CHAPTER 1

Introduction

1.1 Introduction

Mixed-mode analog circuits are important in modern electronic systems because they can handle both current and voltage signals. These circuits provide considerable benefits by allowing easy integration of voltage-mode (VM) and current-mode (CM) circuits, which is essential for a variety of signal processing applications. Mixed-mode circuits have several uses, including telecommunications, biomedical engineering, and portable electronic devices, where flexibility and power efficiency are important.

Universal filters are critical components in analog signal processing, capable of executing filtering tasks such as low-pass (LP), high-pass (HP), band-pass (BP), band-stop (BS), and all-pass (AP). The ability to conduct these actions in several modes—VM, CM, TAM, and TIM—increases the filters' versatility and application. A universal filter that can work efficiently in various modes is crucial for developing advanced analog systems.

The development of operational transconductance amplifiers (OTAs) has made it possible the construction of mixed-mode filters. OTAs are known for their electrical tunability and simplicity of integration into a variety of circuit topologies. However, typical OTAs have problems in processing numerous signals at the same time, prompting the development of multiple-input multiple-output OTAs (MIMO-OTAs). MIMO-OTAs improve functionality by providing multiple inputs and outputs in both voltage and current modes.

The paper "58-nW 0.5-V Mixed-Mode Universal Filter Using Multiple-Input Multiple-Output OTAs" describes a new mixed-mode universal filter design that takes use of the capabilities of MIMO-OTA. This design focuses on ultra-low power consumption and low voltage operation to meet the rising need for energy-efficient and portable technology. The suggested filter may perform all typical filtering operations in several modes, giving significant flexibility and adaptability in a wide range of applications.

This design's key innovation is the use of the multiple-input MOS transistor technology (MI-MOST), which allows for the production of a single differential pair while consuming the least amount of power. The filter's inherent frequency and quality factor may be electrically adjusted, allowing for dynamic changes to meet specific application needs. Simulation findings utilizing TSMC 0.18µm CMOS technology show the design's practical feasibility, particularly for low-power, low-voltage applications.[1] Mixed-mode universal filters (TAM and TIM) may be readily coupled to create higher order filters and provide various filter transfer functions when built as integrated circuits (ICs). The open source literature has several mixed-mode universal filters using various active devices.[2],[3],[4] However, the filters do not have the full capability of a universal mixed-mode filter, which includes twenty transfer functions in a single circuit.[5]

1.1.1 Ciruit Diagram

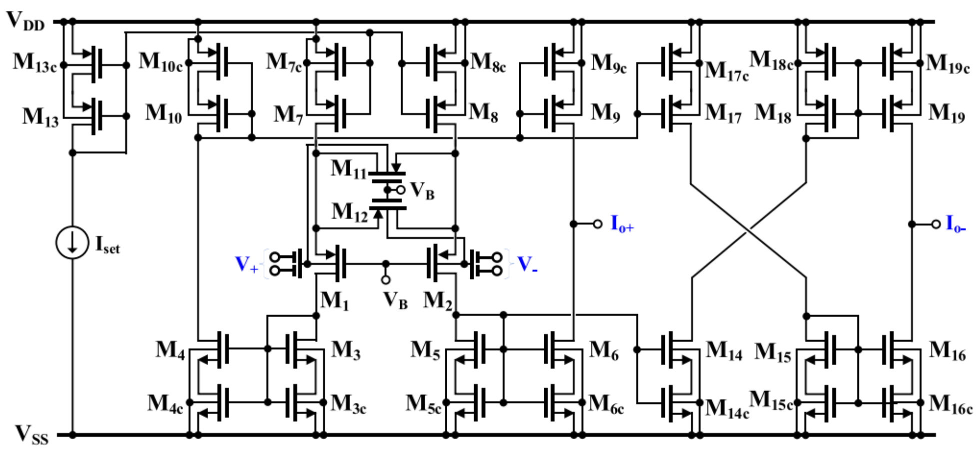

Figure 1.1: CMOS structure of the MIMO-OTA.

1.2 Motivation

The desire to reduce and mobility of electronic devices has resulted in an increased need for circuits that are not only multipurpose but also power efficient. Low power consumption is critical in applications such as portable biomedical devices, wearable electronics, and energy-harvesting sensors to ensure long-lasting battery life and dependable operation. Traditional analog filters, while useful in their intended applications, frequently fall short in terms of power economy and operational flexibility.

Mixed-mode circuits, which can handle both voltage and current signals, are a viable solution that combines the advantages of voltage-mode (VM) and current-mode (CM) operations. These circuits provide the adaptability required for complicated signal processing tasks, but they have historically experienced issues with power consumption and the ability to handle many input and output signals effectively.

MIMO-OTAs overcome these problems by providing greater capability through simultaneous signal processing. MIMO-OTAs are very useful for designing universal filters that can operate in a variety of modes (VM, CM, TAM, and TIM) and give a variety of filtering responses (low-pass, high-pass, band-pass, band-stop, and all-pass). However, using such powerful filters frequently leads in higher power consumption and complexity.

The aim of this research is to create a mixed-mode universal filter that takes use of MIMO-OTA capabilities while consuming very little power and operating at low voltage. The suggested design, which uses the multiple-input MOS transistor technology (MI-MOST), intends to use as little power as possible while maintaining functionality and performance. This method is especially useful in applications requiring high power efficiency, such as portable biomedical equipment and energy-harvesting sensors.

moreover, the ability to electrically alter the filter's natural frequency and quality factor is a key benefit, allowing for real-time modifications and adaptation to different signal processing needs. This functionality is critical in dynamic contexts where signal properties might vary, requiring a flexible and responsive filtering solution.

1.3 Objectives

The objective of the research is to build a low-voltage, low-power mixed-mode universal filter using multiple-input multiple-output operational transconductance amplifiers (MIMO-OTAs). These amplifiers can provide second-order low-pass, high-pass, band-pass, band-stop, and all-pass transfer functions in voltage-mode, current-mode, transadmittance-mode, and transimpedance-mode. Additionally, they have the ability to electronically tune the filter and control its natural frequency and quality factor orthogonally. The research will be validated through simulation utilizing TSMC 0.18µm CMOS technology in the Cadence Virtuoso environment, which includes Monte-Carlo analysis and process, voltage, and temperature corners.

1.4 Thesis Contribution

This thesis contributes significantly to the field of analog signal processing, namely in the design and implementation of low-power, mixed-mode universal filters. The key contribution is the creation of a mixed-mode universal filter with an ultra-low power consumption of 58 nW, making it ideal for portable and battery-powered applications. Furthermore, the filter is intended to perform successfully at a low supply voltage of 0.5 V, making it suitable for low-power and energy-constrained situations such as wearable electronics and biomedical equipment.

A key innovation in this study is the use of multiple-input multiple-output operational transconductance amplifiers (MIMO-OTAs), which allow the filter to process several signals at the same time, considerably increasing its flexibility and performance. The filter provides a wide range of filtering capabilities, including low-pass, high-pass, band-pass, band-stop, and all-pass, in several modes (voltage mode, current mode, transadmittance mode, and transimpedance mode). This adaptability allows the filter to be used for a wide range of signal processing tasks.

