ACTIVE FILTER DESIGN - SECOND ORDER LOW PASS AND HIGH PASS

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***Abstract*—This study presents the design and simulation of a biquad active low-pass and high-pass filter employing a two-stage differential amplifier topology with a custom-designed operational amplifier. The proposed design utilizes switched capacitor circuits instead of traditional resistors, leveraging the advantages of switched capacitor technology, such as high precision and low sensitivity to process variations.The active filter architecture is implemented using Cadence Virtuoso in a 180nm technology node. Simulation results demonstrate the functionality and performance of the designed biquad active low-pass and high-pass filters. The filters exhibit desirable frequency response characteristics, including cutoff frequencies, passband gain, and stopband attenuation, meeting the specifications outlined for the project. The use of switched capacitor circuits enhances the filter's performance, providing improved linearity and noise rejection compared to conventional resistor-based designs.**

***Index Terms*—Active Filters,Low Pass, High Pass,Band Pass,Two stage Opamp.**

I. INTRODUCTION

Active filters play a crucial role in modern electronic systems, providing essential signal processing capabilities for a wide range of applications including communications, audio processing, and instrumentation. Unlike passive filters, which rely on passive components such as resistors, capacitors, and inductors, active filters utilize active components such as operational amplifiers (op-amps) to achieve desired filtering characteristics.

In recent years, there has been a growing demand for active filters with improved performance, smaller footprints, and lower power consumption to meet the requirements of modern integrated circuits. One promising approach to address these demands is the integration of switched capacitor circuits into active filter designs. Switched capacitor circuits offer several advantages over traditional resistor-based circuits, including higher precision, reduced sensitivity to process variations, and the ability to implement complex filtering functions using digital control techniques.

This project focuses on the design and simulation of biquad active low-pass and high-pass filters using a two-stage differential amplifier topology integrated with custom-designed op-amp symbols. The design aims to leverage the benefits of switched capacitor technology to achieve superior filter performance while minimizing area and power consumption.

The selection of Cadence Virtuoso as the simulation platform and the use of a 180nm technology node enable accurate modeling and characterization of the proposed active filter designs. Through careful component sizing, circuit configuration, and compensation techniques, the active filters are optimized to meet specific frequency response requirements and performance metrics.

The integration of a custom-designed op-amp symbol tailored to the active filter topology ensures efficient signal processing and optimal performance. By replacing traditional resistor elements with switched capacitor circuits, the active filters exhibit enhanced linearity, noise rejection, and versatility, making them well-suited for a variety of analog signal processing applications.

The objectives of this project are outlined to guide the systematic development and evaluation of the designed biquad active low-pass and high-pass filters. The primary goals encompass both technical and practical aspects, aimed at achieving a comprehensive understanding of active filter design principles and their application in real-world scenarios.

a. Design and Implementation of Biquad Active Filters:

The foremost objective is to design and implement biquad active filters capable of performing low-pass and high-pass filtering functions. This involves selecting appropriate circuit topologies, component values, and operational amplifier configurations to achieve the desired filter characteristics, including cutoff frequencies, passband ripple, and stopband attenuation.

b. Integration of Two-Stage Differential Amplifier Topology:

The project aims to incorporate a two-stage differential amplifier topology into the active filter design to enhance filtering performance and signal fidelity. This involves analyzing the advantages of differential amplifiers in terms of common-mode rejection, gain bandwidth product, and distortion characteristics, and integrating them effectively into the filter architecture.

c. Custom Op-Amp Symbol Design:

To optimize the performance and efficiency of the active filters, custom operational amplifier symbols will be designed to match the specific requirements of the filter topology. This includes considerations such as input impedance, output impedance, slew rate, and bandwidth, ensuring compatibility with the overall filter design and simulation environment.

Utilization of Switched Capacitor Technology:

d. The project aims to leverage switched capacitor circuits as a viable alternative to traditional resistor-based implementations, offering advantages such as improved linearity, reduced sensitivity to process variations, and enhanced flexibility in filter design. The use of switched capacitor technology will be explored to optimize filter performance while minimizing area and power consumption.

e. Simulation and Verification Using Cadence Virtuoso:

The active filter designs will be simulated and verified using Cadence Virtuoso in a 180nm technology node. Simulation results will be analyzed to validate the functionality, stability, and performance of the designed filters across a range of operating conditions, ensuring compliance with project specifications and design objectives.

f. Performance Evaluation and Analysis:

Finally, the project aims to evaluate the performance of the designed active filters in terms of key metrics such as frequency response, phase response, noise performance, and dynamic range. Comparative analysis with existing filter designs and theoretical predictions will be conducted to assess the effectiveness and practical utility of the proposed approach.

