CMOS CDTA BASED ANALOG FILTER REALIZATION

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MASTER OF TECHNOLOGY

IN

CONTROL & INSTRUMENTATION

by

Aditi Raj Singh

2K22/C&I/01

Under the supervision of

Prof. Ram Bhagat

Professor, Department of Electrical Engineering, DTU

and Co-Supervision of

Assist.Prof. Shreyansh Upadhyaya

Assistant Professor, Department of Electrical Engineering, DTU

To the

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, New Delhi-110042

MAY, 2024

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, New Delhi-110042

CERTIFICATE

I hereby certify that the Project Reoprt titled " **CMOS CDTA Based Analog Filter Realization**" which is submitted by **Aditi Raj Singh**, **2K22/C&I/01** of M.Tech (Control & Instrumentation), Department of Electrical Engineering, Delhi Technological University, New Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place : New Delhi

Supervisor 29/5/24

Date : 29/05/24

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, New Delhi-110042

CANDIDATE'S DECLARATION

I, **Aditi Raj Singh**, **2K22/C&I/01** of M.Tech (Control & Instrumentation), hereby declare that the project Report titled "**CMOS CDTA Based Analog Filter Realization** " which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, New Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or similar title or recognition.

Aditi Raj Singh

Aditi Raj Singh

Place : New Delhi

Date : 29/05/24

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ABSTRACT

This thesis explores the design and analysis of a CMOS-based universal inverse bi-quad filter utilizing a Current Differencing Transconductance Amplifier (CDTA). The proposed circuit leverages a minimal passive component set, consisting of grounded capacitors and strategically chosen resistors, to achieve reconfigurable lowpass, bandpass, and highpass filtering functionalities. This eliminates the need for hardware reconfiguration for different filter types, enhancing circuit flexibility.

The design prioritizes manufacturability by employing grounded capacitors, facilitating integration into compact ICs. Furthermore, a non-ideal analysis reveals low sensitivity to component variations, ensuring robust performance under practical operating conditions.

SPICE simulations, incorporating realistic transistor model parameters, were conducted to validate the theoretical predictions of the circuit's behaviour. The simulated results exhibit close agreement with the theoretical analysis, demonstrating the accuracy of the proposed design.

This universal inverse biq-uad filter offers several technical advantages that the circuit offers the flexibility to achieve lowpass, bandpass, and highpass filtering responses through the selection of passive component values, eliminating the need for hardware modifications.

The utilization of grounded capacitors simplifies the design and facilitates integration into ICs due to reduced layout complexity and compatibility with standard fabrication processes. Non-ideal analysis demonstrates low sensitivity to component variations, resulting in robust circuit performance despite potential manufacturing tolerances or environmental variations.

This design presents a versatile and efficient solution for various analog signal processing applications demanding reconfigurable filtering functionalities and compatibility with IC integration.

CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

The quest for electronic circuits operating at ultra-low supply voltages and minimal power consumption stands as a pivotal and enduring trend shaping the advancement of microelectronic technologies. In numerous applications, additional requisites arise, notably concerning the speed or accuracy of signal processing. However, simultaneously meeting these diverse demands proves challenging, necessitating practical trade-off solutions. Over the past two decades, the progression of modern analog signal processing applications has aligned with the current mode paradigm, wherein signals representing processed information manifest as electric currents. In contrast to conventional voltage mode circuits reliant on electric voltages, current mode circuits, under certain conditions, can offer advantages such as higher bandwidth and improved signal linearity. Due to their design for lower voltage swings, they accommodate the use of smaller supply voltages. Concurrently, mixed-mode circuits have garnered attention, given the imperative to optimize interfaces between sub-blocks operating in different modes. Additionally, the consideration of mixed-mode operation and even reverting to conventional voltage mode finds justification, as some widely accepted assertions regarding the superiority of the current mode may lack empirical basis.

1.1 Analog Signal Processing (ASP)

Over the years, both analog and digital designers have shifted their focus to thinking and calculating primarily in terms of voltages instead of currents, even though many signals in analog circuits begin as currents. Analysing the ASP paths in Fig. 1.1 reveals that sensor senses the output signals, then currents, or charges, are converted to voltages by current-to-voltage converters before being processed in purely voltage-based circuits, as shown in Fig. 1.2. This pre-processed voltage becomes the input signal. A similar process occurs at the system's output, where the current from the digital-to-analog converter is initially converted to voltage, post-processed, and then frequently changed back to current in order to power a transducer.

A more straightforward approach is to use analog circuits that directly process signals as currents, as illustrated in Fig. 1.3. This method would bypass the need for voltage-to-current and current-to-voltage converters that adjust the input signal for voltage processing and digital conversion. This could reduce both the chip area and the energy required for signal processing, while also eliminating a potential source of errors. However, current signal processing has not become widespread due to the lack of high-performance current processing circuits.

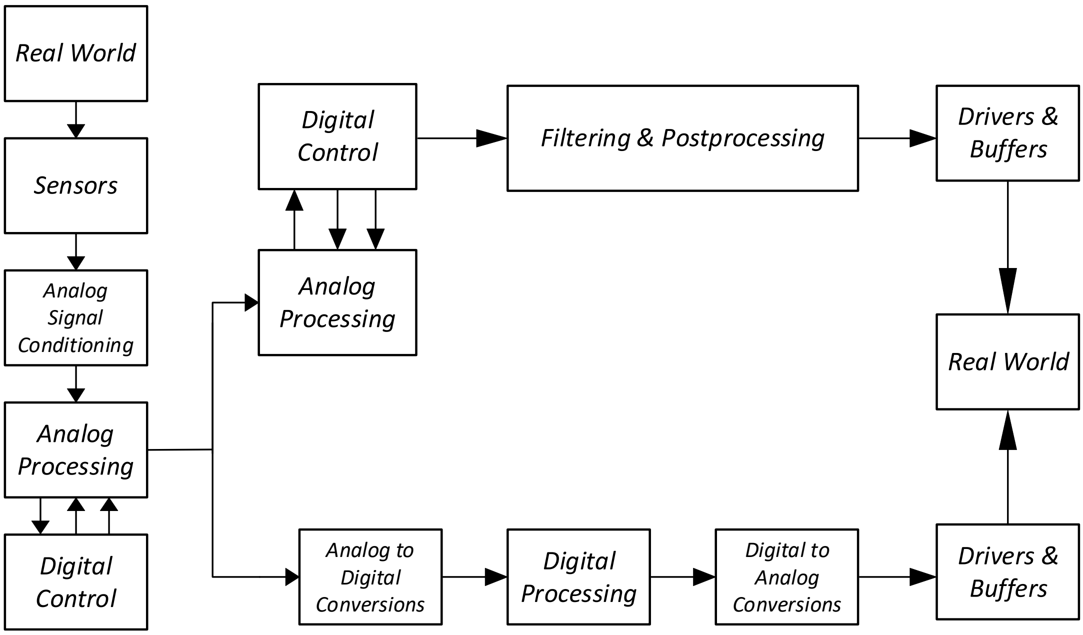


Fig.1.1 Universal Signal Processing System

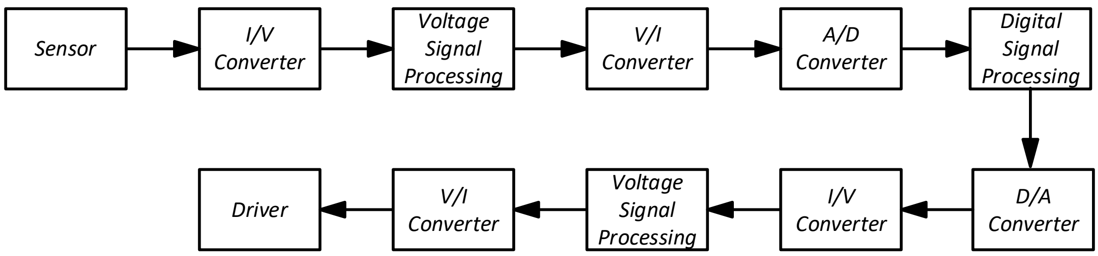


Fig.1.2 Voltage Signal Processing System

Although there are numerous building blocks for voltage processing, such as operational amplifiers and comparators, there has been insufficient focus on developing equivalent building blocks for current processing circuits.

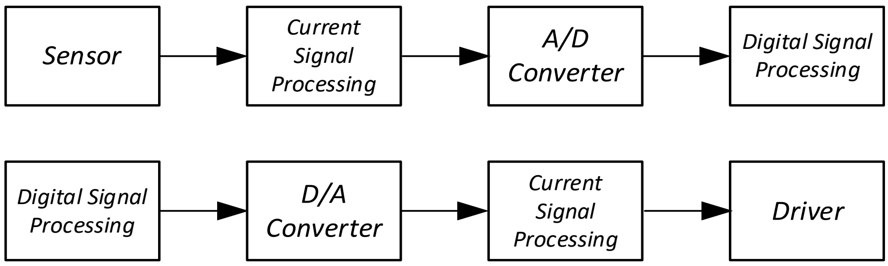


Fig.1.3 Current Signal Processing System

1.2 Aim of Project

This work concentrates on active building blocks for modern integrated circuits operating in current-mode or mixed-mode.

1.2.1 Active Building Blocks in Analog Signal Processing

While various approaches exist, here are the most common active devices used to realize universal biquad filters:

- **Operational Transconductance Amplifier (OTA):** This is a building block for many analog circuits, including bi-quad filters. It takes a voltage difference as input and produces a current as output.
- **Second-Generation Current Conveyor (CCII):** This device comes in different variations (CCII+, CCII-) and can be used to create current mirrors, summers, and other functionalities helpful in filter design.
- **Current Differencing Transconductance Amplifier (CDTA):** As discussed previously, CDTAs are gaining popularity due to their ability to simplify filter design and offer high-frequency performance. They combine current differencing and transconductance amplification functionalities.
- **Voltage Differencing Transconductance Amplifier (VDTA):** Like the CDTA but operates in the voltage mode, VDTA can also be used for bi-quad filter design, although less common than the options.

The choice of active device depends on factors like:

- **Desired filter characteristics:** Different devices offer varying control over filter response (cutoff frequency, quality factor).

- **Circuit complexity:** Some devices may require fewer external components, leading to simpler filter designs.
- **Performance considerations:** Factors like operating frequency and power consumption may influence device selection.

In recent years, CDTA has emerged as a compelling choice for universal bi-quad filter design due to its advantages in circuit simplicity and high-frequency performance.

The primary focus of the report is to explore the use of a commercially available modern integrated circuit, the Current Differential Transconductance Amplifier (CDTA), in various new electronic blocks, even though some of these blocks are already established in their voltage-mode versions. This thesis will emphasize applied research rather than fundamental research, specifically targeting the currently available current-mode amplifiers.

The aims of this dissertation are as follows:

i. Investigate the effects of imperfections in current mode amplifiers.
ii. Design and verify circuits that are insensitive to these imperfections using current mode amplifiers.
iii. Develop new analog designs to realize inverse filters (ILPF, IHPF, and IBPF).

1.3 States of Art

Analog integrated circuit design has become increasingly significant with the expansion of new opportunities. IC processing techniques have advanced to a stage where high-performance and innovative "special" devices can be integrated. This progress has sparked a renewed interest in circuit design techniques that were previously constrained by the available technology. Essentially, we are now witnessing technology-driven advancements in circuit design. One such example is the development of "current mode" techniques (Toumazou 1990, Current mode approach [11]), many of which have only become practically feasible with the advent of true complementary bipolar and MOS technology processes.

1.3.1 The Rise of Current-Mode Circuitry

While voltage-mode circuits have long been the workhorse of analog design, a new contender is emerging. Current-mode signal processing offers several exciting advantages, making it a compelling choice for modern circuits.

Firstly, current-mode circuits shine in environments with limited voltage headroom, like those powered by 3.3 volts or less. This is becoming increasingly common as chip sizes shrink. Additionally, they often require simpler designs, especially when processing current signals from sensors or probes. This can lead to lower power consumption as well.

However, there are hurdles to overcome. Achieving high gain and bandwidth while maintaining low offset current and fast operation can be tricky. Traditionally, gain is boosted through feedback resistors, but this comes at the cost of speed. Current-mode circuits excel because they can operate with minimal voltage swings at each stage, allowing for high-speed processing near the transistor's transition frequency.

1.3.2 A Novel Set of Modern Building Elements

The world of CMOS technology is witnessing the rise of a new generation of current-mode circuits – often referred to as switched-current or dynamic current circuits. These include innovative components like switched-current filters, dynamic current mirrors, and even current memory cells.

Furthermore, engineers are developing entirely new building blocks specifically for current-mode operation. These include current amplifiers, followers, and conveyors, which mirror the functionality of their voltage-mode counterparts like voltage comparators and followers. This shift towards current-mode design is largely driven by the ever-shrinking size of transistors in digital CMOS processes. As supply voltages drop (currently at 3.3V with potential reductions to 1.5V), these processes are optimized for digital performance, which can hinder voltage-mode circuit behaviour. By operating entirely or partially in the current domain, these challenges can be effectively addressed.

1.4 Organisation of Thesis

Chapter 1: Introduction

Includes the introduction of ASP, Active Building Blocks, and brief about research work.

Chapter 2: Literature Review

This chapter gives brief about CDTA as active building block, also about the Bi-quad filters and give the brief about all Inverse Universal Bi-quad filters designed till now.

Chapter 3: Realization of Universal Bi-quad Filters using Conventional Topologies

In this chapter, realisation of Universal Bi-quad Filters using CDTA with high gain trans conductance and conventional circuits.

Chapter 4: Proposed Work - Realisation of Universal Inverse Bi-quad Filters

In this chapter, I have proposed the new circuit topologies using CDTA with high gain trans conductance to realise Inverse Filters (ILPF, IBPF and IHPF).

Chapter 5: Simulation Results

In this chapter, analysis of all the plots of CDTA with high gain trans conductance and Universal Inverse Bi-quad Filters.

Chapter 6: Conclusion and Future Scope

This chapter includes the conclusion about the research work and future scope further.