Another significant advance is the development of electronic tuning capabilities for the filter's natural frequency and quality factor. This capability enables real-time modifications and adaptation to changing signal characteristics, making the filter ideal for dynamic situations and applications that require responsive filtering solutions. Simulations utilizing Cadence Virtuoso and TSMC 0.18µm CMOS technology illustrate the design's practical feasibility. These simulations involve assessments under various process, voltage, and temperature (PVT) settings, ensuring that the filter design is resilient and reliable.

The thesis provides a filter design that achieves ultra-low power consumption and low voltage operation, making it ideal for portable biomedical equipment and energy-harvesting sensors. Furthermore, the design reduces circuit complexity and size while maintaining performance, which is critical for incorporating the filter into compact, portable devices and lowering manufacturing costs.

1.5 Thesis Organization

The thesis is thoroughly organized to lead the reader through the research process, from fundamental principles to comprehensive implementation and validation of the suggested design. It starts with the chapter 1, which provides an outline of the study issue and emphasizes the significance of mixed-mode universal filters in current electronic systems. This chapter also discusses the rationale for the study, the precise aims, and a brief explanation of the thesis framework, providing the reader a sense of what to expect.

Following the chapter 1, In chapter 2 looks into existing research on mixed-mode universal filters and MIMO-OTAs. This detailed study not only highlights key advances in the area, but also reveals gaps and limits in present technology, demonstrating the necessity for the suggested research. By reviewing past publications, this chapter lays the groundwork for understanding the study's context and significance.

In chapter 3 describes the theoretical foundation and design ideas that underpin the proposed filter. It describes the design decisions, the usage of MIMO-OTAs, and the methods used to achieve ultra-low power consumption and low voltage operation. This part is critical because it gives a step-by-step explanation of the design process, allowing the reader to follow and grasp the technical complexities involved.

The Design and Implementation part of the thesis describes the practical features of the suggested filter design. This covers the circuit schematics, simulation environment, and design-specific parameters. The chapter discusses how the design objectives are realized, as well as the practical issues and challenges that arise during implementation.

In chapter 4 ,the simulation results and discussion is presented.The findings are reviewed and compared to current solutions to show the benefits and efficiency of the new design.

The thesis finishes with the chapter 5, which summarizes the research's significant results and contributions. It evaluates progress in relation to the initial goals and examines the consequences of the findings. This chapter also identifies prospective topics for further study, suggesting how the work should be broadened or improved in following research.

CHAPTER 2

Literature Survey

2.1 Literature Survey

The field of mixed-mode universal filters, particularly those that use multiple-input multiple-output operational transconductance amplifiers (MIMO-OTAs), has advanced significantly in recent years. These filters are essential in applications that need effective processing of both voltage-mode (VM) and current-mode (CM) signals, such as biomedical devices, portable electronics, and sensor interfaces.

2.1.1 Importance

Mixed-mode circuits can handle signals in both current and voltage states, making them useful in a variety of applications. Universal filters in mixed-mode setups can provide several filter responses (low-pass, high-pass, band-pass, band-stop, and all-pass) in various modes (VM, CM, transadmittance mode (TAM), and transimpedance mode (TIM). Their versatility makes them extremely helpful in integrated circuit design.

2.2 Research

2.2.1 Current Conveyors and Feedback Amplifiers

Early designs of mixed-mode filters frequently included current conveyors and feedback amplifiers. However, these systems lacked electronic tuning capabilities and used passive component matching, limiting their versatility and integration possibilities.

2.2.2 Operational Transconductance Amplifiers (OTAs)

OTAs have gained popularity in recent designs due to their ability to tune electronically and their simplicity in circuit construction. OTA-based filters do not require resistors, making them ideal for monolithic integration. However, many contemporary OTA-based filters do not provide the entire range of twenty transfer functions (five filter types in four modes) and are not designed for low-voltage, low-power environments.

2.2.3 Active Device Innovations

Recent improvements have resulted in the introduction of novel active devices such as the voltage differencing buffered amplifier (VDBA), voltage differencing gain amplifier (VDGA), and differential difference transconductance amplifier. While these devices have enhanced the performance and usefulness of mixed-mode filters, they frequently run at higher supply voltages, which is unsuitable for ultra-low-power applications.

2.2.4 Multiple-Input Active Analog Building Blocks

Differential difference amplifiers (DDAs) and differential difference current conveyors (DDCCs) have been investigated to minimize the number of application blocks and power consumption. These blocks handle differential and difference signals well, but their complicated internal structures increase power consumption and chip space.

CHAPTER 3

Methodology

3.1 MIMO

The design and usage of a mixed-mode universal filter which allows the use of a multiple-input multiple-output operational transconductance amplifier (MIMO-OTA). The multiple-input MOS transistor technology (MI-MOST) is used in the design of the MIMO-OTA, allowing for a single differential pair and thus reducing power consumption. Multiple input and output formats, including voltage and current modes, are supported by this amplifier. Twenty distinct transfer functions, including low-pass, high-pass, band-pass, band-stop, and all-pass filters in both inverting and non-inverting configurations, may be achieved using the universal filter using the MIMO-OTA in a single circuit. Because the filter's related frequency and quality factor may be electrically adjusted, it can be used in low-voltage and low-power applications like energy-harvesting sensors and portable biomedical equipment. TSMC 0.18µm CMOS technology was used for modeling the design, proving its practicality in modern electronic systems.

3.1.1 Working

An operational transconductance amplifier (MIMO-OTA) with multiple inputs and multiple outputs is essential to the construction and functioning of a mixed-mode universal filter. By using a single differential pair, this MIMO-OTA maintains low power consumption with the multiple-input MOS transistor technology (MI-MOST). The MIMO-OTA offers versatility in mixed-mode signal processing by having the ability to handle signals in both voltage and current forms.

Using the MIMO-OTA, the universal filter may generate a range of transfer functions, including as band-pass, band-stop, low-pass, high-pass, and all-pass.

With four modes to choose from—voltage-mode (VM), current-mode (CM), transadmittance-mode (TAM), and transimpedance-mode (TIM)—these transfer functions are highly versatile. In addition, the filter provides electronic tuning, which is essential for adjusting to various signal processing requirements, and it allows orthogonal control of its natural frequency and quality factor.

This design is especially useful for low-frequency applications that need limited voltage and power, including energy-harvesting sensors and portable medical equipment. The MIMO-OTA-based filter uses just 58 nW for a 4 nA setting current and runs at a supply voltage of 0.5 V. Empirical findings utilizing TSMC 0.18µm CMOS technology validate the practicability and efficacy of this approach.