II. Literature survey

The paper 'Design and Analysis of CMOS Two Stage OP-AMP in 180nm and 45nm Technology' presents the buffered CMOS two stage op-amp which uses 180nm and 45nm process for design and analysis of CMOS two stage op-amp. Keeping 1.8V power supply, 20µA bias current, aspect ratio W/L, slew rate 20V/µs,input common mode ratio constant. The trade-off among various parameters such as Open loop gain, Phase margin, Gain Bandwidth Product and Power consumption are measured. It has been demonstrated that due to recent development through scaling the size of transistors decreases power dissipated through the device also decreases. This design has been carried out in Cadence design tools [1].

In the year 2020 'Design Method for Two-Stage CMOS Operational Amplifier Applying Load or Miller Capacitor Compensation' introduces a two-stage CMOS Op-amp design featuring a miller capacitor, nulling resistor, and common-gate current buffer for frequency compensation. Design parameters were determined using relevant equations for gain, slew rate, phase margin, and power dissipation. HSPICE simulations validated the design, confirming high unity-gain, wide input common-mode range, reasonable gain bandwidth, and practical slew rate [2].

The design of high gain and power of analog components can be designed by using fully differential circuit concepts with the help of Operational Amplifiers (Op-Amps). The Op-Amp can be designed by providing the amplification of input voltages at two stages. The two stage Op-Amp features can be improved by providing the concepts like CS Amplifier , cascade etc. The Op-Amp design for high speed applications requires proper selection of biasing, logic style, and CS Amplifier as the technology is scaling down. This basic Op-Amp performance metrics can be improved by adding the CS Amplifier. The OpAmps are designed for both with single operational amplifier and CS Amplifier with gain improvement using Cadence full custom design suite for 90nm technology [3].

S. Saini, H. Rana and P. Bhulania presented low power novel universal biquad filter design, where the universal Biquad filter using GmC has been proposed and implemented on 180 nm CMOS technology.State variable filters treat both the signal and its derivatives as variables and offer a generic systematic approach to the active filter design process. All three major parameters (gain, Q and omega) can be adjusted independently, and low-pass, high-pass, and band-pass outputs are available simultaneously [4].

In this thesis [5], a detail comparison of various OTAs with respective small signal models are presented and simulated in 180nm CMOS technology. A passive Butterworth filter has been implemented using Op Amp-RC and Gm-C integrators using Ladder synthesis and biquad respectively. Op amp-RC integrators are simulated in Multisim Environment; transistor level simulation based on Gm-C biquad has been implemented in Tanner v.14.1 Software. Opamp-RC based filter offers a band width of 425 kHz, pass band gain of 0 dB, whereas Gm-C integrator based filter offers 85 MHz, pass band gain of 0 dB. Over-all power dissipation of the Gm-C filter is 4.3mW with 1.8V DC Supply.

In the book, 'MOS Switched-Capacitor and Continuous-Time Integrated Circuits and Systems' by Analysis and Designwe describe two large classes of analog integrated circuits: switched capacitor (SC) networks and continuous-time CMOS (unswitched) circuits. SC networks are sampled-data systems in which electric charges are transferred from one point to another at regular discrete intervals of time and thus the signal samples are stored and processed. Other circuits are charge transfer devices (CTD) and charge coupled dev ices (CCD). In contrast to SC circuits, continuous-time CMOS circuits operate continuously in time [6].

III. Methodology

Filters are essential building blocks of any Electronic and Communication Systems that alter the amplitude and/or phase characteristics of a signal with respect to frequency. Filter is basically linear circuit that helps to remove unwanted components such as Noise, Interference and Distortion from the input signal. Ideally Filter alters the relative amplitudes of the various frequency components and the phase characteristics and its 'Gain' depends entirely on the signal frequency.

A filter is a circuit capable of passing (or amplifying) certain frequencies while attenuating other frequencies. Thus, a filter can extract important frequencies from signals that also contain undesirable or irrelevant frequencies.