CHAPTER 2
LITERATURE REVIEW

Analog filters are essential components in various fields, from communication to instrumentation and control systems. However, with the growing demand for portable and battery-powered devices, there's a crucial need for circuits that function efficiently at low voltages. This is where current-mode circuits come in – they're perfectly suited for these applications. Compared to traditional voltage-mode circuits, current-mode circuits boast several advantages. They offer a wider dynamic range, meaning they can handle a larger range of signal strengths without distortion. Additionally, they achieve higher bandwidths, allowing them to process faster signals. They also exhibit greater linearity, ensuring accurate signal reproduction. Current-mode circuits often require simpler designs, leading to lower power consumption. This is a major benefit for portable devices where battery life is a top priority.

A new star is emerging in the world of current-mode analog signal processing: the CDTA. This innovative building block offers several exciting features. Firstly, CDTAs boast superior speed and bandwidth compared to previous solutions. This allows them to handle even faster signals with greater efficiency. Another key advantage is their freedom from parasitic input capacitances. These unwanted capacitors can slow down traditional circuits, but CDTAs eliminate this issue. Finally, CDTAs offer electronic tenability, meaning their properties can be easily adjusted to meet specific design requirements. Several current-mode filters have already been successfully designed using CDTAs as their core building block. This technology holds great promise for the future of low-power, high-performance analog circuits in portable devices.

2.1 Current Differencing Transconductance Amplifier (CDTA)

The CDTA is a groundbreaking innovation in the realm of analog circuit design. This versatile building block specifically caters to current-mode signal processing applications.

2.1.1 CDTA – (History & Present)

Over the past 15 years, the (CDTA) has become a hot topic in analog circuit research. This innovative building block has sparked a wave of development, with researchers proposing new designs and implementing them in various applications. The concept of the CDTA first emerged in 2003, courtesy of D. Biolek. He envisioned it as a combination of two existing building blocks: a current difference unit (CDU) and an OTA. Biolek later put his idea into practice by building a CDTA circuit using MOS transistors in 2006. He even demonstrated its practical value by creating a KHN filter using this CDTA.

Around the same time (2007), H. Kuntman also presented a CDTA circuit design. Since then, numerous researchers have explored different ways to implement CDTAs, using either bipolar junction transistors (BJTs) or MOS transistors as the basic building blocks. However, the conventional CDTA structure found in most literature relies on a standard current differencing amplifier followed by a typical trans conductor. This approach can lead to discrepancies between the expected performance of the CDTA and its actual behaviour in a circuit.

Here's what makes CDTAs so interesting: unlike traditional voltage-mode circuits, they operate entirely in the current domain. This means they take current as input and produce current as output. This characteristic makes them highly valuable for designing modern analog modules that prioritize low power consumption and high-frequency operation [1-6].

The versatility of CDTAs goes beyond just processing mode. They can be used to implement a wide range of functions and find applications in various analog signal processing and generation circuits. From current limiters and filters to performing arithmetic operations, creating oscillators, and rectifying signals, CDTAs offer a powerful tool for analog circuit designers.

Researchers are constantly striving to improve the performance of current-mode active elements like OTAs and second-generation current conveyors (CCIIs). These efforts often focus on achieving a wider linearity range in the input stages and a high output impedance in the output stages. Thankfully, CDTAs can achieve good linearity, high accuracy, and high output resistance through careful design choices, such as employing high-performance current mirrors and well-designed input stages.

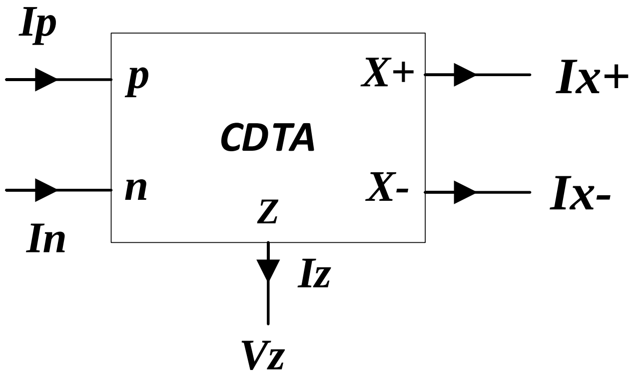


Fig.2.1. Basic Symbol of CDTA [52]

2.1.2 The CDTA's Two-Stage Act: Subtracting Currents and Controlling Voltage

The (CDTA) operates like a well-rehearsed duo. It has two key stages that work together seamlessly:

- **Input Current Subtractor:** This first stage acts like a minus sign, taking two incoming current signals and calculating the difference between them. This difference current becomes the key player for the next stage.
- **Dual Output Transconductance Stage:** The difference current doesn't stay alone for long. It's sent to a special zone called the "z terminal." Here, things get interesting:

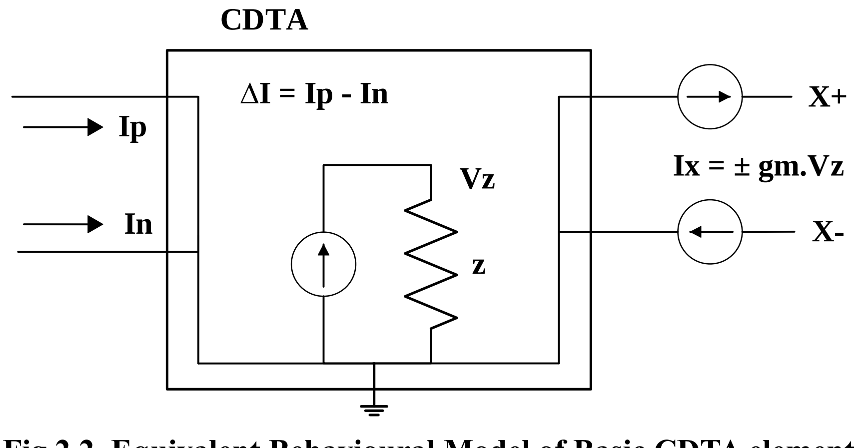


Fig.2.2. Equivalent Behavioural Model of Basic CDTA element [52]

- **Temporary Voltage Conversion:** An external impedance, like a resistor, is used to convert the difference current into a voltage at the z terminal.

- **Current Control with Voltage:** This voltage at the z terminal then acts as a control signal for two internal circuits. These circuits use the voltage information to manipulate the flow of current within the CDTA, ultimately generating two output currents as the final act.

This analogy simplifies the CDTA's operation, but it captures the essence: taking in currents, processing the difference, and producing new currents as the output.

2.1.2 Equations

CDTA can also be considered as a current operational amplifier, as presented in Fig.2.1, and the characteristics equations in matrix form as shown in Eq. (2.1).

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_x \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_x \\ V_z \end{bmatrix} \tag{2.1}$$

Considering the deviation of the voltage and current gains from their ideal values, the characteristics equation of the CDTA is given in Eq. (2.2).

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_x \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \alpha_p & -\alpha_n & 0 & 0 \\ 0 & 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_x \\ V_z \end{bmatrix} \tag{2.2}$$

Where, g_m is the transconductance gain, p and n are the input terminals, z and ± x are the output terminals, and Z_z is an external impedance connected at the terminal z. and $\boldsymbol{\alpha_p}$ & $\boldsymbol{\alpha_n}$ are current gains, $\boldsymbol{\alpha_p}$ =1-$\boldsymbol{\varepsilon_p}$, and $\boldsymbol{\alpha_n}$=1-$\boldsymbol{\varepsilon_n}$. Here, $\boldsymbol{\varepsilon_p}$and $\boldsymbol{\varepsilon_n}$ are the current tracking errors, and their absolute values are much less than the 1.

The diagram representing a CDTA might seem like a jumble of letters and symbols. Let's break it down to understand its functionality better:

Input Terminals (p & n): These are the entry points where two separate current signals enter the CDTA.

Output Terminals (z, +x, & -x): The CDTA processes the input currents and delivers the results at these terminals.

z Terminal: This acts as an intermediate stage.

+X & -X Terminals: These are the final outputs, where the CDTA produces two new current signals.

Behind the symbol how the CDTA works, the CDTA performs its magic in two key steps: Current Subtraction and Conversion.

The CDTA calculates the difference between the two input currents at terminals p and n. This difference current is then directed towards the z port. An external component, typically a resistor, is connected to the z port. This resistor helps convert the difference current into a voltage.

Voltage Control and Current Creation: The voltage generated at the z terminal acts as a control signal for the CDTA's internal circuitry. This control voltage influences two internal "trans conductors" – special circuits that can manipulate current flow. One trans conductor creates a positive output current at the +X terminal, while the other creates a negative output current at the -X terminal. The strength of these output currents is determined by a value called "transconductance gain" (represented by the symbol g_m).

$$V_n = V_p = 0 \tag{2.3}$$

$$I_z = I_p - I_n \tag{2.4}$$

$$I_{x+} = g_m V_z \; ; \; I_{x-} = -g_m V_z \tag{2.5}$$

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t) \tag{2.6}$$

$$g_m = \sqrt{2 . \mu_n C_{ox} \frac{W}{L}} . \sqrt{I_B} \tag{2.7}$$

The equations mentioned earlier account for a slight imperfection in the CDTA's operation. These imperfections, called "current tracking errors," are represented by the symbols ε_p and ε_n. These errors are very small and have minimal impact on the overall performance of the CDTA circuit. By understanding this interplay between input currents, voltage conversion, and controlled current generation.

2.2 CMOS Implementation of CDTA

The basic design of a CDTA block, as illustrated in Figure 2.3, can be broken down into two key stages working together:

- **Current Differencing Unit (CDU):** This first stage utilizes two specific circuits known as "current conveyors." These clever components help the CDTA calculate the difference between the incoming currents.
- **Dual-Output Operational Transconductance Amplifier (OTA):** The processed difference current from the first stage is then fed into a special amplifier called a "dual-output OTA." This amplifier takes the current information and transforms it into two separate output currents, completing the CDTA's processing cycle.

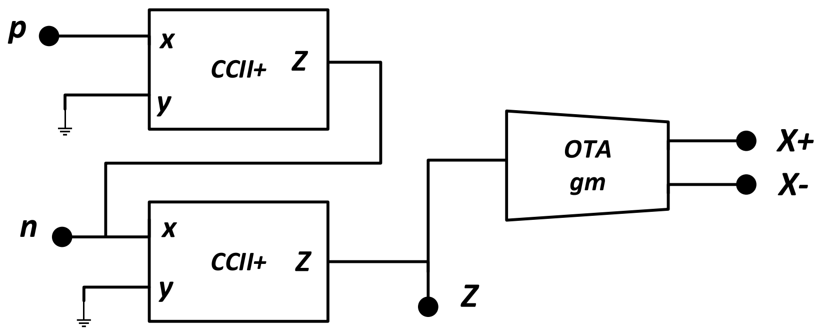


Fig.2.3. Two-stage basic implementation of CDTA [52]

The concept of the (CDTA) first emerged in 2003, courtesy of D. Biolek's groundbreaking work presented at the European Conference on Circuit Theory and Design (ECCTD). Three years later, in 2006, Biolek brought this idea to life by creating the first practical CDTA circuit built using CMOS technology. This initial CDTA design was quite basic. It relied on two specialized circuits called "differential current conveyors" to handle the current subtraction. The processed difference current was then fed into a unique amplifier known as a "single-input double-current-output OTA." This clever combination required a total of 24 transistors – 12 for the current conveyors and 12 for the OTA – to achieve the desired functionality. Additionally, the circuit employed three biasing currents and a dual supply voltage to operate effectively. While this initial implementation laid the foundation for future CDTA development, it wasn't the end of the story. Researchers have continuously explored various approaches to refine and improve upon this initial design.

This CDTA was implemented in PSPICE using 0.18-nm MIETEC transistor model

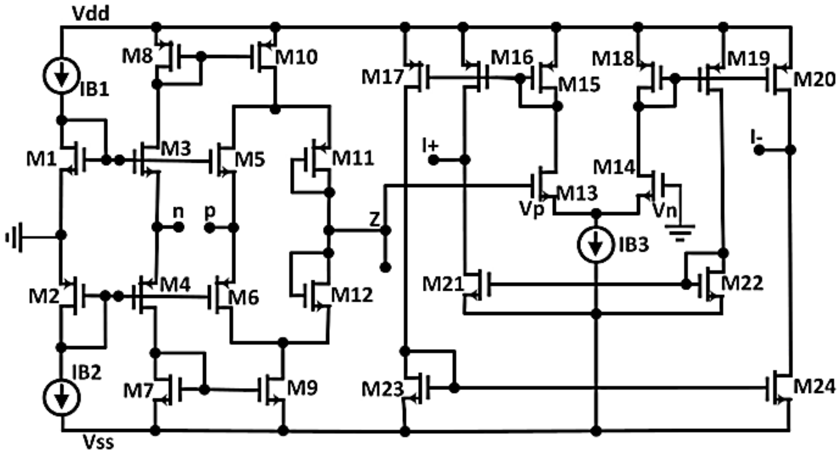


Fig.2.4 Standard CMOS based CDTA [1]

characteristics varying from 4:1 to 16:1 in transistor aspect ratio. This CDTA has a trans-conductance of 0.479 mA/V and a biasing current of 200A. 400 MHz is the bandwidth obtained as indicated in Table 2.1, which is far more than the few MHz of bandwidth that can be achieved from an OPAMP. This indicates quite clearly that, when compared to OPAMPs and other current/voltage-mode fundamental building blocks, this CDTA can function across a greater frequency range.

Traditional CDTAs have a limitation – their gain, a measure of signal amplification, can only be increased so much by adjusting a bias current. This approach also leads to higher power consumption.

2.3 Circuit Description of CDTA with High Gain Transconductance

Researchers have proposed new CDTA structures (CDTA-I) to overcome these limitations and achieve significantly higher gains. Here's the key idea:

- **ICommoncing Common-Source Amplifiers:** Tiny amplifier circuits called "common-source amplifiers" are strategically placed between the gate and source terminals of the MOSFETs in the conventional CDTA's differential pair.
- **Increased Gate-Source Voltage:** These added amplifiers boost the voltage difference between the gate and source terminals of the differential pair MOSFETs. This, in turn, significantly increases the overall transconductance gain of the proposed CDTA. To evaluate the performance of the proposed CDTA design, researchers used computer simulations based on the characteristics of a common 0.18 μm CMOS technology.