3.1.2 Ciruit Diagram

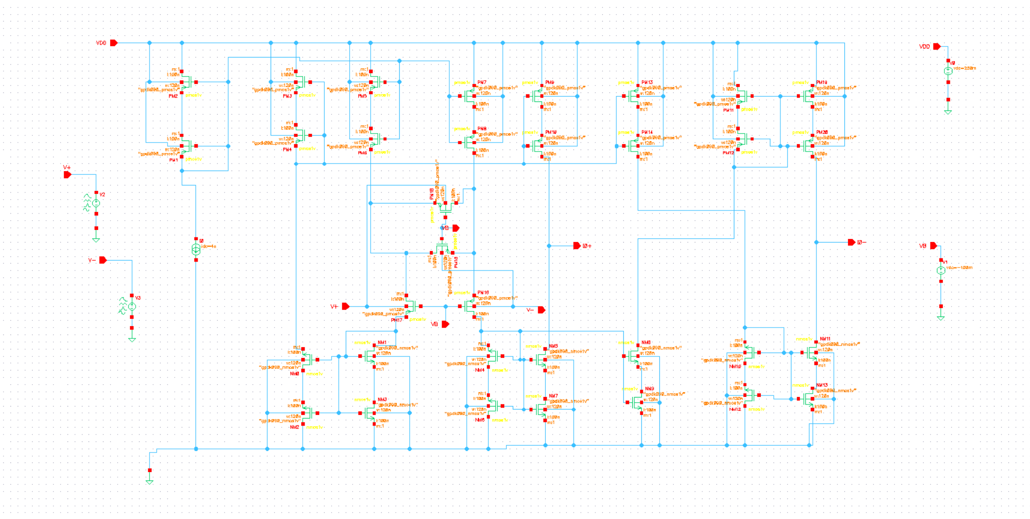

Figure 3.1: CMOS structure of the MIMO-OTA.

3.2 Operational Amplifier Design

An operational amplifier (op amp) is a DC-coupled electronic voltage amplifier with a differential input, a single-ended output, and an extremely high gain. By using negative feedback, an op amp circuit's characteristics can be determined by external components and have little dependence on temperature coefficients or engineering tolerance in the op amp itself. This flexibility has made the op amp a popular building block in analog circuits. Today, op amps are used widely in consumer, industrial, and scientific electronics. The op amp is one type of differential amplifier. Other differential amplifier types include the fully differential amplifier, the instrumentation amplifier, the isolation amplifier, and the negative-feedback amplifier.

3.2.1 Operation

The amplifier's differential inputs consist of a non-inverting input (+) with voltage V_+ and an inverting input (-) with voltage V_-; ideally, the op amp amplifies only the difference in voltage between the two, which is called the differential input voltage. The output voltage of the op amp V_{out} is given by the equation:

$$V_{\text{out}} = A_{\text{OL}}(V_+ - V_-) \tag{3.1}$$

where A_{OL} is the open-loop gain of the amplifier.

3.2.2 Circuit Diagram

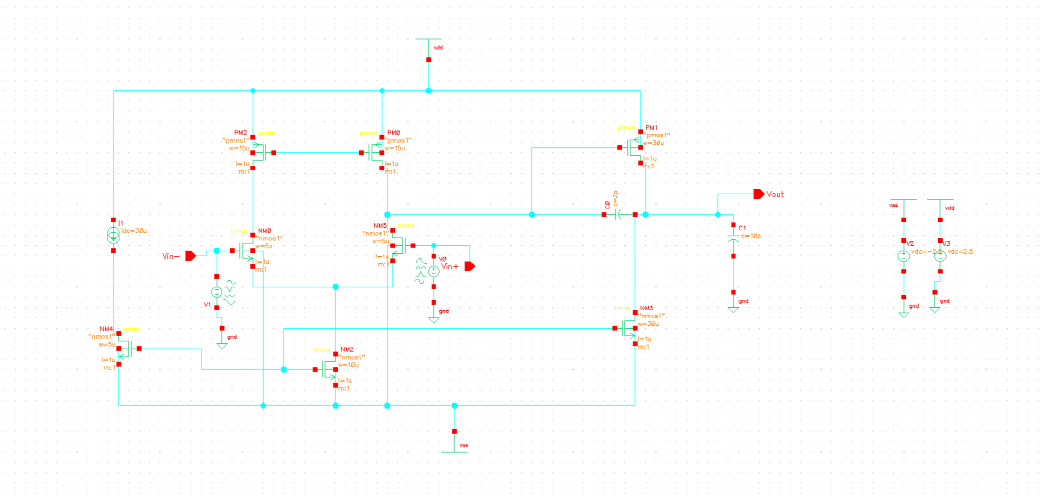

Figure 3.2: OP-Amp Schematic

3.2.3 Transistor Sizing for Op Amp

Designing and sizing transistors for an operational amplifier involves several steps to ensure proper performance, including gain, bandwidth, power consumption, and noise characteristics.

3.2.4 Differential Pair Input

1. Select Bias Current (I_{bias}): - Assume $I_{\text{bias}} = 10\mu A$.
2. Determine g_m: - For a typical op amp, g_m might be 1mS.
3. Calculate V_{ov}: - Assuming $V_{ov} = 200\text{mV}$, then:

$$g_m = \frac{I_{\text{bias}}}{V_{ov}} = \frac{10\mu A}{200\text{mV}} = 0.05\text{mS}$$

4. Select W/L Ratio: - Using the process transconductance parameter $\mu C_{ox} = 100\mu A/V^2$:

$$\frac{W}{L} = \frac{2I_{\text{bias}}}{\mu C_{ox}(V_{ov})^2} = \frac{2 \times 10\mu A}{100\mu A/V^2 \times (0.2V)^2} = 2.5$$

3.2.5 Current Mirror

1. Select Reference Current: - Assume $I_{\text{ref}} = 10\mu A$.
2. Match the Current Mirror: - For a simple 1:1 mirror, $\left(\frac{W}{L}\right)_{\text{out}} = \left(\frac{W}{L}\right)_{\text{ref}}$.

3.2.6 Gain Stage

1. Select Load Resistance R_{out}: - Assume $R_{\text{out}} = 20\text{k}\Omega$.
2. Calculate Gain: - $A_v = g_m R_{\text{out}} = 0.05\text{mS} \times 20\text{k}\Omega = 1000$.
3. Size Transistors: - Ensure transistors are sized to handle the load and meet the gain requirement.

3.2.7 Compensation

Add compensation capacitors to ensure stability. Miller compensation is often used in two-stage op amps. Size the compensation capacitor C_c based on the phase margin requirement:

$$f_c = \frac{1}{2\pi R_1 C_c}$$

3.3 Current Mirror

A current mirror is a circuit designed to copy a current through one active device by controlling the current in another active device of a circuit, keeping the output current constant regardless of loading. The current being "copied" can be, and sometimes is, a varying signal current. Conceptually, an ideal current mirror is simply an ideal inverting current amplifier that reverses the current direction as well, or it could consist of a current-controlled current source (CCCS). The current mirror is used to provide bias currents and active loads to circuits. It can also be used to model a more realistic current source (since ideal current sources do not exist).

The circuit topology covered here is one that appears in many monolithic ICs. It is a Widlar mirror without an emitter degeneration resistor in the follower (output) transistor. This topology can only be done in an IC, as the matching has to be extremely close and cannot be achieved with discretes.

Another topology is the Wilson current mirror. The Wilson mirror solves the Early effect voltage problem in this design.

Current mirrors are applied in both analog and mixed VLSI circuits.

3.3.1 Mirror Characteristics

A current mirror is a fundamental building block in analog integrated circuits. It is used to copy (mirror) the current flowing in one active device (transistor) into another, ensuring a constant current source or sink. In this document, we will design a simple NMOS current mirror and determine the appropriate width-to-length (W/L) ratios for the transistors.

There are three main specifications that characterize a current mirror. The first is the transfer ratio (in the case of a current amplifier) or the output current magnitude (in the case of a constant current source). The second is its AC output resistance, which determines how much the output current varies with the voltage applied to the mirror. The third specification is the minimum voltage drop across the output part of the mirror necessary to make it work properly. This minimum voltage is dictated by the need to keep the output transistor of the mirror in active mode. The range of voltages where the mirror works is called the compliance range and the voltage marking the boundary between good and bad behavior is called the compliance voltage. There are also a number of secondary performance issues with mirrors, for example, temperature stability.