The voltage transfer function $H(s)$ of a Filter Circuit is written as:

$$H(s) = \frac{V_{\text{out}}(s)}{V_{\text{in}}(s)}$$

Where:

$$V_{\text{out}} = \text{Output voltage}$$
$$V_{\text{in}} = \text{Input Voltage}$$
$$s = \text{Complex Frequency}$$

By replacing the variable s in the above equation with $j\omega$, where j is equal to $\sqrt{-1}$ and ω is the radian frequency $(2\pi f)$, we can find the filter's effect on the Magnitude and Phase of the Input signal.

Transitioning from Passive to Active Filters:

Passive filters, consisting primarily of resistors, capacitors, and inductors, are widely used in electronic circuits to shape or manipulate signals. They are relatively simple in design and implementation, and they perform essential filtering functions such as low-pass, high-pass, band-pass, and band-stop filtering. Passive filters are advantageous for their simplicity, low cost, and ease of integration into circuits.

However, despite their advantages, passive filters have inherent limitations that sometimes make them unsuitable for certain applications. One significant drawback is the reliance on inductors. While inductors are crucial components for many circuits, they present several challenges. Firstly, inductors tend to be bulky and heavy, making them impractical for applications where size and weight are critical factors. Secondly, inductors are susceptible to temperature variations and environmental conditions, which can affect their performance and stability. Moreover, the design and implementation of inductors require careful consideration of factors such as core material, wire gauge, and winding configurations, which can complicate the manufacturing process and increase costs.

To overcome these limitations and address the evolving needs of electronic systems, active filters emerged as a viable alternative to passive filters. Active filters leverage operational amplifiers (op-amps) to achieve filtering functions without the need for bulky inductors. Op-amps offer several advantages over traditional passive components. They are compact, lightweight, and highly versatile, allowing for the implementation of complex filtering topologies in a relatively small footprint. Op-amps also exhibit excellent performance characteristics, such as high input impedance, low output impedance, and wide bandwidth, making them well-suited for a wide range of filtering applications.

By replacing inductors with op-amps, active filters offer improved performance, reliability, and flexibility compared to their passive counterparts. They can be easily configured and adjusted to meet specific design requirements, and they exhibit superior stability and precision across varying operating conditions. Additionally, active filters can provide higher order filtering capabilities and sharper roll-off characteristics, enabling more precise signal processing and noise rejection.

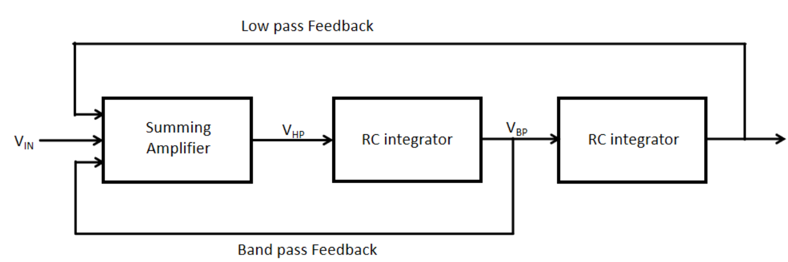

Fig. 1. Block diagram of universal biquad filter

Summing Amplifier (Input Stage):

- The summing amplifier combines the input signal with the feedback signals from the low-pass and band-pass filter stages.
- It is represented by a node where all the signals are summed.

RC Integrators (Two Stages):

- Each RC integrator represents a stage of filtering.
- The RC integrators implement the necessary frequency-dependent behavior for the filter.
- The first RC integrator typically represents the low-pass filter behavior, while the second RC integrator represents the band-pass filter behavior.
- The transfer function of each RC integrator is given by the equation of an RC circuit, which is a first-order low-pass filter:

$$H(s) = \frac{1}{1 + RCs}$$

where s is the Laplace variable and R and C are the resistance and capacitance values, respectively.

Low-pass Feedback:

- The output of the second RC integrator is fed back to the input of the first RC integrator to provide low-pass feedback.
- This feedback reinforces the low-pass filtering behavior of the circuit.
- The transfer function of the low-pass feedback loop depends on the gain of the operational amplifier used in the integrator and the feedback resistance and capacitance. It is typically represented as:

$$H_{\text{LPF\_feedback}}(s) = \frac{R_f}{R_f + R_i}$$

where:

  - R_f is the resistance in the feedback path.
  - R_i is the input resistance of the operational amplifier.