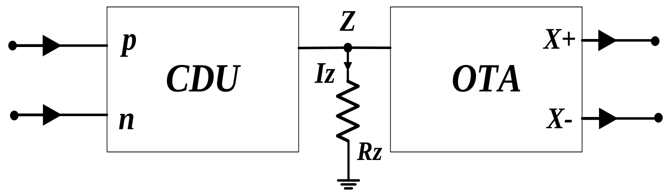


Fig. 2.5 Symbolic Representation of CDTA consisting of CDU and OTA

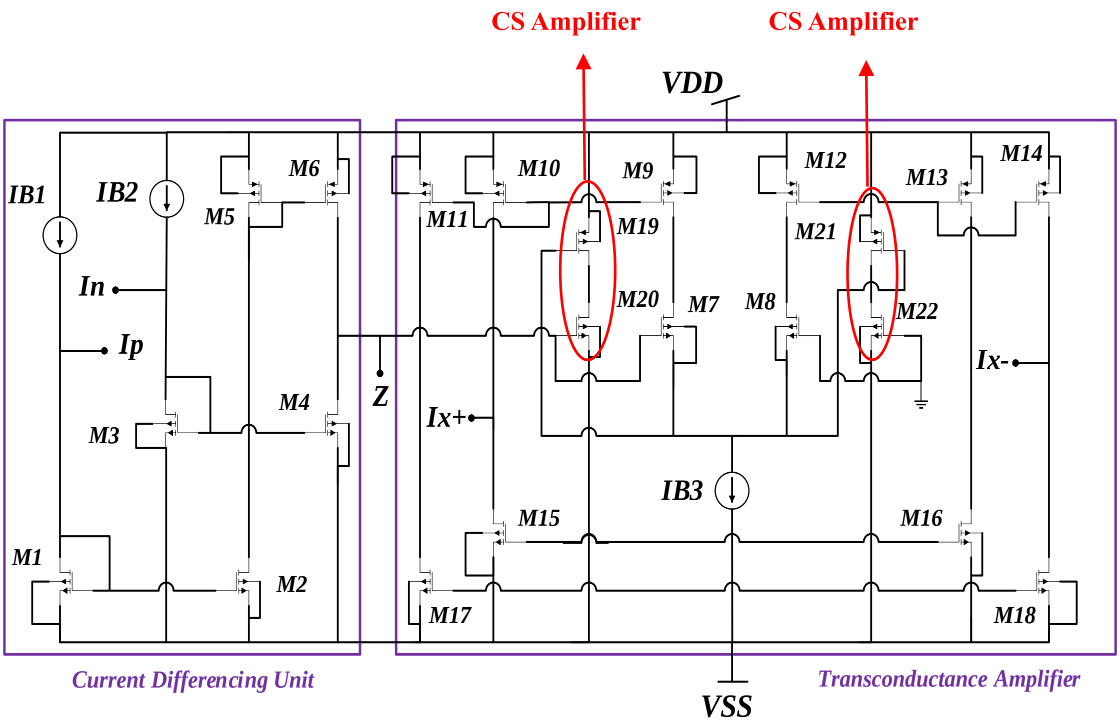


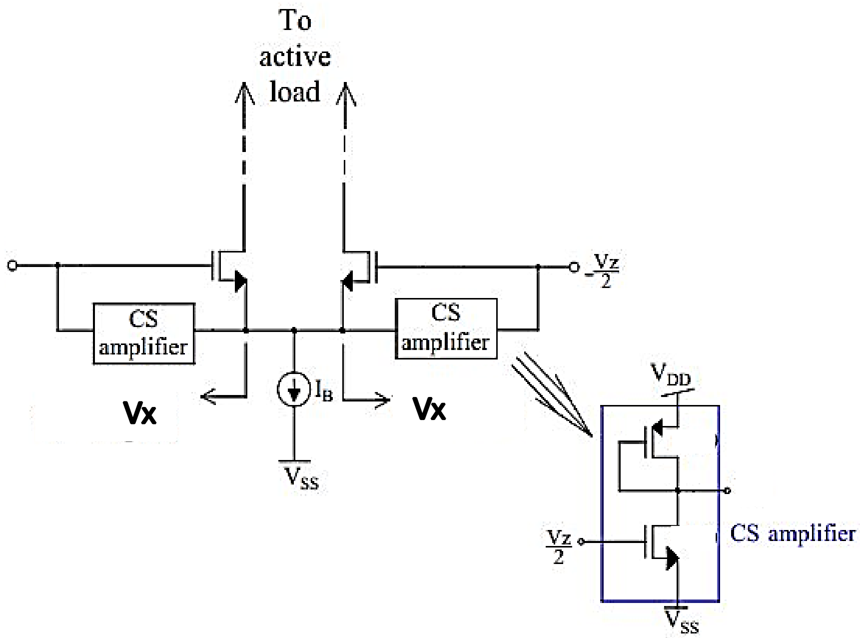
Fig. 2.6 Full CDTA Circuit Diagram Based on the suggested g_m Boosting Method [53]

The secret behind the higher gain of CDTA lies in a clever addition to its design – common-source amplifiers. As shown in Figure 2, these tiny amplifier circuits are strategically placed between the gate and source terminals of the MOSFETs in the differential pair (a key component of the CDTA).

Here's how they work:

- **Voltage Boost:** The inputs to both the differential pair MOSFETs and the common-source amplifiers are connected to the voltage across the "Z" ports of CDTA. However, the outputs of the common-source amplifiers are cleverly fed back to the source terminals of the differential pair MOSFETs. Because of the symmetrical design, the voltage at each side of the differential pair is considered half the voltage at the Z port (Vz/2).

- **Phase Shift and Increased Potential:** The common-source amplifiers introduce a 180-degree phase shift between their inputs and outputs. This, in turn, creates a larger voltage difference between the gate and source terminals of the differential pair MOSFETs.
- **Impact on Gain:** Traditionally, the gain of a CDTA depends on this voltage difference (V_{gs}) between the gate and source of the differential pair MOSFETs. By introducing the common-source amplifiers, CDTA effectively increases the applied V_{gs} , which ultimately boosts the overall transconductance gain of the circuit. For a complete picture, Fig.2.6 showcases the entire CDTA circuit. The core component, the CDU (current differencing unit), uses six MOSFETs (M_1-M_6) operating in a specific mode (saturation region) to handle current processing. The OTA (operational transconductance amplifier) is built using transistors M_7-M_{22}. Here's the key point: transistors M_{19}-M_{20} and M_{21}-M_{22} are the common-source amplifiers cleverly embedded within the differential pair, as illustrated in Figure 2.



<u>Fig.2.7 Proposed transconductance gain enhancement technique [53]</u>

- **Increased Currents, Increased Gain:** The common-source amplifiers effectively raise the gate-to-source voltages of the differential pair MOSFETs. This, in turn, results in a significant increase in their drain currents (I1 and I2).

The final output currents (Ix+ and Ix-) of the CDTA are simply the sum of these amplified drain currents. Consequently, the CDTA achieves a higher transconductance gain compared to the conventional design, all while maintaining the same input voltage (Vz) as its predecessor.

2.4 Small Signal Analysis of Proposed CDTA

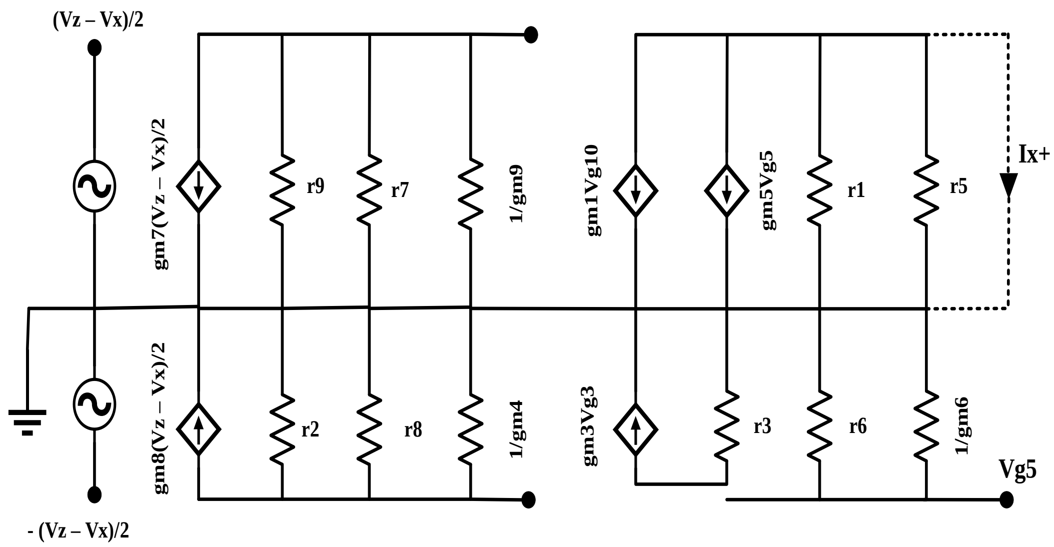


Fig.2.8 AC equivalent circuit of OTA [53]

Fig. 2.8 displays the small-signal equivalent model of OTA in CDTA. The output voltage Vx of the CS amplifier is determined by applying a modest signal voltage Vz to the "Z" port.

$$V_x = -\frac{V_z}{2}\left(\frac{g_{m2}}{g_{m9}}\right) \tag{2.8}$$

where Vz/2 is considered due to half symmetry of OTA.
The vgs7 and vgs8 of M_7 and M_8, respectively are given as

$$V_{gs7} = \frac{V_z - V_x}{2} \tag{2.9}$$

$$V_{gs8} = -\left(\frac{V_z - V_x}{2}\right) \tag{2.10}$$

The voltage Vg1 can be obtained after applying KCL at node A

$$V_{g1} = -g_{m7}\left(\frac{V_z - V_x}{2}\right)\left(\frac{1}{g_{m9}}\,||r_7||r_9\right) \quad \textbf{(2.11)}$$

The value of 1/gm9 is smaller than the values of r7 and r9. So, the parallel combination of 1/gm9, r7, and r9 reduces to 1/gm9 which results in:

$$V_{g1} \cong -\frac{g_{m7}}{g_{m9}}\left(\frac{V_z - V_x}{2}\right) \quad \textbf{(2.12)}$$

Replacing the value of Vx from Eq. (8) into Eq. (12) gives

$$V_{g10} \cong -\frac{g_{m7}}{g_{m9}}.\frac{V_z}{2}\left(1 + \frac{1}{2}.\frac{g_{m2}}{g_{m9}}\right) \quad \textbf{(2.13)}$$

Applying KCL at node B for calculation of voltage Vg3 results in

$$V_{g3} = g_{m8}\left(\frac{V_z - V_x}{2}\right)\left(\frac{1}{g_{m2}}\,||r_8||r_2\right) \quad (2.14)$$

The value of 1/gm12 is smaller than the values of r8 and r2. Therefore the Eq. (14) can be approximated as

$$V_{g3} \cong -\frac{g_{m8}}{g_{m2}}\left(\frac{V_z - V_X}{2}\right) \quad \textbf{(2.15)}$$

After replacing the value of Vx from Eq. (8) to Eq. (15), we get

$$V_{g3} \cong \frac{g_{m8}}{g_{m2}}.\frac{V_z}{2}\left(1 + \frac{1}{2}.\frac{g_{m4}}{g_{m9}}\right) \quad \textbf{(2.16)}$$

The voltage vg15 can be obtained as

$$V_{g5} = -g_{m3}\cdot V_{g3}\left(\frac{V_z - V_y}{2}\right)\left(\frac{1}{g_{m6}}\,||r_3||r_6\right) \quad \textbf{(2.17)}$$

The value of Vg3 is substituted from Eq. (16) in Eq. (17) and we get,

$$V_{g5} \cong -\frac{g_{m3}}{g_{m6}}.\frac{g_{m8}}{g_{m12}}\frac{1}{2}.\frac{V_z}{2}\left(1 + \frac{1}{2}.\frac{g_{m4}}{g_{m9}}\right) \quad \textbf{(2.18)}$$

KCL is applied at node D to obtain the value of current ix+, which yields,

$$i_{x+} = -g_{m15}v_{g15} - g_{m10}v_{g10} \quad (2.19)$$

Substituting the values of Vg1 and vg5 from Eqs. (2.13) and (2.18) in Eq. (2.19) gives,

$$i_{x+} \cong g_{m8}.\frac{g_{m5}}{g_{m6}}.\frac{g_{m3}}{g_{m2}}.\frac{V_z}{2}\left(1 + \frac{1}{2}.\frac{g_{m4}}{g_{m9}}\right) + g_{m7}.\frac{g_{m1}}{g_{m9}}.\frac{V_z}{2}\left(1 + \frac{1}{2}.\frac{g_{m20}}{g_{m19}}\right) \quad \textbf{(2.20)}$$

Due to symmetrical aspect ratios, the respective transconductances of MOSFETs are assumed as,

$$g_{m5} = g_{m6} , g_{m2} = g_{m3} , g_{m9} = g_{m1} , g_{m20} = g_{m22} , g_{m19} = g_{m20} \quad \textbf{(2.21)}$$

Using Eqs. (2.19) and (2.20), the value of current Ix+ is obtained as,

$$i_{x+} = g_m . V_z (1 + A) \quad \textbf{(2.22)}$$

Where,

$$A = \frac{g_{m20}}{g_{m19}} \quad \textbf{2.23)}$$

If we compare Eq. (4) and Eq. (22) then the value of trans conductance of the suggested CDTA is greater than the transconductance of the traditional CDTA by a factor of one plus A. The suggested CDTA's transconductance is represented by the expression in Eq. (2.24).

$$G_m = (1 + A) . g_m \quad (2.24)$$

Table 2.1 Transistor W/L ratios used in CDTA circuit simulation

Transistor	W/L Ratio (µm)
M_1-M_6	*8/1*
M_7-M_{10}	*5/1*
M_{11}-M_{12}	*20/2*
M_{13}-M_{14}	*16/1*
M_{15}-M_{20}	*6/1*
M_{21}-M_{24}	*4/1*

The biasing current values are as follows: IB1 = 500 µA, IB2 = 500 µA, and IB3 = 486.2 µA.

The supply voltages have values of ± 0.5 V.

2.5 Realisation of Universal Bi-quad Filters using CDTA

The CDTA has emerged as a versatile building block for analog circuit design, particularly in the realm of current-mode applications.

Universal Bi-quad Filters: These filters are crucial components for processing electronic signals. They can remove unwanted noise or selectively amplify specific frequency bands. The term "universal" refers to their ability to perform various filtering functions **(low-pass, high-pass, band-pass, and band-reject)** by adjusting circuit parameters.