The basic current mirror operation involves a reference current source and one or more output transistors mirroring the reference current. Each stage introduces additional complexity to improve performance metrics such as matching accuracy, output impedance, or compliance voltage range.

3.3.2 Circuit Diagram

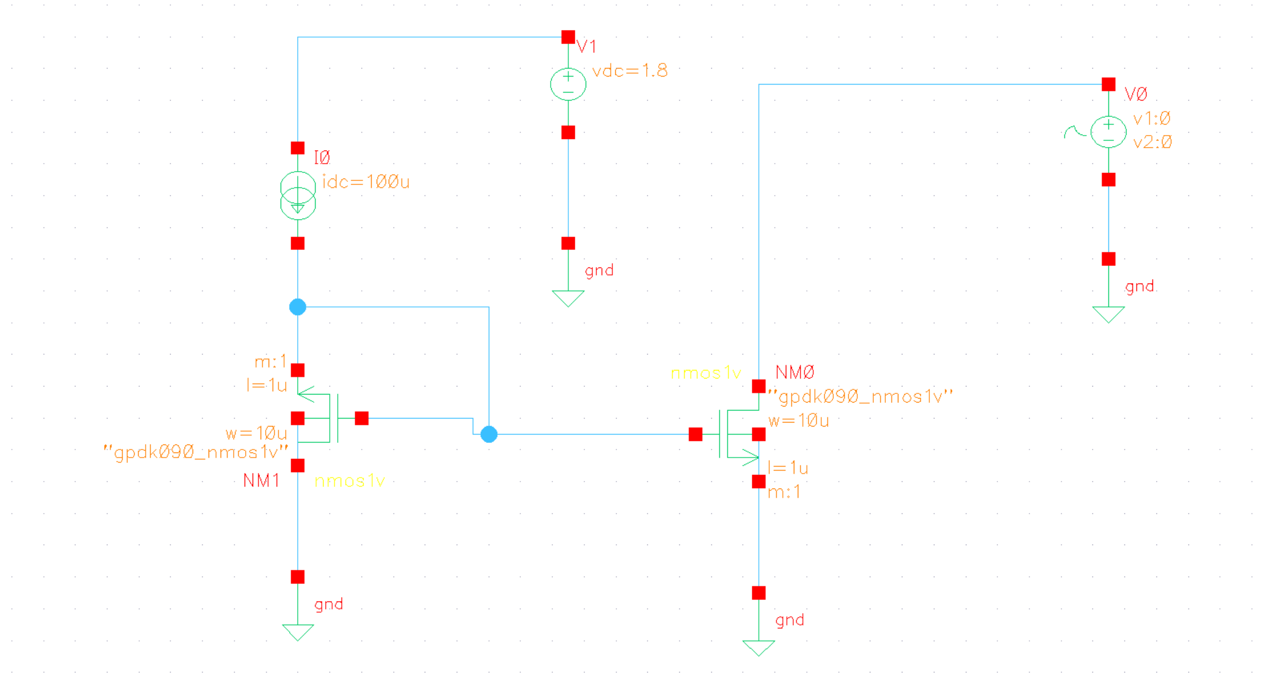

Figure 3.3: Current Mirror

3.3.3 Single-Stage Current Mirror

A single-stage current mirror consists of a reference transistor and an output transistor. The reference current flows through the reference transistor, and the output transistor mirrors this current. The output current is ideally equal to the reference current, scaled by the ratio of the output transistor's width-to-length (W/L) ratio to the reference transistor's W/L ratio.

3.3.4 Multi-Stage Current Mirror

In a multi-stage current mirror, multiple current mirror stages are cascaded to achieve improved performance. Each stage typically consists of a reference transistor and an output transistor. The output transistor of each stage mirrors the current set by the previous stage. This cascading improves precision and linearity while also increasing the output impedance.

3.4 Design Procedure

3.4.1 Define Specifications

Specify the design requirements including:

- Reference current (I_{ref}),
- Number of stages,
- Supply voltage (V_{DD}),
- Technology parameters (threshold voltage, mobility, etc.).

3.4.2 Calculate W/L Ratios

For each stage in the current mirror:

- Size the reference transistor for the desired I_{ref},
- Determine the output transistor's W/L ratio based on the desired mirroring ratio and technology parameters.

3.4.3 Cascade Stages

Connect the output transistor of each stage to the reference transistor of the next stage. Ensure proper connectivity to maintain current mirroring across all stages.

3.4.4 Verify Design

Simulate the multi-stage current mirror using SPICE or a similar tool to verify:

- Current mirroring accuracy,
- Output impedance,
- Compliance voltage range.

Iteratively adjust W/L ratios and stage configurations to meet design specifications.

3.5 Theory

A basic NMOS current mirror consists of two NMOS transistors, M_1 and M_2. The drain current of M_1 is mirrored to M_2 due to the gate-source voltage V_{GS} being equal for both transistors.

The drain current I_D for an NMOS transistor in saturation is given by:

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{th})^2(1 + \lambda V_{DS}), \tag{3.2}$$

where:

- μ_n is the electron mobility,
- C_{ox} is the oxide capacitance per unit area,
- W/L is the width-to-length ratio of the transistor,
- V_{GS} is the gate-source voltage,
- V_{th} is the threshold voltage,

- λ is the channel length modulation parameter,
- V_{DS} is the drain-source voltage.

For simplicity, assuming $\lambda \approx 0$ (ignoring channel length modulation), the current mirror relationship becomes:

$$I_{D1} = I_{D2}. \tag{3.3}$$

If M_1 and M_2 are identical, the current mirrored will be the same. If they have different W/L ratios, the mirrored current scales proportionally:

$$I_{D2} = I_{D1} \frac{(W/L)_2}{(W/L)_1}. \tag{3.4}$$

3.6 Design Procedure

3.6.1 Define Specifications

Assume we need to design a current mirror with:

- Reference current, $I_{ref} = 10\mu A$,
- Supply voltage, $V_{DD} = 1V$,
- Threshold voltage, $V_{th} = 0.3V$,
- Mobility, $\mu_n C_{ox} = 200\mu A/V^2$.

3.6.2 Calculate W/L for M_1 and M_2

For transistor M_1:

$$I_{D1} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2. \tag{3.5}$$

Rearranging for W/L:

$$\frac{W}{L} = \frac{2I_{ref}}{\mu_n C_{ox} (V_{GS} - V_{th})^2}. \tag{3.6}$$

Assuming $V_{GS} = V_{DD} - V_{DSsat} \approx 0.7V$:

$$\frac{W}{L} = \frac{2 \times 10\mu A}{200\mu A/V^2 \times (0.7V - 0.3V)^2} = \frac{20\mu A}{200\mu A/V^2 \times 0.16V^2} = \frac{20}{32} = 0.625. \quad (3.7)$$

For transistor M_2 to mirror the same current, we set:

$$\left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_1 = 0.625. \quad (3.8)$$

CHAPTER 4

Results and Discussion

4.1 Results

4.1.1 Waveform of Transient Response of MIMO OTA

A sine wave input to a Multiple Input Multiple Output (MIMO) Operational Transconductance Amplifier (OTA) results in a corresponding sine wave output, which may be altered in amplitude, phase, and potentially distorted based on the amplifier's characteristics and circuit design.

