CAPSTONE TEAM-31

Project Title : Design and Implementation of an Analog EEG Sensor
Project Guide : Prof. Lokesh L
Project Team : 31
Team Members :

Rohil S
Aditya J
Chris Dsouza

Agenda

- Introduction and Motivation
- Problem Statement
- Abstract and Scope
- Literature Survey
- Current progress and simulation results
- References

Problem Statement

- **Project Aim:** Design and implement a cost-effective, high-sensitivity, low-noise analog EEG sensor with a complete layout ready for tape-out. This sensor will support accurate brain signal acquisition and seamless integration into brain-computer interface (BCI) systems, fostering wider accessibility and innovation in neurotechnology.

Introduction and Motivation

Introduction:

- Develop an analog front-end EEG sensor to capture and process brain signals.
- Supports applications in medical diagnostics and BCIs.

Motivation:

- Need for affordable, high-performance EEG solutions.
- Commercial devices are often costly and inaccessible.
- Enhances hands-on experience in circuit design and IC tape-out.
- Benefits healthcare and neurotech research.

Constraints / Dependencies / Assumptions / Risks

Legal Implications

- Ensure compliance with medical device regulations if used for clinical purposes.
- Data privacy concerns if storing or transmitting EEG data.

Usage Limitations

- Designed for academic and research purposes, not medical diagnosis.
- Performance may vary due to noise interference or electrode placement.

Software/Hardware Requirements

- **Software:** Cadence for circuit design, Matlab for generating EEG signals.
- **Hardware:** Tapeout circuit for testing eeg signals

EEG Waves

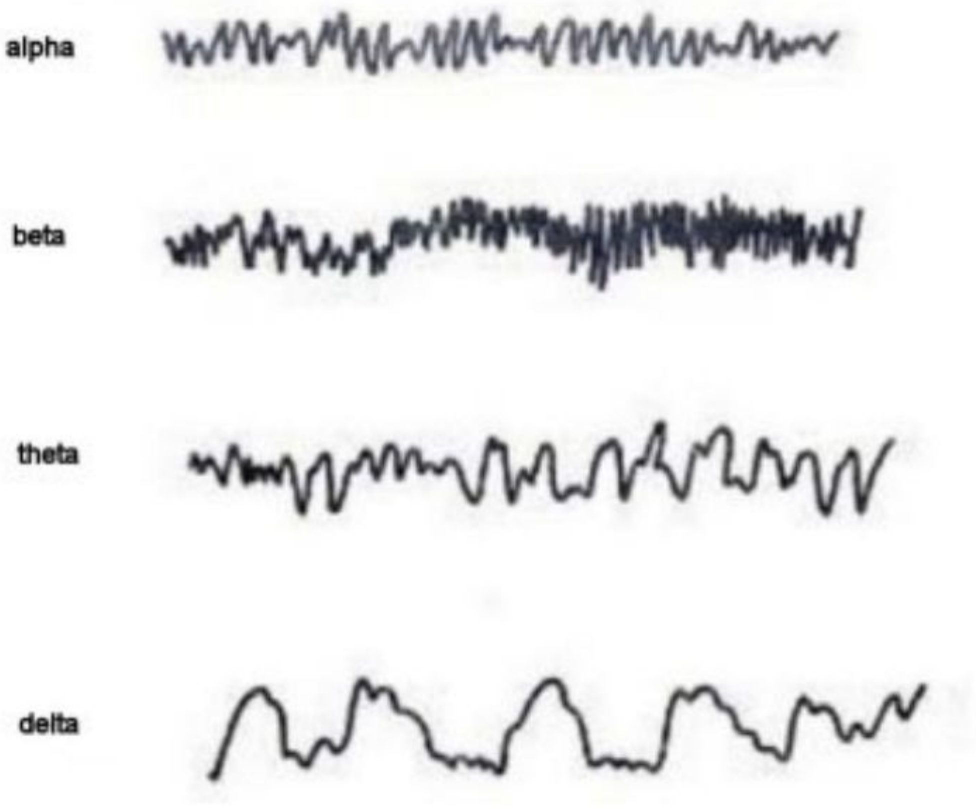

Fig. 1. EEG waveforms

1. **Alpha Waves (7.5–15 Hz):**
   - Relaxed, conscious state with eyes closed.
   - Strongest in the **occipital, parietal, and frontal regions**.
2. **Beta Waves (15–100 Hz):**
   - Active during alertness, anxiety, or eyes open.
   - May reach up to **80 Hz in intense activity**.
3. **Theta Waves (3.5–7.5 Hz):**
   - Large amplitude, low frequency; seen in **sleep and young children**.
   - Abnormal in awake adults, concentrated in **parietal and temporal regions**.
4. **Delta Waves (<3.5 Hz):**
   - High amplitude, low frequency; normal in **infants** and **deep sleep in adults**.