Universal bi-quad filters are the chameleons of the signal processing world. These versatile filters can be configured to perform various functions – low-pass, high-pass, band-pass, and band-reject – by adjusting circuit parameters.

The chosen active building block forms the core of the filter circuit. Additional passive components like resistors and capacitors are then strategically placed to achieve the desired filter response. The specific number and arrangement of these components depend on the chosen active device, filter type, and desired characteristics.

Referring to existing research on realizing universal bi-quad filters using active building blocks, is a solid foundation for your work. Here are some ways to leverage this existing knowledge. **Analyse Existing Designs:**

- **Circuit Topologies:** Review the specific circuit configurations used in the papers you referenced. Identify common themes and variations in how CDTAs are employed within the filter circuits.
- **Component Selection:** Analyse the types and values of passive components (resistors, capacitors) used in conjunction with the CDTAs in different filter designs.
- **Filter Response Control:** Understand how the papers adjust circuit parameters (e.g., component values) to achieve different filter responses (LP, HP, BP and BR).

Here, are the papers that referred to realize the Universal Bi-quad Filters and Universal Inverse Bi-quad filters using CDTA.

Table 2.2 Summary for analysis of Realised Filters using ABB.

Reference, Year	Name & No. of ABB used	Passive Elements	Realised Filters
[4]	CDBA (1)	2C, 2R	LPF, HPF, BPF
[24]	CFOA (3)	6R	LPF, HPF, BPF, BRF, APF
[14]	CFOA (4)	2C	LPF, HPF, BPF
[5]	CFOA (1)	2C, 1R	LPF, HPF, BPF
[6]	CFA (1)	2C, 1R	LPF, HPF, BPF
[8]	VCII+ (3)	3C, 2R	LPF, HPF, BPF
[16]	CCII+ (2)	2C, 2R	LPF, HPF, BPF
[10]	OTA (2)	2C	LPF, HPF, BPF
[15]	OTA (2)	2C, 1R	LPF, HPF, BPF
[13]	OTRA	2C, 6R	LPF, HPF, BPF
[11]	VDTA (1)	2C, 1R	LPF, HPF, BPF
[12]	VDTA (2)	2C	LPF, HPF, BPF

CDTA's Advantages: Using CDTAs to create universal bi-quad filters offers various advantages:

- **Simplified Design:** Compared to traditional voltage-mode circuits, CDTAs can implement these filters with less components, leading to more compact designs.
- **High-Frequency Performance:** CDTAs excel at handling high-frequency signals, making them ideal for modern applications.
- **Electronic Tuning:** The properties of a CDTA-based filter can be easily adjusted electronically, allowing for greater flexibility and customization.

Research Focus: Researchers have actively explored various approaches to realizing universal bi-quad filters using CDTAs. Here are some key areas of focus:

- **Minimizing Components:** A significant effort is directed towards designing filters with minimum number of passive components (resistors and capacitors) while maintaining desired filter characteristics.
- **Current-Mode Operation:** Researchers strive to maintain pure current-mode operation for the entire filter, maximizing the benefits of CDTA technology.

- **Filter Response Control:** Developing methods to precisely control the filter's response (cutoff frequency, quality factor) through adjustments within the CDTA circuit is another area of investigation.

The existing research on active building blocks, especially CDTAs in bi-quad filters, is a great starting point. Here's how to leverage it:

- **Analyse designs:** See how researchers use CDTAs and passive components in filter circuits.
- **Identify improvements:** To reduce the components or improve filter control.
- **Plan your design:** Choosing filter types, components, and simulate the circuit.

Table 2.3 Summary for analysis of Application Of CDTA

Reference	No. of Devices	Components	Realization
[1]	CDTA (2)	2 C	LPF, HPF, BPF
[22]	CDTA (1)	2 C, 2 R	LPF, HPF, BPF
[18]	CDTA (1)	2 C, 1R	LPF, HPF, BPF
[19]	CDTA (1)	1 C, 1R	LPF, BPF
[21]	CDTA (3)	2 C, 2 R	IHPF
[20]	CDTA (1)	1 C, 1 R	IAPF

Overall, the research on CDTA-based universal Bi-quad filters highlights the potential of this approach for creating efficient, high-performance filters for various analog signal processing applications. The field of analog filter design has seen a surge in interest in using CDTAs for realizing universal bi-quad filters. These filters offer the flexibility to perform various filtering functions.

2.6 Realisation of Universal Inverse Bi-quad Filters using CDTA

In the realm of signal processing, filters play a vital role in manipulating specific frequency components of a signal. While traditional bi-quad filters focus on attenuating or eliminating unwanted frequencies, inverse bi-quad filters take a different approach.

Imagine a scenario where you have a signal that has been altered by a known bi-quad filter. An inverse bi-quad filter aims to reverse this alteration, essentially restoring the original signal. It acts like a mathematical mirror, undoing the frequency response imposed by the original bi-quad filter.

2.6.1 Inverse Filters

- **Inverse Low Pass Filter:** A regular low-pass filter is like focusing on the smooth, blurry parts of the picture and ignoring the sharp edges and details. An inverse low-pass filter would be like a sharpening filter, trying to bring back those lost details.
- **High Pass Filters:** This specialized filter attempts to undo the work of the regular high-pass filter. Ideally, it recovers the original signal by amplifying the low-frequency components that were blocked by the original filter.
- **Inverse Band Pass Filter:** Aims to recover the original signal that was filtered by a band-pass filter.it amplifies the frequencies that were attenuated by the original filter, restoring the complete signal.

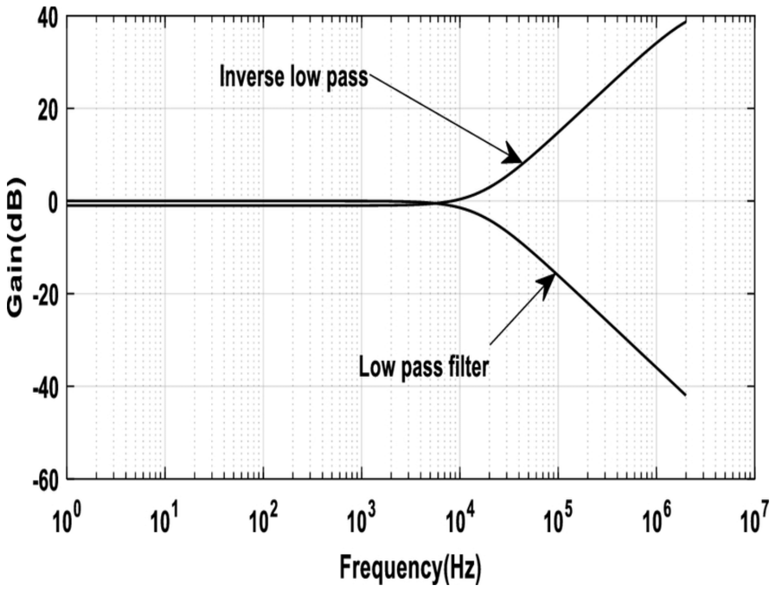


Fig.2.9 Inverse Low Pass filter.

This specialized filter aims to reverse the effects of a known bi-quad filter, essentially restoring the original signal. It acts like a mathematical mirror, inverting the frequency response imposed by the original filter, revealing the hidden message within the

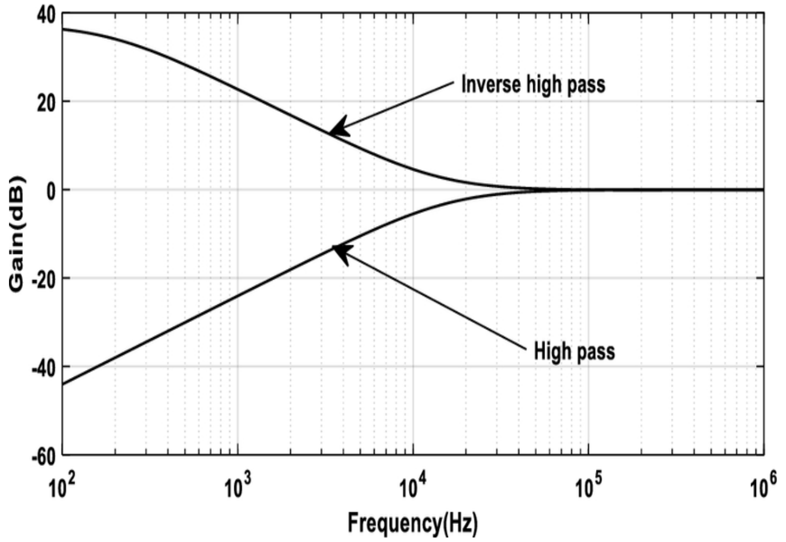


Fig.2.10 Inverse High Pass filter.

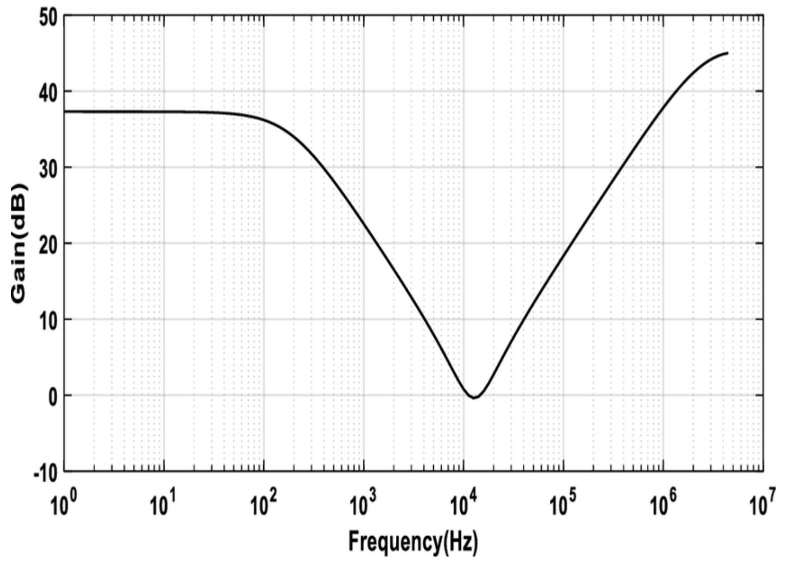


Fig.2.11 Inverse Band Pass filter.

Scrambled code. A great starting point with existing research on active devices (especially CDTAs) for inverse bi-quad filters. Here's how to use it:

- **Analyse designs:** See how researchers use active devices and components in existing inverse filters.
- **Focus on CDTAs:** Explore how CDTAs can be used for potentially simpler inverse filter designs.
- **Consider challenges:** Address stability and noise concerns during your design process.

Table 2.4 Summary for analysis of Realised Inverse Filters using ABB

Reference	Name & No. of ABB used	Passive Elements	Realised Filters
	Op-Amp (1)	4R, 2C	IHPF
[27]	Op-amp (1)	½R, ½C	IHPF, IBPF
[36]	OTA (5/6)	2C	ILPF, IHPF, IBPF
[37]	OTA (4/5)	2C	ILPF, IHPF, IBPF, IBRF
	CCII (1)	2R, 1C	IAPF
[40]	CFOA (3)	4R, 2C	ILPF, IHPF, IBPF, IBRF
[41]	CFOA (3)	3/5R, 2C	ILPF, IHPF, IBPF, IBRF
[42]	CFOA (3)	2/3R, 2/3C	ILPF, IHPF, IBPF
[43]	CFOA (2)	4/6R, 2C	ILPF, IHPF, IBPF, IBRF
[44]	FTFN (1)	4R, 2C	ILPF, IHPF, IBPF, IBRF, IAPF
[45]	FTFN (1)	3R, 1C	IAPF
[46]	OTRA (2)	4/6R, ¾C	ILPF, IHPF, IBPF
[47]	OTRA (1)	3R, 3C	IBRF
[38]	CDBA (2)	4/5R, RC	IBRF, IAPF
[39]	CDBA (2)	3R, 2C	ILPF, IHPF, IBPF, IBRF
[17]	CDBA (2)	9R, 9C	IBPF
[23]	CDBA (1)	2/3R, 2/3C	ILPF, IHPF, IBPF, IBRF
[6]	CDTA (1)	1R, 1C	IAPF
[24]	CDTA (3)	2R, 2C	ILPF
[25]	VDTA (2/4)	2C	ILPF, IHPF, IBPF, IBRF
[26]	VDTA (4)	1/8R, 2C	ILPF, IHPF, IBPF, IBRF
[48]	VCII (2/3)	4/6R, ½C	ILPF, IHPF, IBPF
[49]	VCII (2)	2R, 2C	ILPF, IHPF, IBPF, IBRF

Research in realizing universal inverse bi-quad filters is active. Advancements in active device technology and design methodologies hold promise for achieving robust and efficient solutions, making them valuable tools in various signal processing applications where signal restoration is critical.

2.6 Hardware implementation of CDTA

The implementation of CDTA using commercially available ICs (AD844 and CA3080) as presented in Fig.2.12.

While dedicated CDTA integrated circuits (ICs) are emerging, you can build a functional CDTA using a combination of readily available ICs like the AD844 and CA3080.