Key Aspects of Input and Output Behavior:

- **Amplitude Gain:** The MIMO OTA scales the amplitude of the input sine wave by its gain factor to produce the output sine wave.
- **Phase Shift:** The output sine wave may exhibit a phase shift relative to the input sine wave due to internal phase characteristics of the OTA.
- **Distortion:** Non-linearities within the OTA can introduce distortion, typically observed as harmonic distortion, where additional frequency components (harmonics) appear in the output signal.
- **Frequency Response:** The OTA's frequency response affects how it processes different frequencies within the input sine wave.

Graphical Representation

- **X-Axis:** Time (for both input and output waveforms).
- **Y-Axis:** Amplitude of the sine wave (in volts or millivolts).

The input and output sine waves can be graphed together to visualize their amplitude, phase relationship, and any distortion present in the output signal.

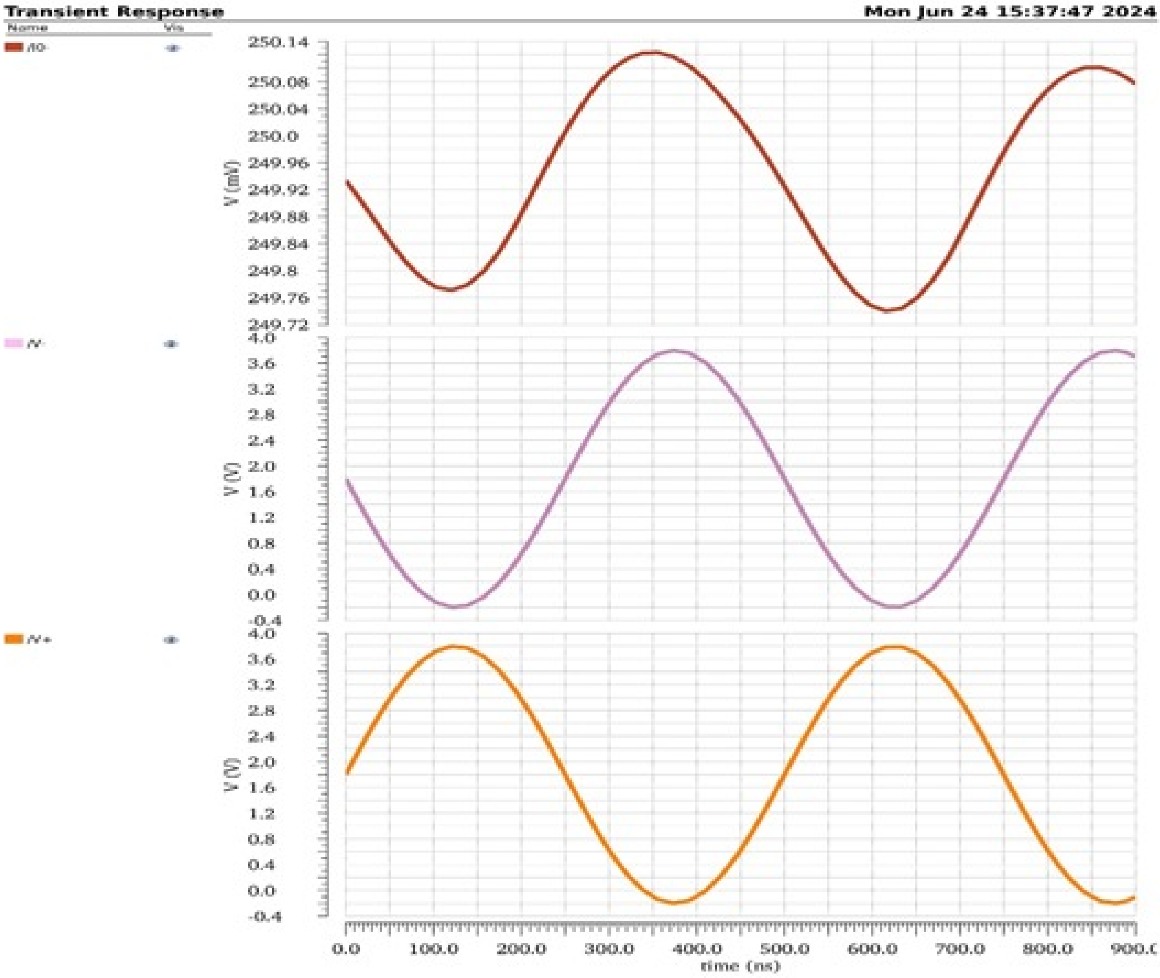

Figure 4.1: Transient Response of MIMO OTA

4.1.2 Waveform of Gain & Phase Margin of OP-Amp

Gain Margin

1. **Definition:** Gain margin measures the amount by which the open-loop gain of an amplifier can be reduced before the system becomes unstable and starts to oscillate.

2. **Bode Plot Representation:** In a Bode plot, gain margin is represented as the amount of gain reduction (in dB) required to bring the phase shift to -180 degrees, where the system oscillates.

3. **Stability Indicator:** A higher gain margin indicates greater stability against oscillations in feedback systems. It ensures that the amplifier can tolerate variations in gain without becoming unstable.

4. **Calculation:** Gain margin can be calculated from the open-loop fre-

quency response of the OP-amp. It is typically determined at the frequency where the phase shift is -180 degrees.

5. **Design Considerations:** Designing with sufficient gain margin ensures robustness against component variations, temperature changes, and other environmental factors that can affect amplifier performance.

Phase Margin

1. **Definition:** Phase margin is the amount of additional phase lag (in degrees) that can be tolerated in a feedback system before the system becomes unstable.

2. **Bode Plot Representation:** In a Bode plot, phase margin is the amount of phase shift (in degrees) at the frequency where the gain is unity (0 dB). It determines how far the phase response is from instability.

3. **Stability Indicator:** A larger phase margin indicates greater stability of the OP-amp in feedback loops. It ensures that the amplifier can handle phase shifts without causing oscillations.

4. **Calculation:** Phase margin is calculated as the difference between the phase shift at unity gain and -180 degrees. It provides insight into the stability of the feedback system.

5. **Design Considerations:** Designing with adequate phase margin is crucial for ensuring stable operation of the OP-amp in various applications, including filters, oscillators, and control systems. Gain margin and phase margin are critical parameters in the design and analysis of Operational Amplifiers (OP-Amps), influencing their stability and performance in electronic circuits.

   Both gain margin and phase margin are calculated and analyzed using Bode plots, which illustrate the gain and phase responses of the OP-Amp over a range of frequencies. These plots provide engineers with valuable insights into the amplifier's behavior, aiding in the optimization of circuit designs to achieve desired performance characteristics. By carefully considering gain and phase margins during the design phase, engineers can ensure the reliability, stability, and functionality of OP-Amp circuits in diverse applications, from audio amplifiers to high-frequency communication systems.