This transfer function determines the strength of the low-pass feedback, which reinforces the low-pass filtering behavior of the circuit.

Band-pass Feedback:

- The output of the second RC integrator is also fed to a band-pass filter stage.
- This band-pass filter enhances the band-pass characteristics of the biquad filter.
- The transfer function of the band-pass feedback loop depends on the design of the band-pass filter stage. It can vary based on the specific implementation and requirements of the filter.

For a simple band-pass feedback stage, the transfer function may be represented as:

$$H_{\text{BPF\_feedback}}(s) = \frac{R_{fb}}{R_{fb} + R_{in}}$$

where:

  - R_{fb} is the resistance in the band-pass feedback path.
  - R_{in} is the input resistance of the band-pass filter stage.

This transfer function determines the strength of the band-pass feedback, which enhances the band-pass characteristics of the biquad filter.

Output:

- The output of the filter is taken from the second RC integrator or from the band-pass filter stage, depending on the desired output characteristics.

This captures the flow of signals through the various stages of the universal biquad filter, incorporating low-pass and band-pass feedback to achieve the desired filtering characteristics. The specific transfer functions and equations for the filter depend on the component values and circuit configurations chosen for the RC integrators, summing amplifier, and feedback loops.

A. *Design alternatives*

a. Sallen-key topology

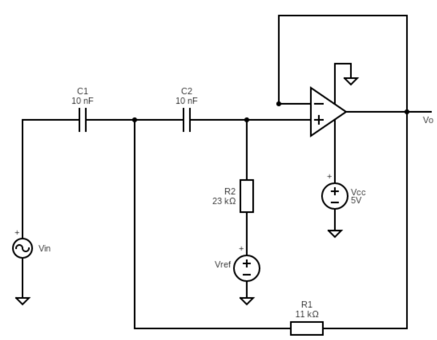

Fig. 2. Second order high pass active filter with sallen-key topology

- The Sallen-Key topology is a popular choice for designing second-order low-pass filters.
- It offers simplicity and flexibility in component values
- It uses operational amplifiers and passive components such as resistors and capacitors.

b. Multiple feedback topology

- The MFB topology is another option for implementing second-order low-pass filters.
- It offers good performance with fewer components compared to the Sallen-Key topology.
- It also employs operational amplifiers and passive components.

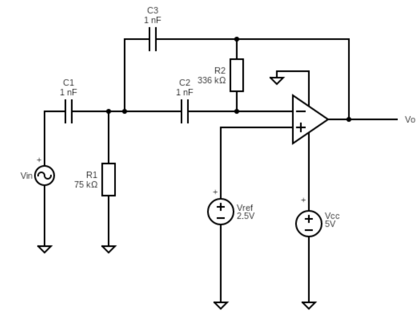

Fig. 3. Second order high pass active filter with multiple feedback topology

B. *Final design*

State-variable filter

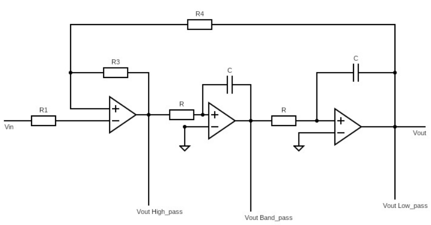

Fig. 4. Block diagram of universal biquad filter

- The state variable filter offers several filter responses (low-pass, high-pass, band-pass, etc.) in a single configuration.
- It utilizes multiple operational amplifiers and passive components.
- It allows for easy control of filter parameters such as bandwidth and quality factor.

C. *Implementation details*

We employ two-stage amplifiers to achieve higher gain than what a single amplifier can provide, as well as to mitigate amplifier noise.