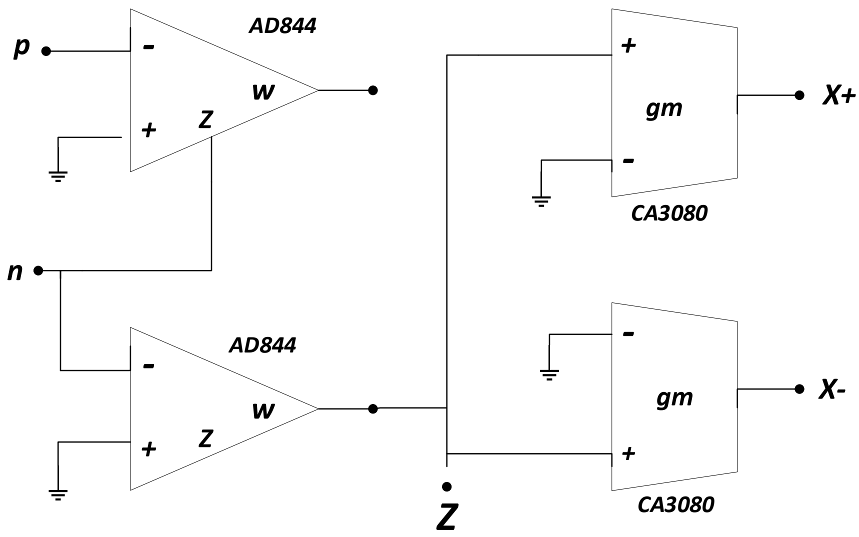


Fig.2.12 CDTA implementation using commercially available ICs [52]

CHAPTER 3
REALIZATION OF UNIVERSAL BI-QUAD FILTERS USING CONVENTIONAL TOPOLOGIES

The depicted current-mode active filter, utilizing a CDTA alongside two grounded capacitors and a switched resistor, is presented in Figure 3.1. By employing grounded capacitors exclusively, the circuit becomes well-suited for integration into IC implementations. The switched capacitor serves as a resistor, thereby minimizing the required fabrication space. This configuration is compatible with CMOS technology. The suggested circuit facilitates essential filter functions such as LP, HP, and BP. The current outputs corresponding to these filter functions are illustrated in Fig.3. Through standard calculations for the presented filter, the current responses can be determined. The presented circuit demonstrates capability in executing fundamental filter functions, including LP, HP, and BP operations. The current outputs corresponding to these filter modes are illustrated in Figure.3.1.

Note, that the p-terminal of the CDTA remains unused. This observation can be leveraged to streamline the input circuitry of the CDTA for this specific application.

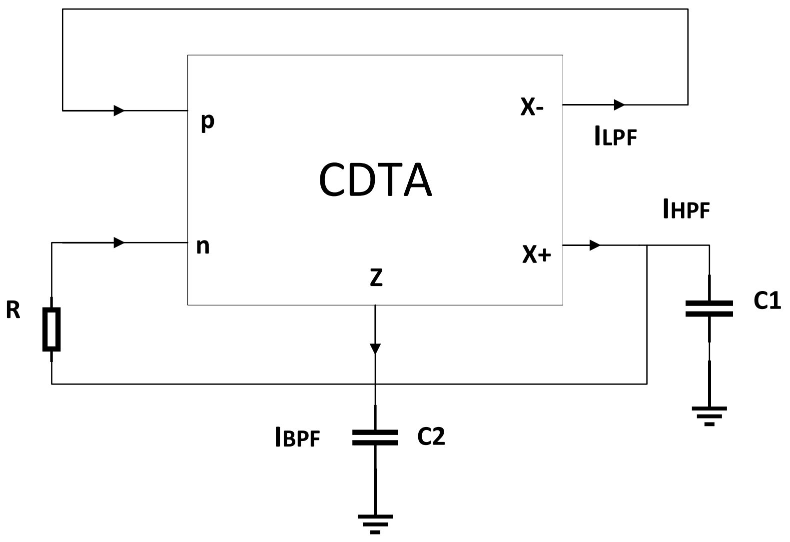


Fig. 3.1 Bi-quad filter using CDTA element [54]

Based on standard existing replies can be expressed as follows in the computations for the filter.:

$$I_{LP} = \frac{\frac{g_m}{RC_1C_2}}{S^2+\frac{1}{RC_1}S+\frac{g_m}{RC_1C_2}} I_{in} \tag{3.1}$$

$$I_{BP} = \frac{\frac{1}{RC_1}S}{S^2+\frac{1}{RC_1}S+\frac{g_m}{RC_1C_2}} I_{in} \tag{3.2}$$

$$I_{HP} = \frac{S^2}{S^2+\frac{1}{RC_1}S+\frac{g_m}{RC_1C_2}} I_{in} \tag{3.3}$$

Bandwidth (BW), natural frequency (ω0) and quality factor (Q) are expressed by:

$$BW = \frac{1}{RC_1}\,;\ \omega_0 = \sqrt{\frac{g_m}{C_1C_2R}}\,;\ Q = \sqrt{g_m R \frac{C_1}{C_2}} \tag{3.4}$$

Equation (5) reveals that the parameter ω_0 is modifiable by transconductance g_m , irrespective of the bandwidth. Chnjaging the biasing current of the CDTA enables the manipulation of transconductance values.

This design utilizes a single CDTA along with two capacitors and two resistors, one grounded and the other virtually grounded. The circuit offers the flexibility of achieving LP, BP, and HP filter responses without modification of the hardware configuration. Additionally, it allows for electronic adjustment of both the natural frequency and quality factor. This circuit achieves LP, BP, and HP filtering functionalities using only one CDTA, two grounded capacitors, and a combination of grounded and virtually grounded resistors. The design eliminates the need for hardware reconfiguration for different filter types. Furthermore, it enables electronic control over the filter's natural frequency and quality factor. This design leverages a single CDTA with minimal passive components: two grounded capacitors and one each of grounded and virtually grounded resistors. The circuit offers the unique capability of realizing LP, BP, and HP filters without any hardware changes. It also provides electronic control over the filter's characteristic frequency and damping factor. The cutoff frequencies of Bi-quad filters using conventional CDTA and CDTA[1] are 40.82 MHz and 3.5 GHz, respectively. The comparative Analysis is presented in Figure 4. (a-c). Their power dissipations are measured at 13mW, and 7.47mW. Consequently, Bi-quad filters implemented with new CDTA provide higher center frequencies and use less power than those achieved with traditional CDTA.

The proposed Bi-quad filters are tailored for a (ω_0 of 159 kHz and a Q-factor of 0.707, achieved through careful selection of the passive elements such as R = 0.1K, and C1 = C2 = 0.1001nF. By using grounded capacitors, this design is well-suited for integration into compact microchips (ICs). This simplifies the fabrication process and reduces overall circuit size. A non-ideal analysis reveals that the circuit exhibits low sensitivity, meaning its performance is minimally affected by variations in component values. Both the active and passive components have sensitivities less than one, indicating a robust design. Extensive simulations were carried out to confirm the theoretical predictions of the circuit's behaviour. The simulated results closely match the theoretical analysis, demonstrating the accuracy of the proposed design.

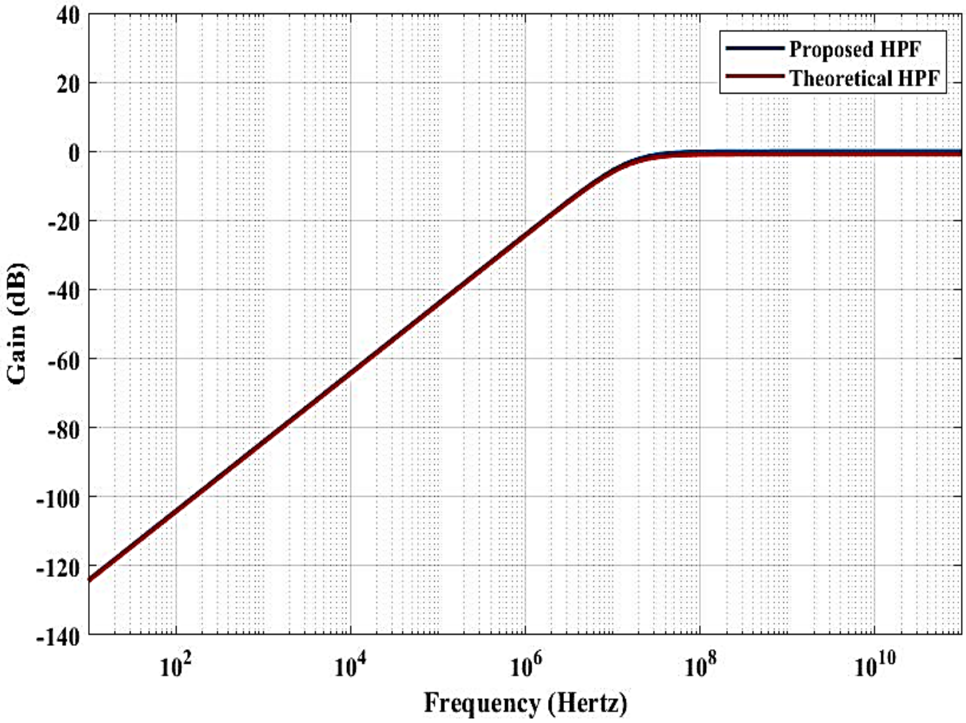


Fig. 3.2 Comparative Analysis of LPF Response for Theoretical and Proposed topologies

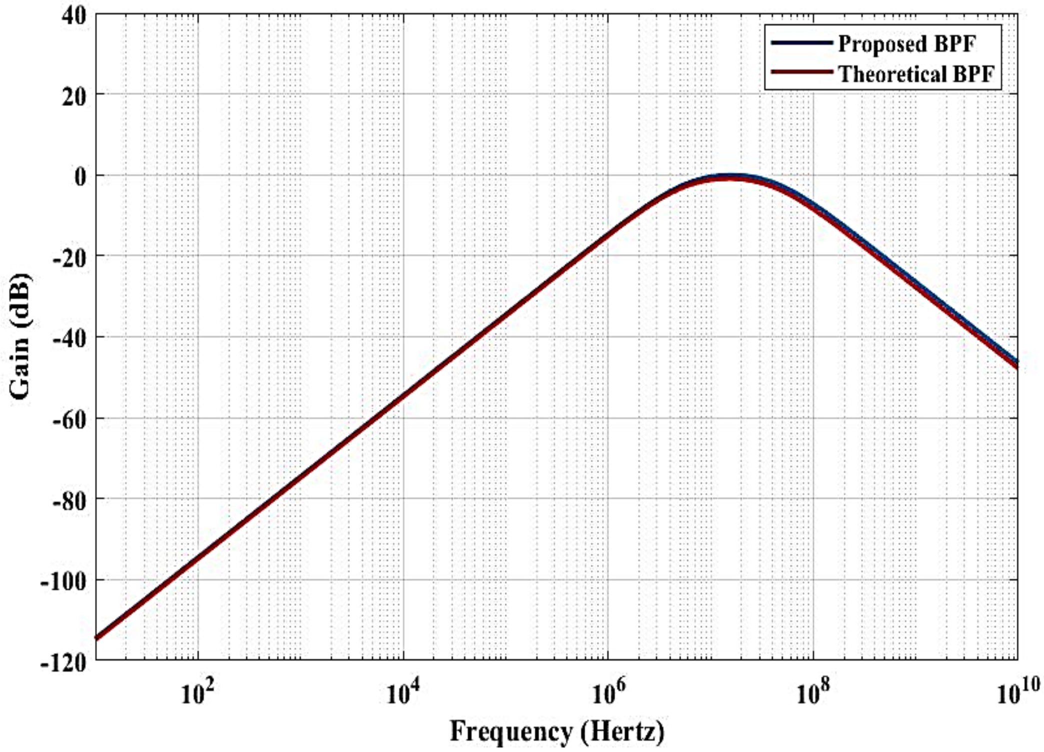


Fig. 3.3 Comparative Analysis of HPF Response for Theoretical and Proposed topologies

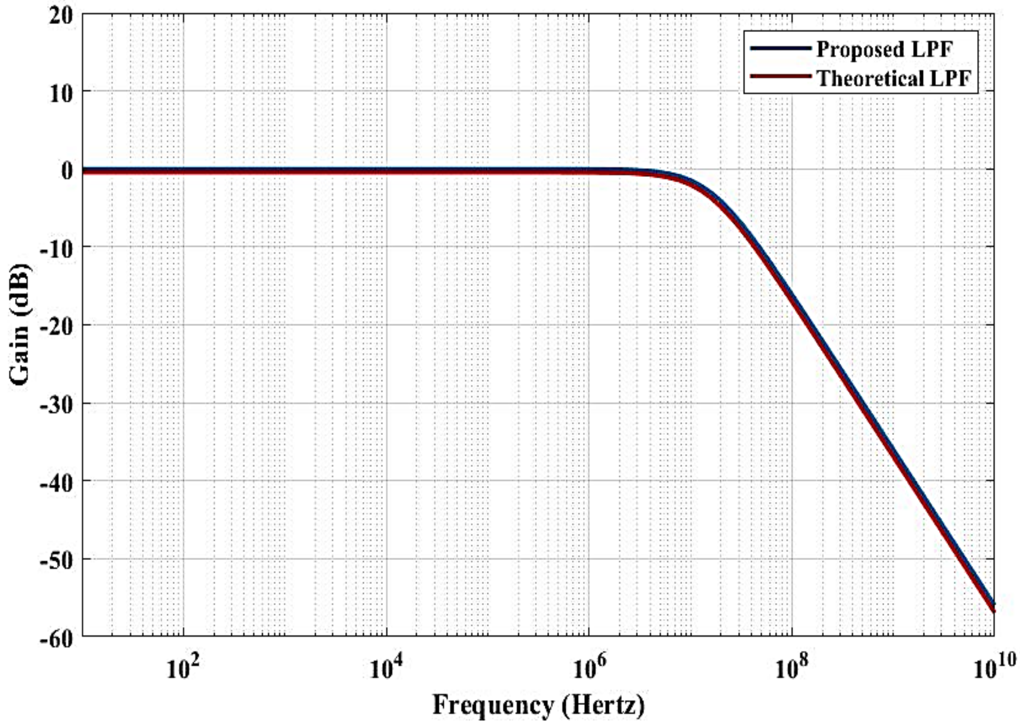


Fig. 3.4 Comparative Analysis of HPF Response for Theoretical and Proposed topologies

The transient response of Bi-quad Filter using CDTA, for an input sinusoidal current with an amplitude of 1μA at 15.9MHz frequency, is depicted in Fig.3.5-3.7.