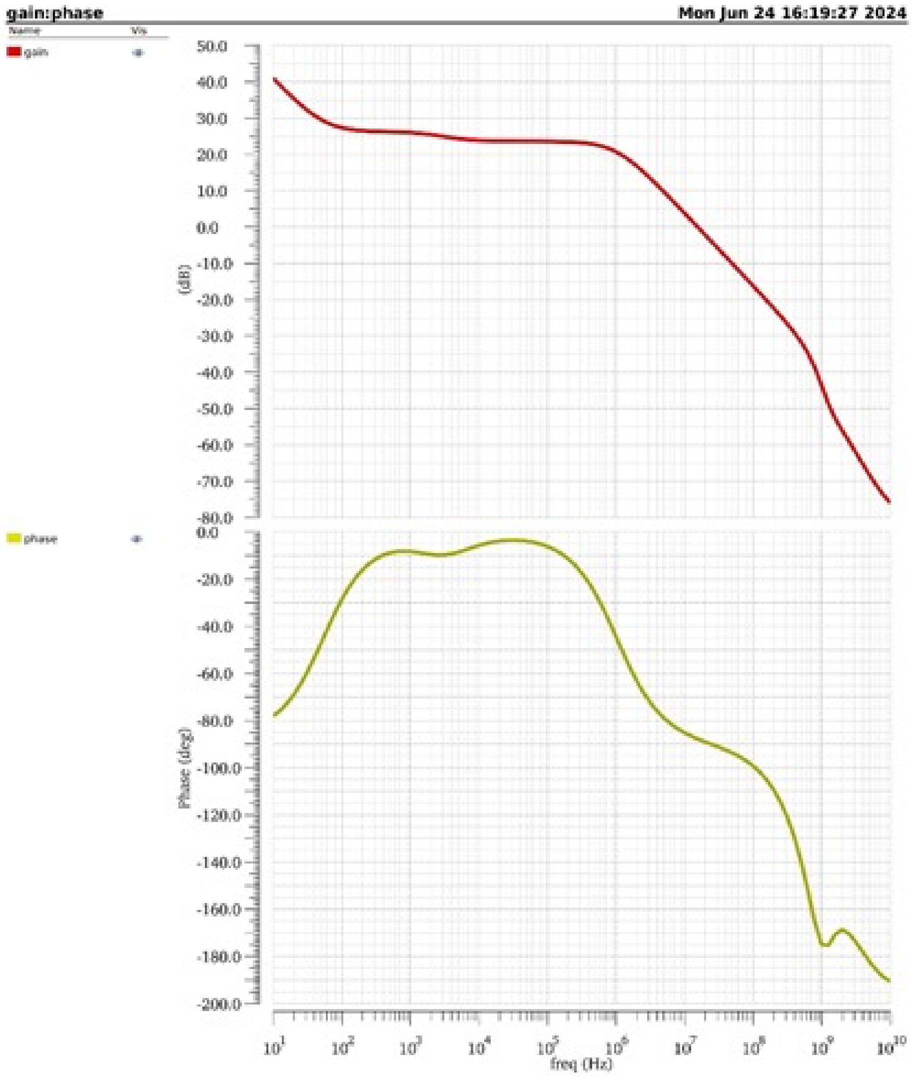

Figure 4.2: Gain Phase Margin of OP-Amp

4.1.3 Waveform of Frequency Response of OP-Amp

The frequency response of an operational amplifier (op-amp) describes how the gain and phase of the op-amp change with frequency. This is crucial for understanding the behavior of op-amp-based circuits in various applications, such as amplifiers, filters, and oscillators. Here is a brief description of the typical waveforms and key characteristics observed in the frequency response of an op-amp:

- **Gain vs. Frequency Response:** The gain vs. frequency response plot shows how the magnitude of the op-amp's gain varies with frequency.
- **Graph Description:**
  - X-Axis (Frequency): Typically plotted on a logarithmic scale, representing a wide range of frequencies from low to high.
  - Y-Axis (Gain): Usually in decibels (dB).
- **Key Characteristics:**
  1. Low-Frequency Region:
     - At low frequencies, the op-amp exhibits a constant gain known as the open-loop gain.
     - The gain is very high, often around 100,000 to 1,000,000 (100 dB to 120 dB). .
  2. Mid-Frequency Region:
     - As frequency increases, the gain begins to decrease.
     - This drop-off typically starts at a point called the corner frequency or cutoff frequency.
  3. High-Frequency Region:
     - Beyond the cutoff frequency, the gain continues to roll off at a rate of -20 dB/decade.
     - This is due to the internal compensation of the op-amp, designed to ensure stability.
  4. Unity Gain Frequency (Gain-Bandwidth Product):
     - The frequency at which the gain drops to 1 (0 dB).
     - This is a key specification for op-amps and determines the bandwidth over which the op-amp can operate with unity gain.

The frequency response of an op-amp is characterized by its gain and phase shift as functions of frequency. At low frequencies, the op-amp exhibits high gain with minimal phase shift, while at higher frequencies, the gain decreases, and the phase shift increases. Understanding these characteristics is crucial for designing stable and efficient op-amp circuits. The gain-bandwidth product and phase margin are key parameters derived from these plots that influence the performance and stability of the op-amp in practical applications.