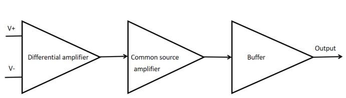

Fig. 5. Two-stage amplifier

Process = 180nm (VDD = 1.8V)
DC gain = 1000 (60 dB)
PM $\leq 60°$
SR = 20V/μs
ICMR+ = 1.6V
ICMR- = 0.8V
CL = 2μf
Power $\leq 300\mu$w
GBW = 30 MHz

1) L = 500nm

2) $C_c \geq 0.22$CL
$C_c \geq 440$fF
Including the effect (Disturbance of parasitic)
$C_c \geq 800$fF let

3) Deciding Is
SR = $\frac{I_s}{C_c}$
$I_5 = \left(\frac{20V}{1\mu s}\right)$ (800fF)
$\text{I}_5 = 16\mu A$
Let $I_5 = 20\mu A$ (For better Slew rate)

4) Design of M1,M2
$g_{m1} = \frac{(GBW)C_c \times 2\pi}{(30\text{MHz}) \times (800}$fF) $\times 2\pi$
$g_{m1} = 150.79\mu s$
$g_{m1} = 160\mu s$
Now from $g_{m1} = \sqrt{2I_{D1} \times (\mu_n C_{ox} \times \frac{W}{L})}$
$\frac{1}{(W/L)_{1,2}} = \frac{g_{m1}^2}{2\mu_n C_{ox}^2 \times (I_2 s)}$
as $I_{D1} = I_{25}$
$\left(\frac{W}{L}\right)_{1,2} = 4.266$

5) Designing of M3,M4
For M1 to be in Saturation
$|Vin| \leq Vd1 + VT1$
$Vd1 = VDD - Vsg3$
where
$Vd1 = V_{DD} - \left\{\sqrt{\frac{2I_{\beta 3}}{3}} + |V_T|\right\}$
$Vin \leq |VD1 + VT1|$
$ICMR+ \leq VD1 + VT1$
$ICMR+ \leq V_{DD} - \sqrt{\frac{2ID3}{\beta 3}} - |VT3| + |VT1|$
$\left(\frac{W}{L}\right)_{3,4} = \frac{2ID3}{\mu_n C_{ox}[V_{DD} - ICMR + -VT3 + VT1]}$
So $\left(\frac{W}{L}\right)_{3,4} = 13.02$ or $\left(\frac{W}{L}\right)_{3,4} = 14$

6) Design for M5
For M5 to be in saturation
$Vin \geq Vgs1 + VDsat5$
$ICMR- \geq Vgs1 + VDsat5$
$ICMR- \geq [\sqrt{\frac{2ID1}{\beta 1}} + VT1] + VDast5$

Or
$VDast5 \leq ICMR - -[\sqrt{\frac{2I_{D1}}{\beta 1}} + VT1]$
From simulation $VT1 = 590$mV

7) Design of M6
For PM=60o
For M6 and M4 (Vgs6=Vgs4)
$\left(\frac{W}{L}\right)_6 \left(\frac{W}{L}\right)_4 = \frac{I6}{I4} = \frac{Gm6}{Gm4}$
$\left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_4 \times \frac{Gm6}{Gm4} = 1600/129 \times 61/14 = 172.82$
$\left(\frac{W}{L}\right)_6 \approx 173$
Now
$\frac{I6}{I4} = \left(\frac{W}{L}\right)_6 \left(\frac{W}{L}\right)_4$
$I6 = 124.28\mu A$ or $I6 = 125\mu A$

8) Design of M7
$Vgs7 = Vgs5$
So
$\frac{I7}{I5} = \left(\frac{W}{L}\right)_7 \left(\frac{W}{L}\right)_5$
$\left(\frac{W}{L}\right)_7 = 75$
$I5 = 20\mu A$
$C_c = 800$fF

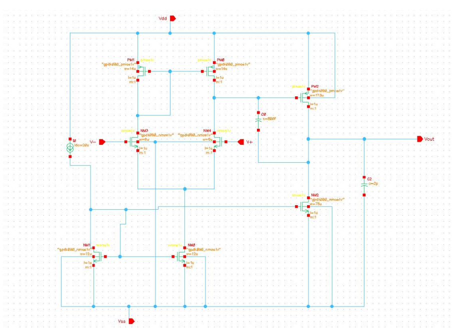

Fig. 6. Two-stage amplifier schematic

Two-stage amplifiers represent a common architecture in integrated circuit design and are widely used due to their ability to provide higher gain and improved performance compared to single-stage amplifiers.At the heart of a two-stage amplifier lies the concept of cascading amplification stages to achieve desired performance characteristics. Each stage typically consists of a an amplifier coupled with a passive component capacitor for biasing.

