits are also suitable for very large-scale integration (VLSI) technologies and low-voltage/power applications. To validate the theoretical calculations, the filter circuits were simulated using the PSpice program. Both the simulated and theoretical results confirm the feasibility of the proposed filters.

Research and Publication Ethics Statement

There are no ethical issues after the publication of this manuscript.

Author's Contributions

Fadile Şen: Drafted and wrote the manuscript, designed the proposed filter structures, performed the simulations, and analyzed the results.

Ali Kırçay: Assisted in the analytical analysis of the proposed structures, supervised the progress of the study, contributed to the interpretation of the results, and reviewed the manuscript.

Buket Sonbaş Cobb: Contributed to the interpretation and evaluation of the results and reviewed and revised the manuscript.

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