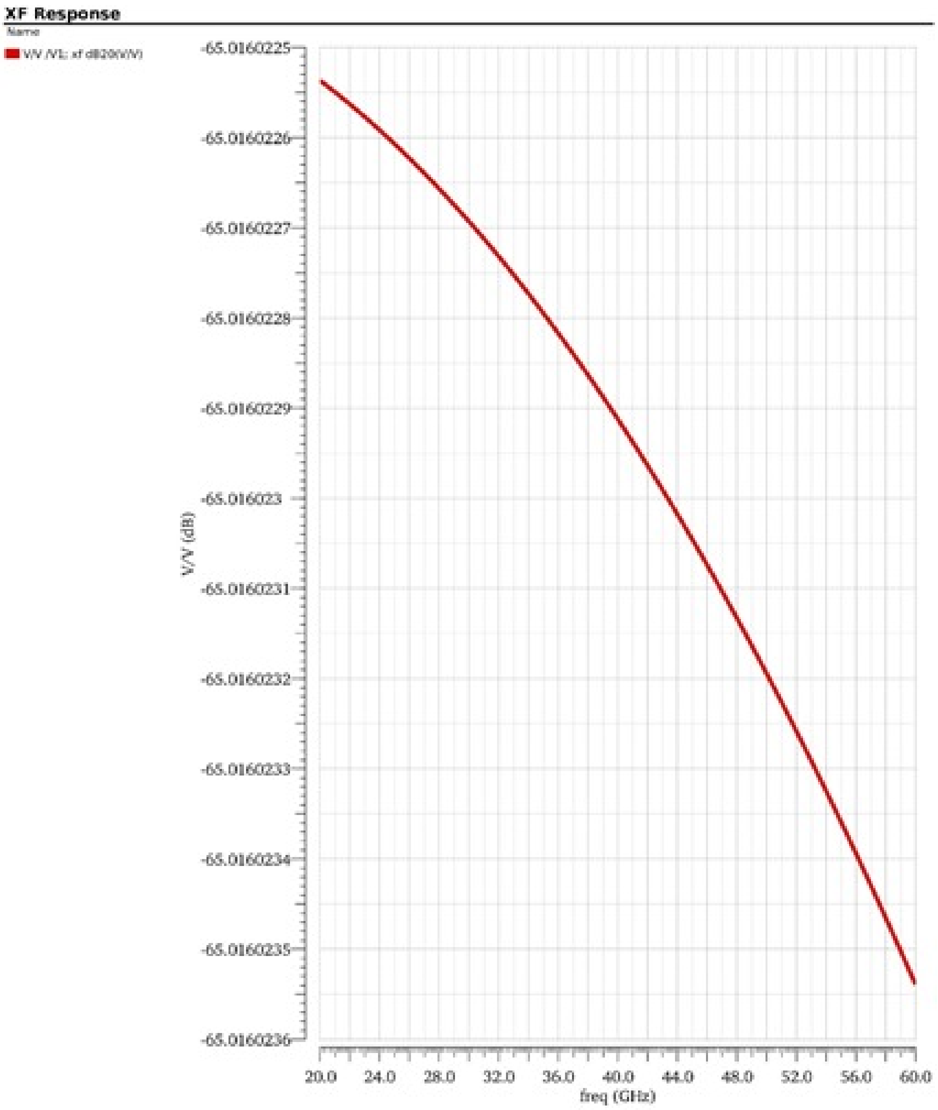

Figure 4.3: Frequency Response of OP-Amp

4.1.4 Waveform of Gain (dB) of OP-Amp

The waveform of the gain (in decibels) of an operational amplifier (op-amp) shows how the amplifier's gain changes with frequency. Here's a brief overview:

X-Axis (Frequency): Typically plotted on a logarithmic scale, representing a wide range of frequencies from low to high. Y-Axis (Gain in dB): Plotted in decibels (dB).

Key Characteristics:

1. Low-Frequency Region: - The gain is constant and very high, often around 100,000 to 1,000,000 (100 dB to 120 dB). - This region is where the op-amp operates with its open-loop gain.

2. Mid-Frequency Region: - The gain starts to decrease as the frequency increases. - The point where the gain begins to drop is called the corner frequency or cutoff frequency.

3. High-Frequency Region: - The gain continues to roll off at a rate of -20 dB/decade beyond the cutoff frequency. - This roll-off is due to the internal compensation of the op-amp, which ensures stability.

4. Unity Gain Frequency: - The frequency at which the gain drops to 1 (0 dB). - This frequency is known as the gain-bandwidth product and determines the bandwidth over which the op-amp can operate with unity gain.

Understanding this gain vs. frequency response is crucial for designing stable and efficient op-amp circuits, as it directly impacts the amplifier's performance in various applications. The waveform of gain in decibels (dB) for an operational amplifier (OP-Amp) describes how the gain varies across different frequencies, typically shown in a Bode plot.

The gain in decibels (dB) of an OP-Amp is plotted against frequency to illustrate its frequency response characteristics. At low frequencies, the OP-Amp exhibits a high gain, often in the range of 100,000 to 1,000,000 (100 dB to 120 dB), which remains relatively constant. This region, known as the low-frequency or DC gain, is essential for applications requiring precise signal amplification without distortion.

In the high-frequency region, well beyond the corner frequency, the gain continues to decrease exponentially at the same -20 dB/decade rate. This phenomenon is a result of the OP-Amp's internal capacitances and other frequency-dependent characteristics that limit its ability to amplify high-frequency signals effectively.

The unity gain frequency, also known as the gain-bandwidth product, represents the frequency at which the gain of the OP-Amp drops to 1 (0 dB). This parameter is crucial for determining the bandwidth over which the OP-Amp can operate while maintaining unity gain, influencing its suitability for applications requiring wideband amplification.