In terms of operation, the first stage, often referred to as the input stage, is responsible for providing the initial amplification and impedance matching to the input signal. This stage sets the foundation for the overall amplification process and is designed to handle the incoming signal with minimal distortion. The second stage, known as the output stage, further amplifies the signal while providing necessary buffering and impedance matching to drive the load. This stage ensures that the amplified signal retains its integrity and can be efficiently transmitted to subsequent stages or output terminals.

D. Flowchart

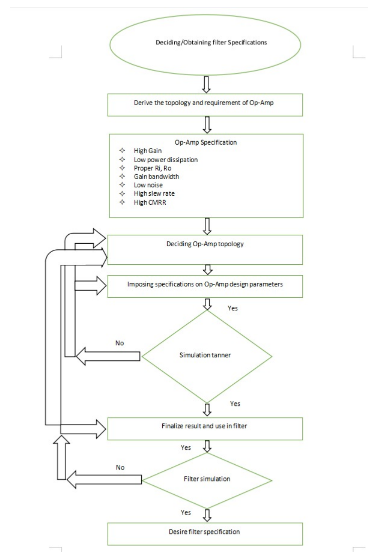

Fig. 7. Flow chart of active filter design

The flowchart depicts the process of obtaining filter specifications. It starts with deriving the topology and requirements of an operational amplifier (op-amp). Based on these requirements, specifications are imposed on the op-amp's design parameters. If these specifications are met, then the op-amp topology is decided upon and the result is finalized for use in the filter. If not, then the process starts again from deriving the topology and requirements of the op-amp. Once the op-amp topology is finalized, a filter simulation is conducted. If the desired filter specifications are met, then the process is complete. If not, then the op-amp specifications are modified and the filter simulation is conducted again.

E. Optimization

In VLSI technology, integrating resistors with large values onto a chip poses challenges. To address this, alternative circuits such as switched capacitors are employed. This report presents the design of a low pass filter using switched capacitors and comparators. The switched capacitor comprises two switches and a capacitor, with an operational amplifier serving as the comparator. The switches, which can be NMOS, PMOS transistors or transmission gates, facilitate switching based on the clock driver output signal applied to their gate terminals. We examine the frequency response of low pass filters using pass transistors and transmission gates, calculating the cutoff frequency in each case using Cadence Virtuoso. Our observations reveal that the transmission gates exhibit superior roll-off compared to pass transistors. Additionally, the combination of PMOS and NMOS in the transmission gate configuration mitigates issues associated with reduced noise margin.

1) Types of Optimization: They are two ways in which the second order low pass and high pass filter can be designed using switched capacitor, they are:

a. Pass Transistor Configuration

In this approach, switched capacitors are integrated in series with two NMOS pass transistors. The pass transistors facilitate the switching action, controlling the flow of charge through the capacitors. This configuration is characterized by its simplicity and efficiency, making it suitable for various low pass and high pass filter applications.

b. Transmission Gate Configuration

Alternatively, switched capacitors can be paired with two CMOS transmission gates in series. Transmission gates offer bidirectional signal flow and improved linearity compared to pass transistors. This configuration is favored for its reduced charge injection, enhanced noise rejection, and superior bandwidth characteristics.

2) Selection and justification of optimization method: Transmission gates are often considered superior to pass transistors for certain applications, including switched capacitor-based filter designs, due to several key advantages:

1) **Improved Linearity**:
   - Transmission gates offer better linearity compared to pass transistors.
   - This is because transmission gates utilize complementary metal-oxide-semiconductor (CMOS) technology, which inherently provides symmetric switching characteristics and reduced distortion.
2) **Reduced Charge Injection**:
   - Charge injection, which refers to the unintentional transfer of charge between the switch terminals and the circuit nodes, is typically lower in transmission gates compared to pass transistors.
   - This is due to the symmetric nature of CMOS transmission gates, which helps minimize charge injection effects and improve signal integrity.
3) **Bidirectional Signal Flow**:
   - Transmission gates allow bidirectional signal flow, meaning they can pass signals in both directions with minimal distortion.
   - This feature is particularly advantageous for certain filter configurations and signal processing applications where bidirectional operation is required.
4) **Lower ON Resistance**:
   - Transmission gates typically exhibit lower ON resistance compared to pass transistors.
   - As a result, transmission gates introduce less voltage drop and attenuation when conducting signals, leading to improved signal fidelity and reduced insertion loss in filter circuits.
5) **Higher Bandwidth**:
   - Due to their improved linearity, reduced charge injection, and lower ON resistance, transmission gates are capable of operating at higher frequencies compared to pass transistors.
   - This makes them well-suited for high-speed and wideband filter applications where maintaining signal integrity and bandwidth is crucial.
6) **Isolation and Noise Rejection**:
   - Transmission gates provide better isolation between the input and output signals, resulting in improved noise rejection and signal-to-noise ratio compared to pass transistor-based circuits.
   - This helps preserve the integrity of the filtered signals and minimizes unwanted noise components.