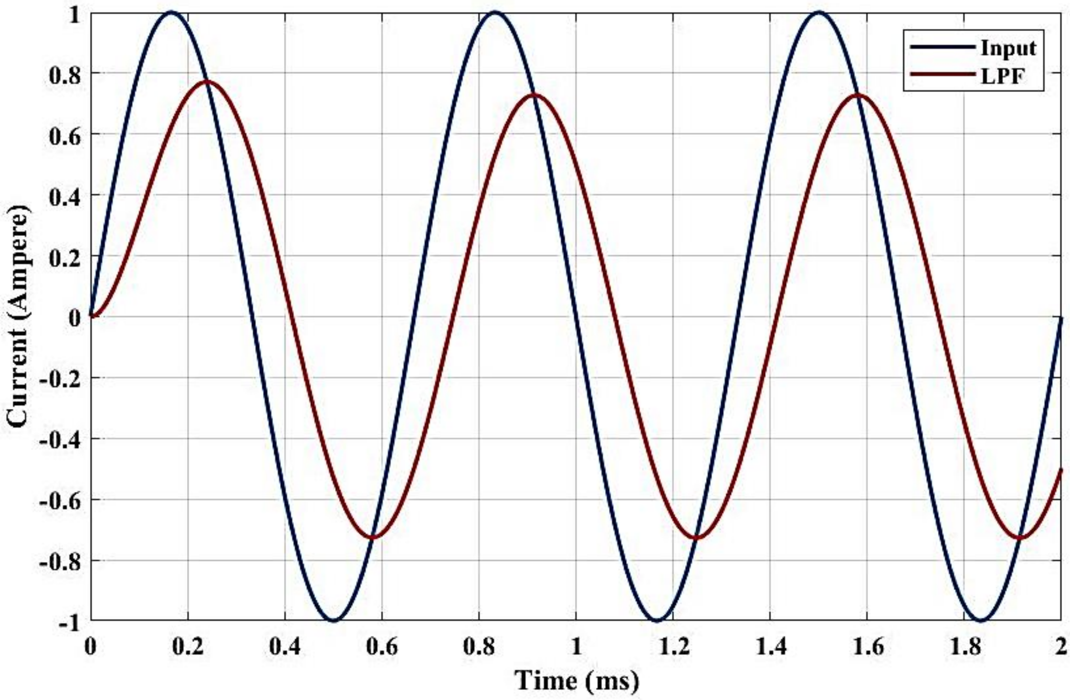


Fig. 3.5 Transient Response of LPF realised by CDTA

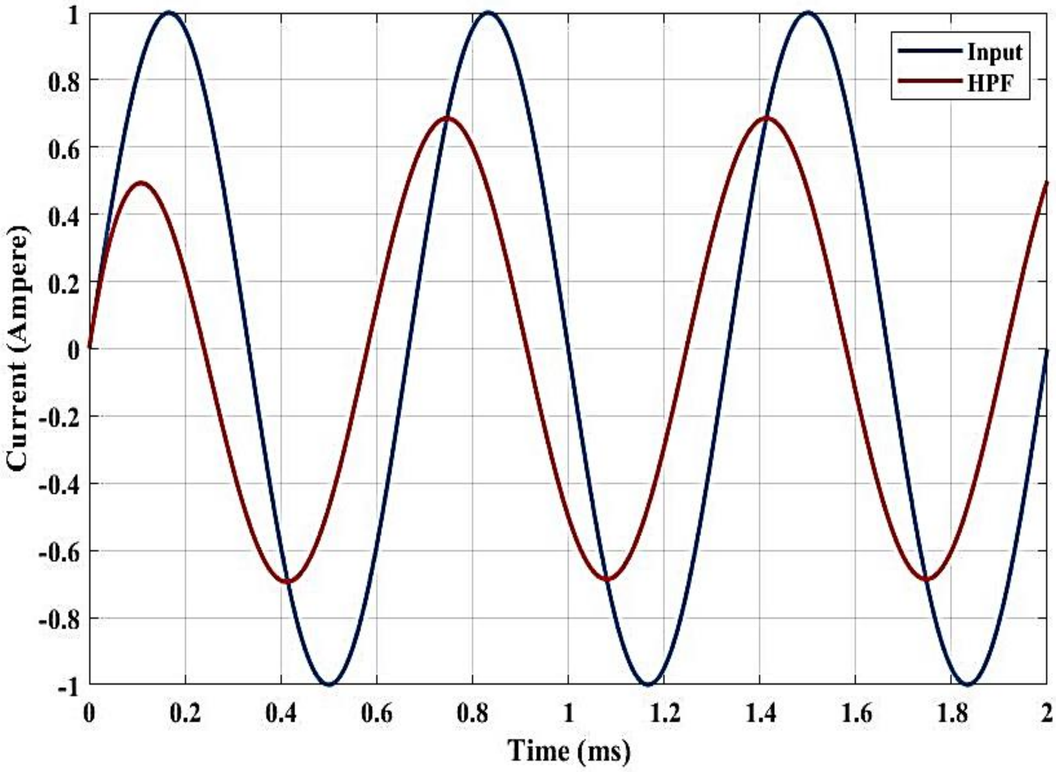


Fig. 3.6 Transient Response of HPF realised by CDTA

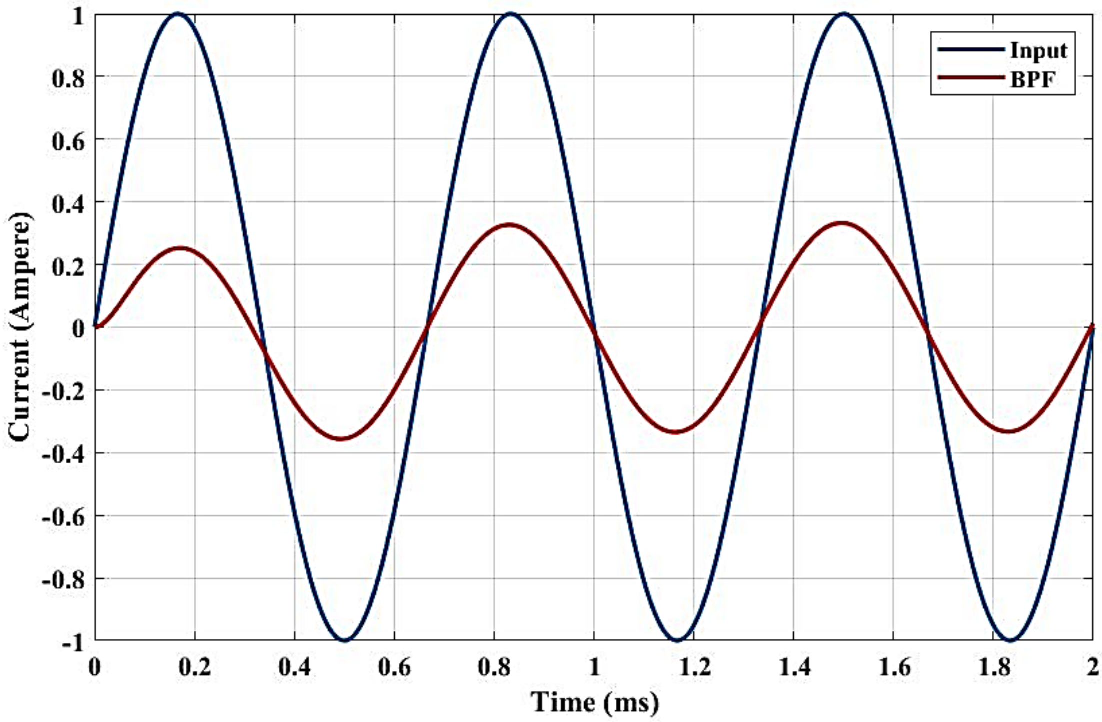


Fig. 3.6 Transient Response of Band Pass Filter realised by CDTA

CHAPTER 4
PROPOSED WORK - REALISATION OF UNIVERSAL INVERSE BI-QUAD FILTERS

Imagine a system that distorts a signal in a specific way. An inverse filter acts like a magic decoder ring – it needs to "know" this distortion beforehand to undo it. The inverse filter essentially mirrors the distorting effect, but in reverse. By doing this, it cancels out the distortion and recovers the original, undistorted signal.

While research has focused heavily on designing digital inverse filters, there's a gap in the world of analog inverse filters. This lack might be due to the limited availability of proven design methods for analog circuits. However, recent trends suggest a renewed interest in this area. Let's take a closer look at the existing research on analog inverse filters in Table 2.4.

Universal inverse filters hold promise for recovering signals distorted by known filters. CDTAs are emerging as interesting active devices for filter design, offering potential benefits for inverse filter realization.

The advantages of using CDTAs:

- **Simpler Designs:** Compared to traditional Active Building Block-based designs, CDTAs might enable simpler circuit configurations for specific inverse filter applications, especially for high-frequency filters. This can lead to more compact and potentially lower-power filter implementations.
- **Current-Mode Operation:** CDTAs operate in current mode, offering certain benefits in terms of dynamic range and linearity compared to voltage-mode counterparts.

Successful CDTA-based inverse filter designs could offer advantages in terms of circuit complexity, component count, and potentially lower power consumption compared to traditional OTA-based approaches. The potential for simpler high-frequency filter designs using CDTAs could be valuable in various applications like communication systems and signal processing for high-bandwidth signals.

4.1 Proposed Circuit Topologies

The IHPF, IBPF, and ILPF circuit topology that is used in its implementation using two CDTA blocks [53] with high gain transconductance with two resistors and two capacitors act as passive elements in circuit is shown in Fig.4.1

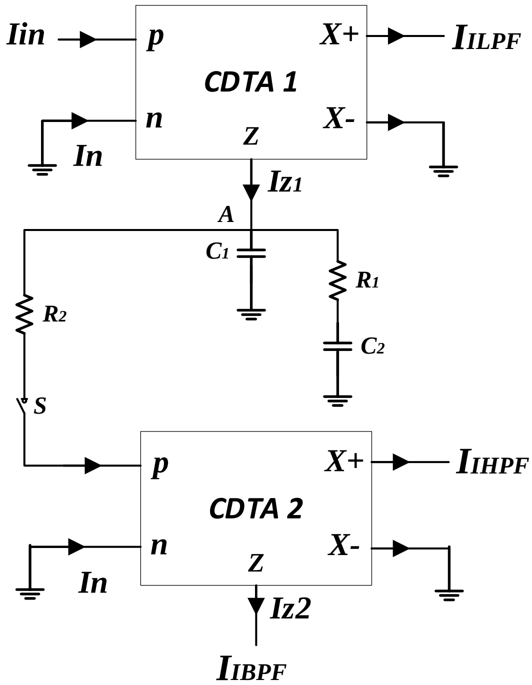


Fig.4.1 Proposed Inverse Filter Topology

This circuit design can act as a LPF, HPF, and BPF. The current outputs for these filtering functions are illustrated in Fig.3. Using standard calculations for this circuit, the mathematical expressions for the current responses are as follows:

By using the general equations of CDTA,

$$H_{ILP}(s) = \frac{I_{out}}{I_{in}} = \frac{g_m R_1 R_2 C_2 s}{sC_1+1} \tag{4.1}$$

$$H_{IHP}(s) = \frac{I_{out}}{I_{in}} = \frac{g_m R_2}{sC_1 R_1+1} \tag{4.2}$$

$$H_{IBP}(s) = \frac{I_{out}}{I_{in}} = \frac{g_m R_2}{(sC_1 R_1+1)(sC_2 R_2+1)} \tag{4.3}$$

To confirm the theoretical predictions, we simulated the proposed universal inverse bi-quad filter configuration using SPICE, a popular circuit simulation software. The

simulation employed a CMOS-based CDTA circuit design [53], as detailed in Figure 2.6. This design incorporates realistic transistor model parameters for all circuit components. The specific dimensions of the transistors are provided in Table 2.1.
With a resistor of 2.24 kΩ connected to the z port of the CDTA, the simulation results indicate a bandwidth of roughly 400 MHz at the x+ and x- terminals. Figure 4 visually represents the outcomes of the universal inverse bi-quad circuit simulations.
The proposed inverse active filters target a specific center frequency (ω0) of 159 kHz and a quality factor (Q) of 0.707. We achieved this by carefully selecting the passive element values: both C1 and C2 capacitors are set to 50 pF, and the transconductance (gm) ranges from 3.74 to 5.56 mS. The circuit operates with symmetrical power supplies of ±2.5 V.
BW, ω_0 and Q are expressed by:

$$\boldsymbol{BW = \frac{1}{RC_1}} \tag{4.4}$$

$$\boldsymbol{\omega_0 = \sqrt{\frac{g_m}{C_1 C_2 R}}} \tag{4.5}$$

$$\boldsymbol{Q = \sqrt{g_m R \frac{C_1}{C_2}}} \tag{4.6}$$

4.2 Sensitivity Analysis

Sensitivity analysis is a technique used to assess how the output of a model or system changes when there are variations in the input values.

Applying the standard interpretation of a function F(a)'s sensitivity regarding a parameter of interest a, that is,

$$\boldsymbol{S_a^{F(a)} = \frac{a}{F(a)} \frac{\partial F(a)}{\partial a}} \tag{4.7}$$

The sensitivities of ω_0, and Q of Bi-quad filters have been tabulated in Table 4.1. It may be noted from Table 4.1. that the sensitivities with respect to all passive components are found to be less than 1.