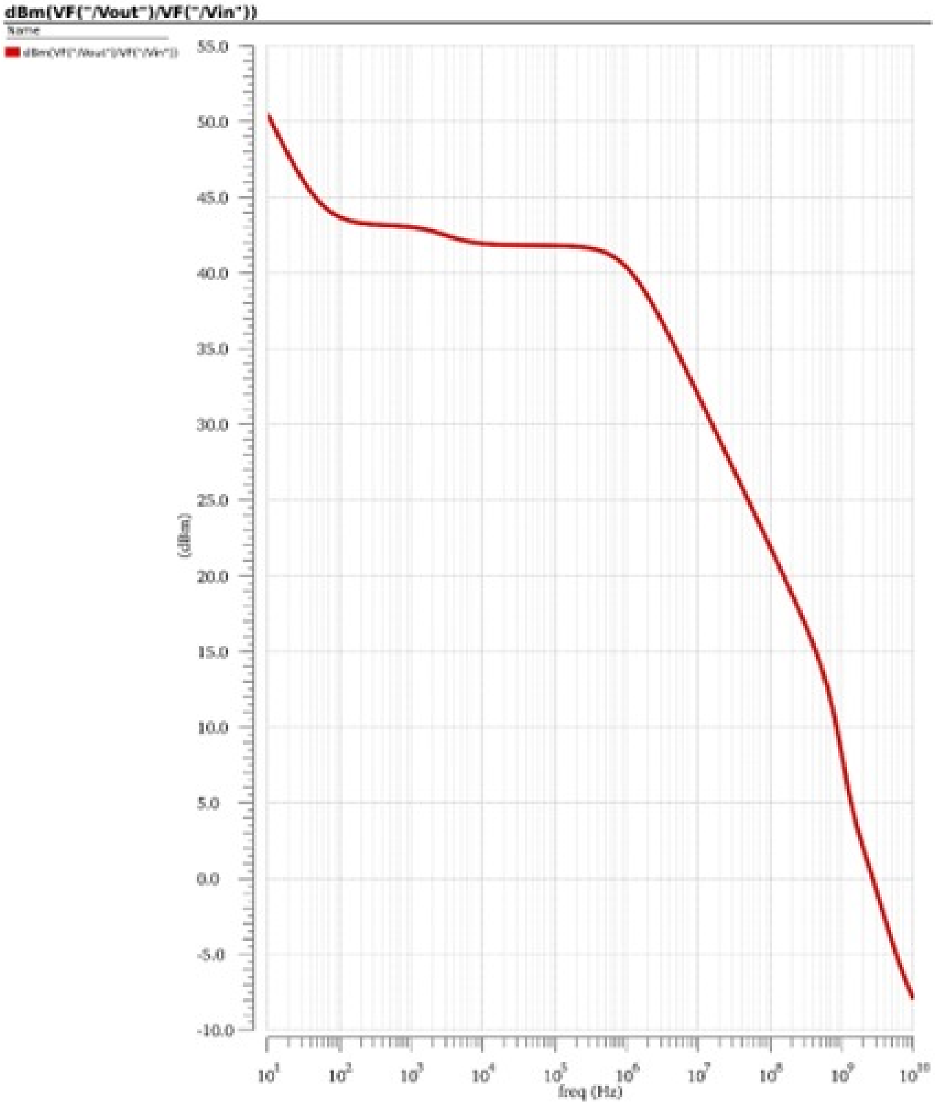

Figure 4.4: Gain (dB) of OP-Amp

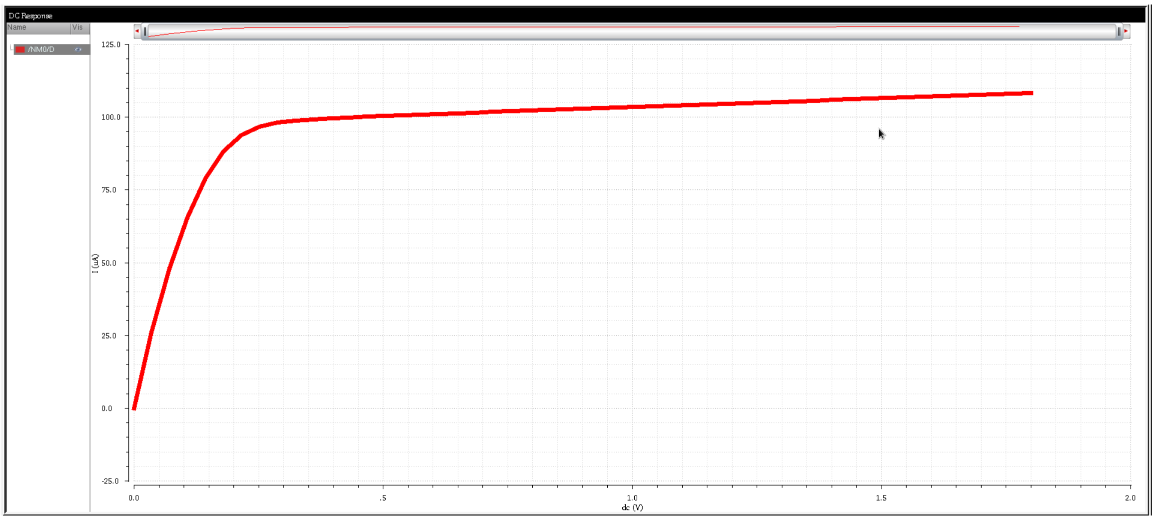

Figure 4.5: Current Mirror DC Response

4.1.5 Waveform of Current Mirror

A current mirror is a circuit designed to copy (mirror) a current from one active device (typically a transistor) to another, maintaining a constant current despite variations in load or supply voltage. Here's a brief overview of the waveform and key characteristics of a current mirror.

Key Characteristics:

1. **Linear Region:** In the ideal case, the output current (I_{out}) mirrors the input current (I_{in}) exactly. This results in a straight line with a slope of 1 in the I_{out} vs. I_{in} plot. The equation $I_{\text{out}} = I_{\text{in}}$ holds true, showing the direct proportionality between the input and output currents.

2. **Output Compliance:** The output current remains constant over a range of output voltages (V_{out}). This means the current mirror maintains a steady current even if the output voltage changes, up to a certain limit.

3. **Saturation Region:** At very high output voltages, the transistor may enter the saturation region where it can no longer maintain the mirrored current. In this region, I_{out} starts to deviate from I_{in}, showing non-ideal behavior.

Graph Description:

X-Axis: Input current (I_{in}) or reference current (I_{ref}), typically plotted in microamperes (μA) or milliamperes (mA).

Y-Axis: Output current (I_{out}), also plotted in μA or mA.

Typical Current Mirror Waveform:

Table 4.1: Observations

Block	**Power (watts)**
Filter	242.79 E-3
Current Mirror	33.26 E-9
Op amp	8.49 E-3

1. **Ideal Current Mirror:**

The plot shows a 45-degree line starting from the origin, indicating that I_{out} is exactly equal to I_{in}.

2. **Real-World Current Mirror:**

The plot will show a line close to the ideal 45-degree line but may deviate slightly due to non-idealities such as mismatches in the transistors, temperature variations, and finite output resistance.

3. **Output Voltage vs. Output Current:**

When plotting V_{out} versus I_{out}, the current remains constant over a range of V_{out}, indicating good output compliance. Beyond a certain V_{out} (when the transistor enters saturation), the current may drop off.

The waveform of a current mirror typically shows a linear relationship between the input and output currents, ideally following the line $I_{\text{out}} = I_{\text{in}}$. The output current remains stable over a range of output voltages, ensuring constant current mirroring. Understanding this behavior is crucial for designing circuits that require precise current control, such as biasing circuits in amplifiers and other analog applications.

In this section, we analyze the performance of the designed mixed-mode universal filter based on several key metrics: gain margin, phase margin, power consumption, and delay. The results are derived from the simulations and plotted graphs obtained using Cadence tools.

4.2 Future Work

Building on these results, future work can focus on:

Optimization: Further optimizing the filter design to reduce power consumption and delay while maintaining or improving gain and phase margins. **Scalability**: Extending the design to support higher-order filters and more complex signal processing tasks. Real-World Testing: Implementing the filter in real-world scenarios to validate performance under practical operating conditions. Integration with Advanced Systems: Exploring integration with advanced communication systems such as 5G and IoT networks to enhance overall system performance.

Overall, the mixed-mode universal filter demonstrates a promising combination of stability, efficiency, and real-time performance, making it a valuable component for a wide range of signal processing applications.

CHAPTER 5

Conclusion and Future scope

5.1 Conclusion

The design and implementation of a mixed-mode universal filter are significant advances in signal processing. Mixed-mode universal filters offer exceptional versatility, adaptability, and performance improvement by combining both analog and digital filtering approaches. These filters offer specialized solutions for a variety of applications, including as wireless communications, audio and image processing, sensor networks, and biomedical systems. They can smoothly switch between various filtering functions, such as low-pass, high-pass, band-pass, and band-stop. Further enhancing their usefulness in complex and dynamic signal processing contexts is their capacity to dynamically modify filter parameters based on current environmental variables and signal characteristics.

5.2 Future Scope

Future research and development in operational amplifier design aim to improve efficiency, reduce delay, and enhance overall performance. Advancements in semiconductor materials and fabrication technologies can lead to faster, more efficient transistors, thereby reducing power consumption and improving speed. Incorporating novel circuit topologies and advanced compensation techniques can further optimize gain-bandwidth product and phase margin, resulting in better stability and performance. Additionally, leveraging artificial intelligence and machine learning for automated circuit design and optimization holds potential for achieving superior performance metrics. The integration of these innovations will enable OP-Amps to meet the increasing demands of high-speed, low-power, and high-precision applications in various industries.

REFERENCES

[1] M.Kumngern F.Khateb and T.Kulej. "58-Nw 0.5-V Mixed-Mode Universal Filter Using MultipleInput Multiple-Output OTAS". In: *IEEE Access.* Vol. 11. 2023, pp. 130345–130357. DOI: 10.1109/ACCESS.2023.332992.

[2] A. Bentrcia M. T. Abuelma'atti and S. M. Al-Shahrani. "A novel mixed-mode current-conveyor based filter". In: *Int. J. Electron* 91.3 (Mar. 2004), pp. 191–197. DOI: 10.1080/00207210410001677039.

[3] D. R. Bhaskar V. K. Singh A. K. Singh and R. Senani. "Novel mixedmode universal biquad configuration". In: *IEICE Electron. Exp.* 2,no. 22,pp. 548–553 (2005,doi: 10.1587/elex.2.548.).

[4] A. Bhattacharyya N. Pandey S. K. Paul and S. B. Jain. ""A new mixed mode biquad using reduced number of active and passive elements". In: *IEICE Electron. Exp.* vol. 3, no. 6. 2006, PP.115–121,doi: 10.1587/elex.3.115.

[5] M. Kumngern and S. Junnapiya. "Mixed-mode universal filter using OTAs". In: *Proc. IEEE Int. Conf. Cyber Technol. Autom., Control, Intell. Syst. (CYBER), Bangkok, Thailand.* May 2012, 119–122. DOI: 10.1109/CYBER.2012.6392537..