IV. Results and Discussions

The two stage opamp is used as building block for the design of desired filter circuit.Opamp used as active element in the circuit.The symbol of opamp is shown below.

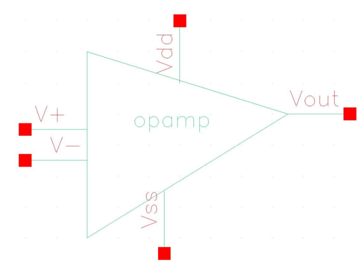

Fig. 8. Symbol of two stage opamp.

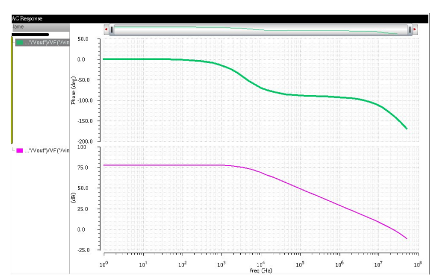

Fig. 9. Open loop magnitude and phase vs frequency.

Taking into consideration the various operation performed by the filter circuit The result obtained is given below.

a. Low pass filter result

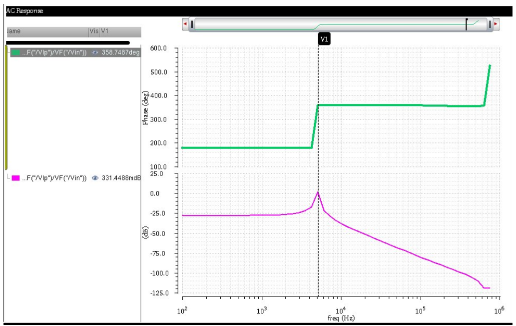

Fig. 10. Low pass filter result.

b. High pass filter result

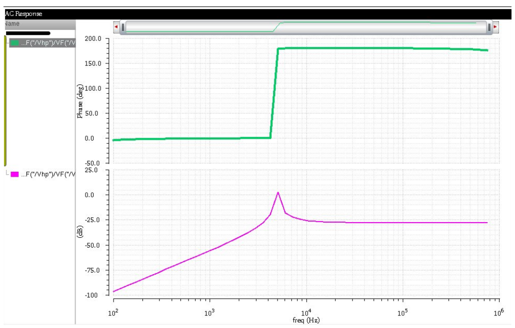

Fig. 11. High pass filter result.

c. Bandpass filter result

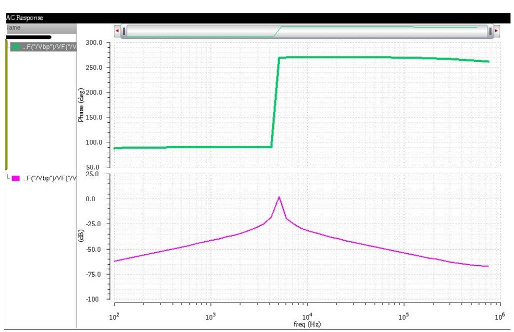

Fig. 12. Band pass filter result.

V. Conclusion

In conclusion, this project successfully designed and simulated a biquad active low-pass and high-pass filter employing a two-stage differential amplifier topology with a custom-designed operational amplifier. By adopting switched capacitor circuits instead of traditional resistors, the filters demonstrated superior performance, showcasing high precision and low sensitivity to process variations. The implementation in Cadence Virtuoso at a 180nm technology node yielded simulation results that met the specified project requirements for cutoff frequencies, passband gain, and stopband attenuation. The advantages of switched capacitor technology were evident, as the filters exhibited enhanced linearity and noise rejection compared to conventional resistor-based designs. This study highlights the efficacy of the proposed design in achieving the desired frequency response characteristics, thereby contributing valuable insights to the field of active filter design.

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