Table 4.1 Filters Sensitivity Analysis

Filter	Sensitivity
LPF	$S_R^{\omega_0} = S_{C1}^{\omega_0} = S_{C2}^{\omega_0} = -\frac{1}{2}$ $S_R^Q = S_{C1}^Q = S_{C2}^Q = -\frac{1}{2}$
HPF	$S_R^{\omega_0} = \frac{1}{2}, \quad S_{C1}^{\omega_0} = S_{C2}^{\omega_0} = -\frac{1}{2}$ $S_R^Q = S_{C1}^Q = S_{C2}^Q = -\frac{1}{2}$
BPF	$S_R^{\omega_0} = \frac{1}{2}, \quad S_{C1}^{\omega_0} = S_{C2}^{\omega_0} = -\frac{1}{2}$ $S_R^Q = 0, \quad S_{C1}^Q = S_{C2}^Q = -\frac{1}{2}$

CHAPTER 5
SIMULATION RESULTS

5.1 The CDTA's DC and AC properties as well as its AC frequency responses

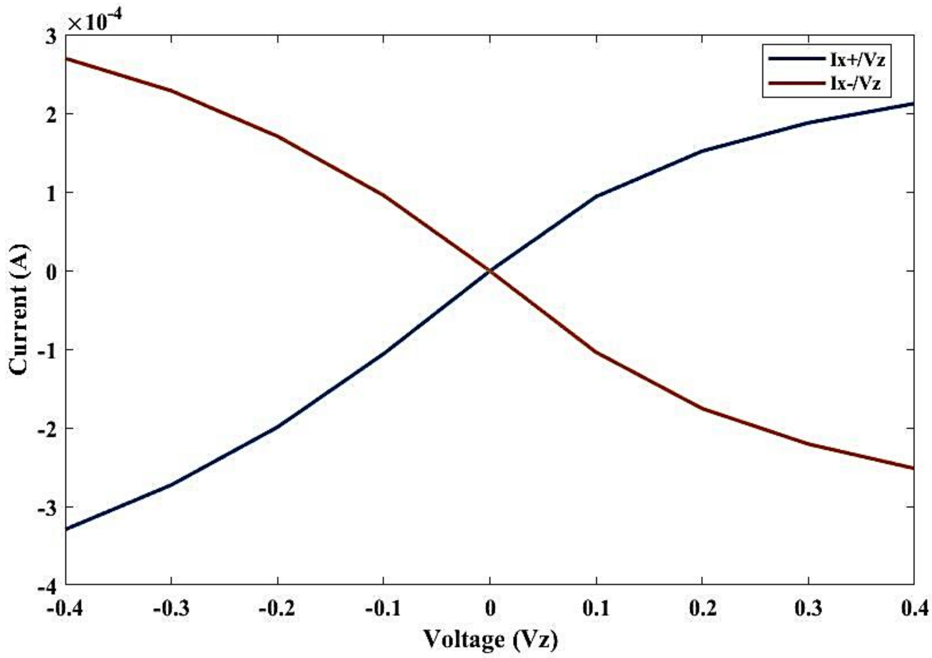


Fig.5.1 DC characteristics of CDTA

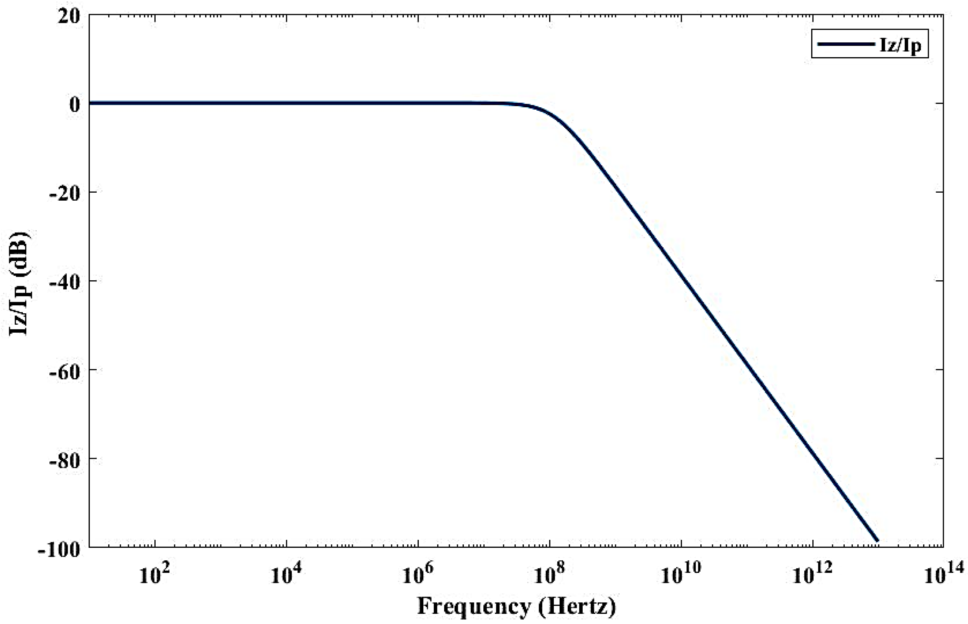


Fig.5.2 AC response (Iz/Ip) of CDTA

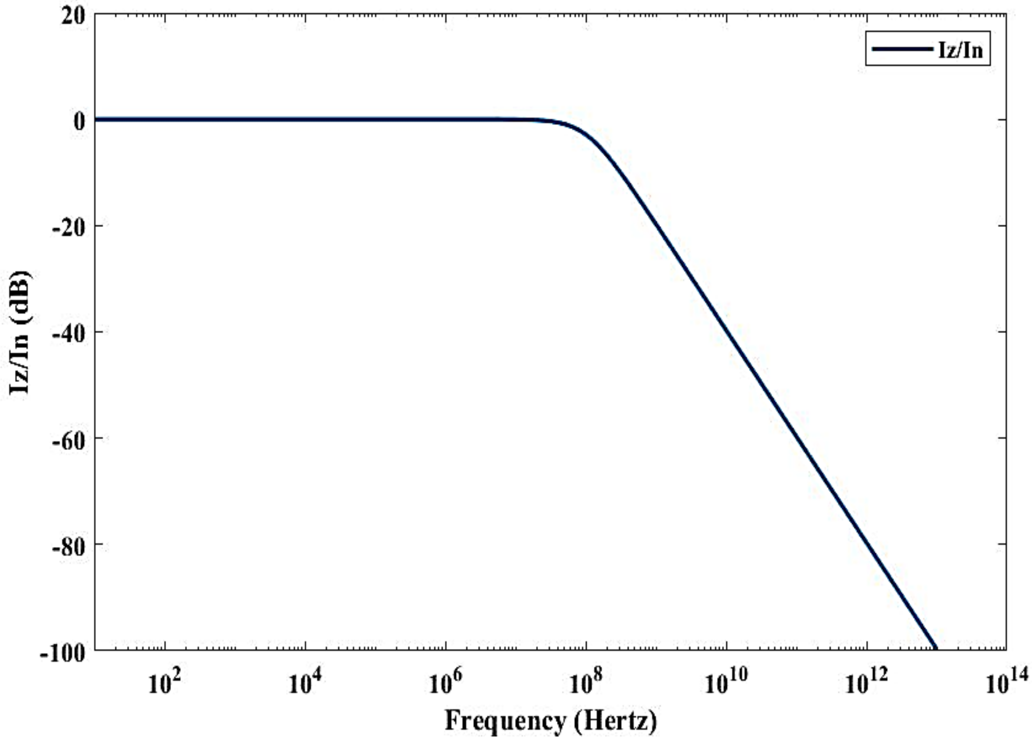


Fig.5.3 AC response (In/Ip) of CDTA

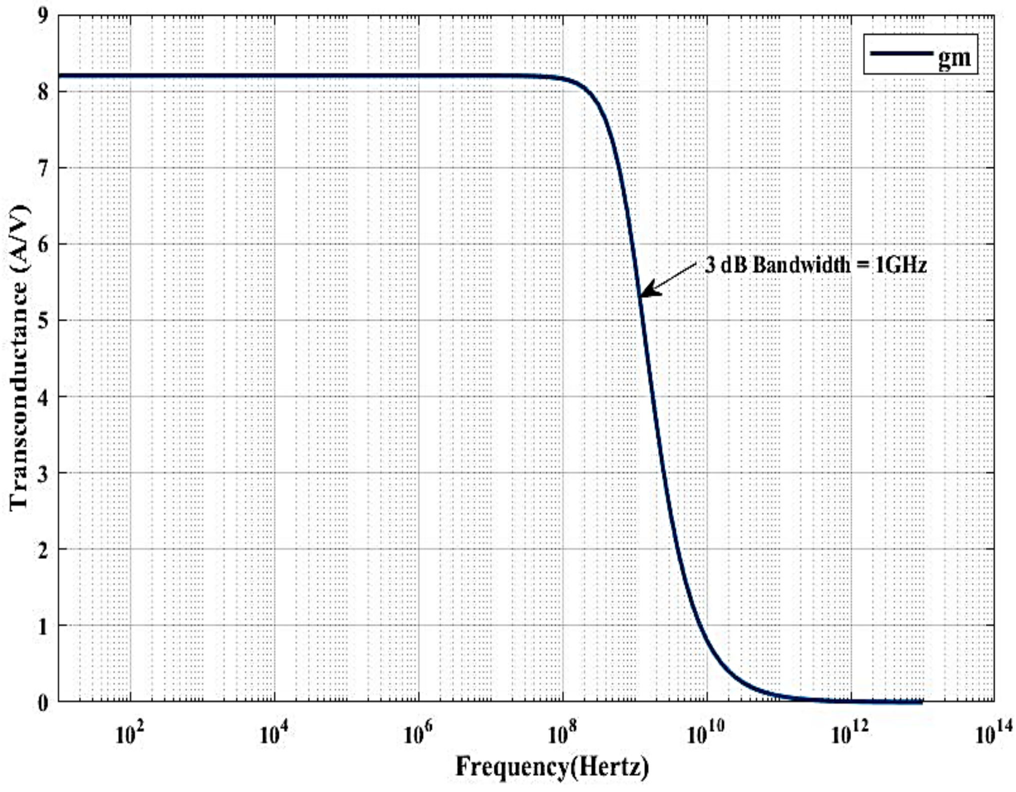
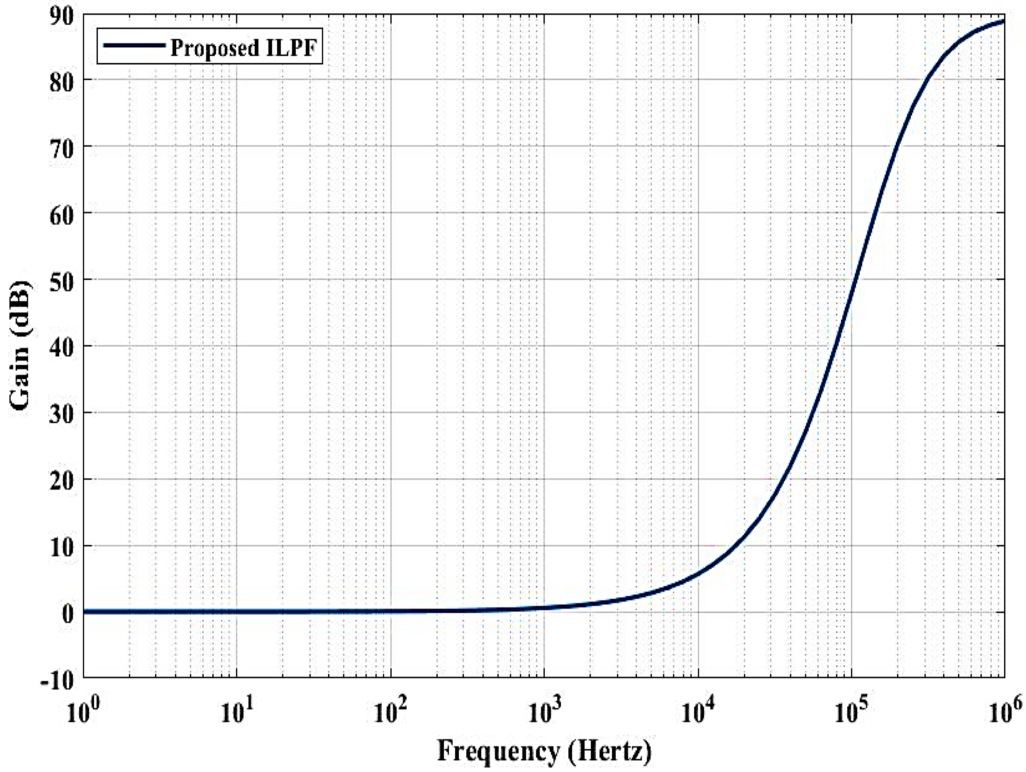
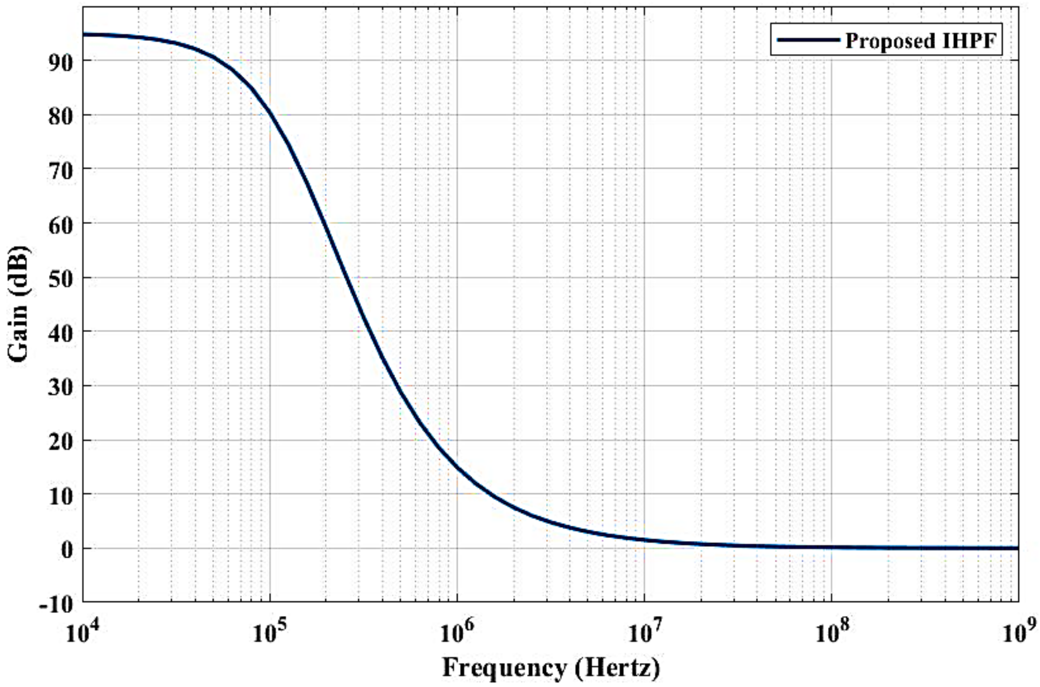


Fig. 5.4 Variation of transconductance gain (gm) with respect to frequency

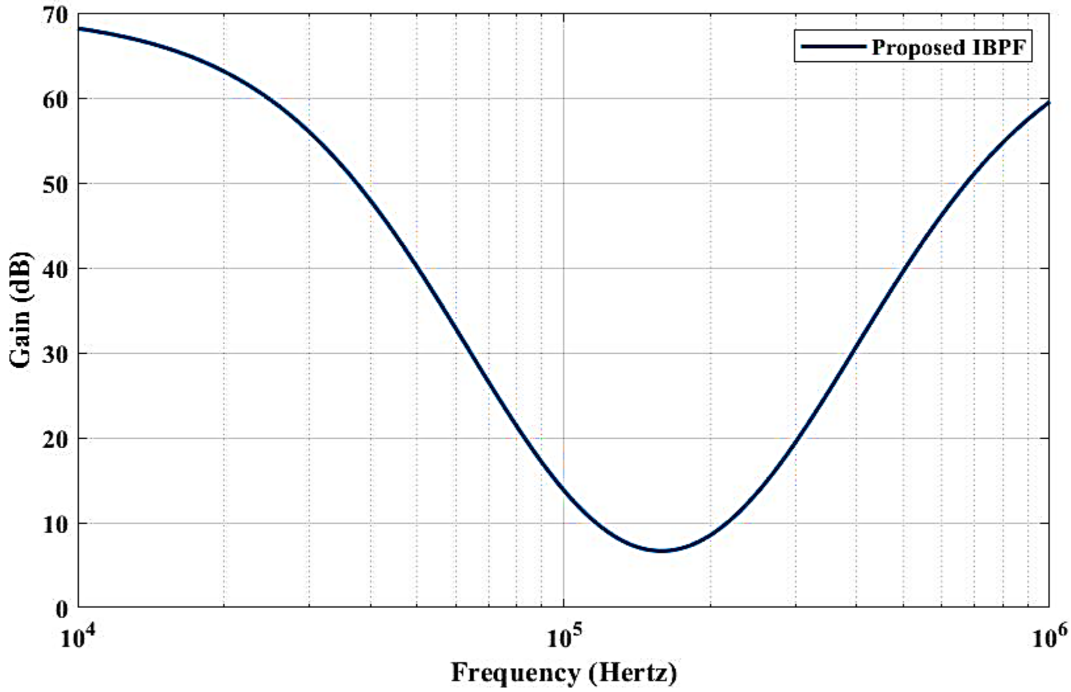
5.2 Frequency Response of Proposed Bi-quad Inverse Filters



(a)

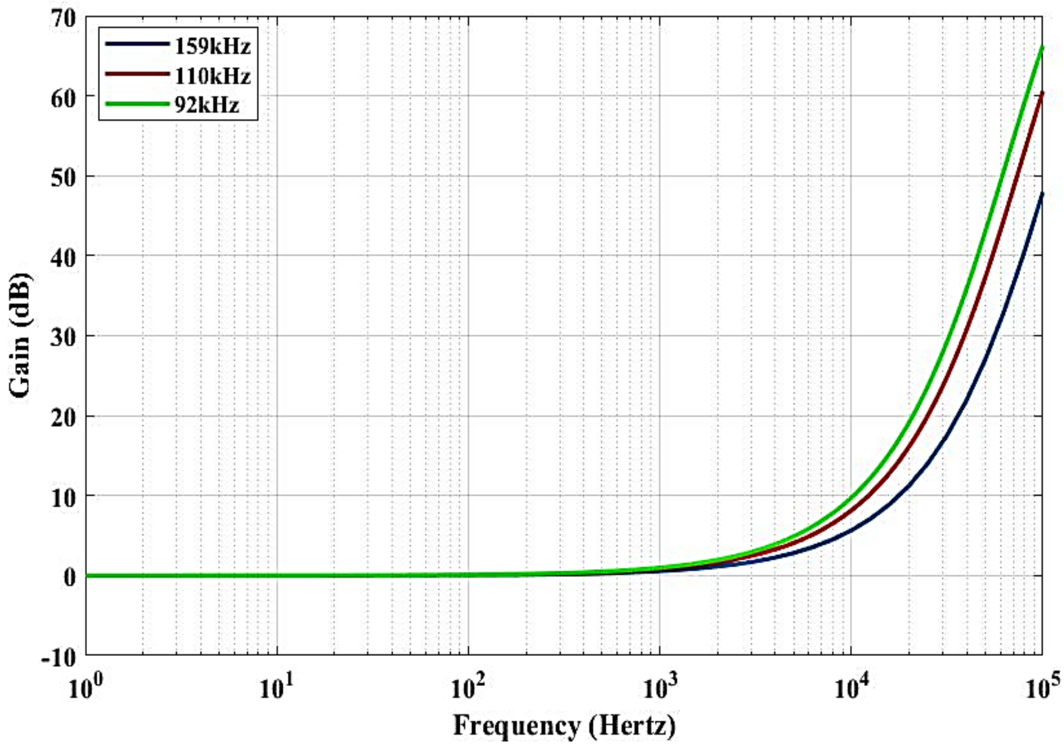


(b)

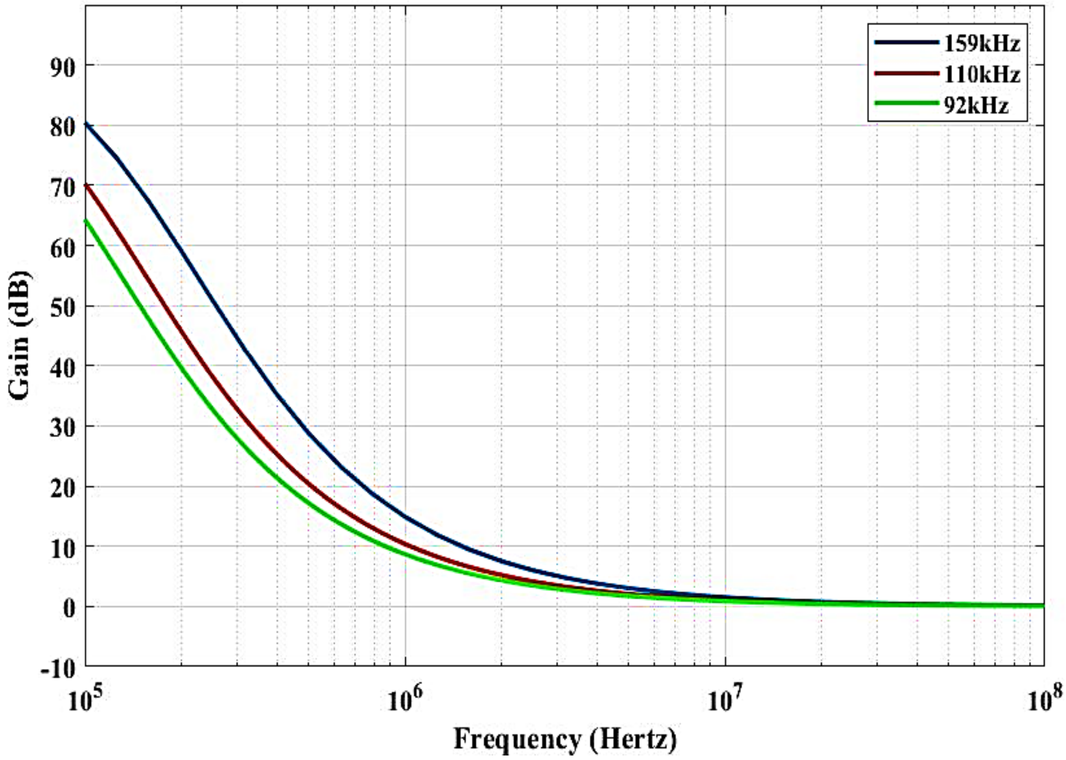


(c)

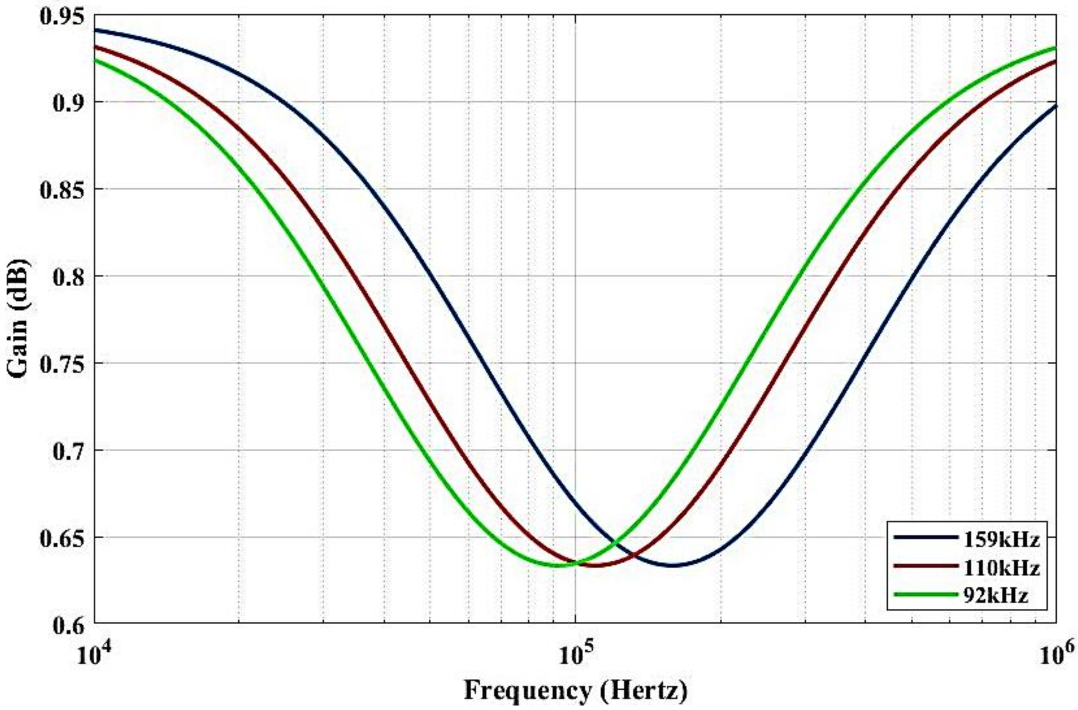
Fig.5.5 Frequency responses of (a) ILPF (b) IHPF (c) IBPF



(a)



(b)



(c)

Fig5.6 Tunability of cut-off frequency (a) ILPF (b) IHPF (c) IBPF

5.3 Layout Designs

Fig.5.7 Layout Design Of CDTA

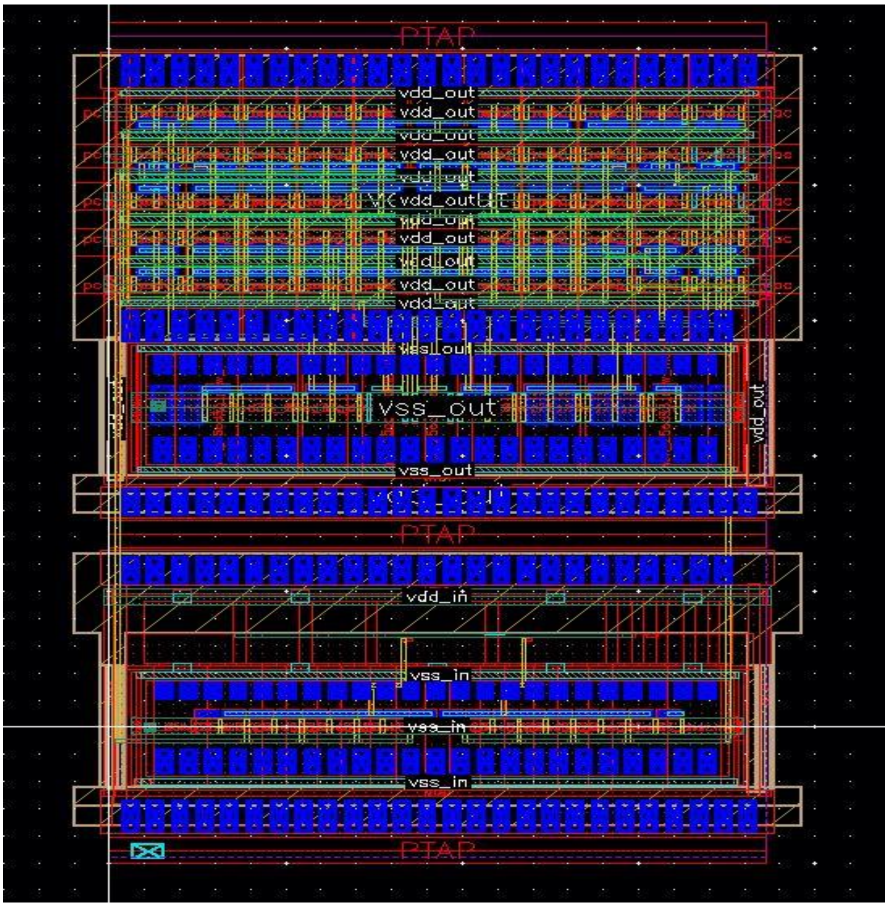


Fig.5.7 Layout Design of CDTA based Universal Bi-quad Inverse Filter

CHAPTER 5
CONCLUSION & FUTURE SCOPE

The future scope outlines potential areas for significant improvement in the capabilities and applicability of these universal bi-quad inverse filters using CDTA technology. By continuing research in these areas, researchers can pave the way for wider adoption of these filters in various signal processing applications.

Enhancing Performance:

- **Higher-Order Filters:** Future research should explore extending the design to higher-order filters for tackling more complex filtering tasks. These filters would have a more intricate structure than the current bi-quad design.
- **Improved Accuracy:** Minimizing errors caused by imperfections in CDTA circuits is crucial. Researchers should investigate techniques to achieve greater accuracy in the filter responses.
- **Wider Bandwidth:** Expanding the operational bandwidth of the filters would allow them to handle a broader range of signal frequencies. This would require further research into design methods.

Advanced Applications:

- **Switched-Capacitor Implementations:** Investigating the feasibility of implementing these filters using switched-capacitor circuits is necessary. This could potentially allow for integration into CMOS technology, making the filters more widely applicable.
- **Programmable Filters:** Developing programmable versions of these filters would enable them to dynamically adjust their characteristics based on real-time requirements. This would require significant design advancements.
- **Nonlinear Filtering Applications:** Exploring the potential application of these filters in nonlinear filtering tasks, such as harmonic distortion removal or edge detection in image processing, could open new avenues for their use.

Integration and Miniaturization:

- **On-Chip Integration:** Researchers should investigate the possibility of incorporating these filters directly onto integrated circuits. This would lead to more compact and efficient signal processing systems.
- **Reduced Power Consumption:** Minimizing the power consumption of these filters is essential for battery-powered applications. Research on low-power design techniques is needed.
- **Microfluidic Integration:** Exploring the potential for integrating these filters with microfluidic devices for lab-on-a-chip applications or bio signal processing holds promise for future advancements.

Research into alternative CDTA implementations using different materials or device structures could potentially achieve better performance or wider operating ranges. Exploring the suitability of emerging nano electronic devices for realizing these filters could lead to significant size reduction and improved performance. This would require investigation into the compatibility of these new materials with the filter design.

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