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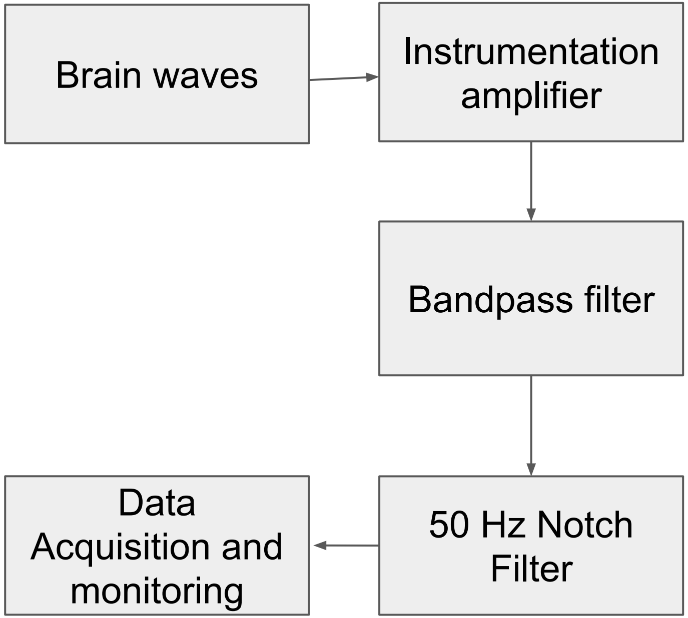

Structure of the System

Electrodes and Signal Detection

- Electrodes positioned per the **8-16 system** for standardized EEG recording.
- Measure voltage fluctuations caused by ionic currents in neurons.
- Raw EEG signals are weak and noisy.

Instrumentation Amplifier

- Amplifies weak EEG signals for further processing.
- Features: High input impedance, excellent common-mode rejection, precise gain.
- Rejects noise and interference from power lines and electronics.

Bandpass filter

- Preserves EEG Signal:Passes 0.5–100 Hz range for brainwave activity.

- Improves SNR: Reduces noise, enhancing signal clarity.

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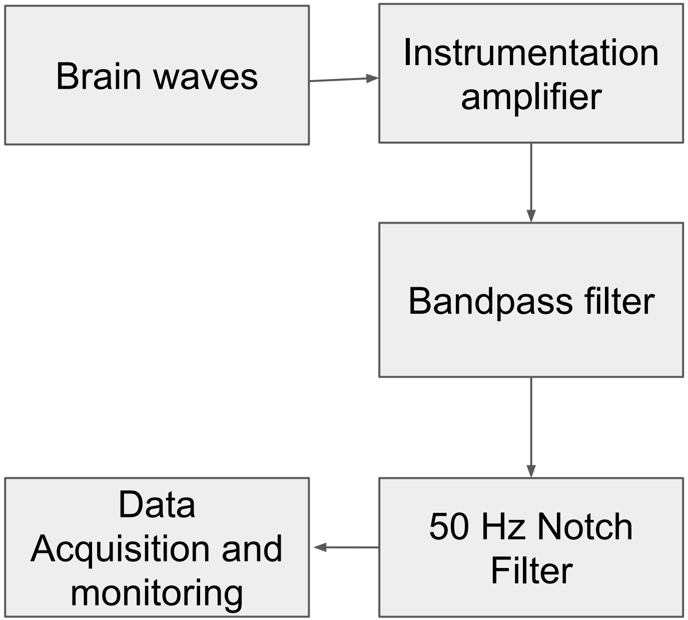


Structure of the System

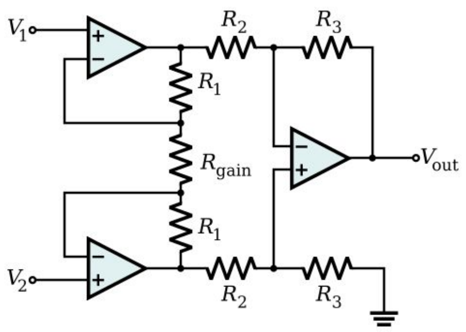
50 Hz Notch Filter

- Targets and removes **power line interference** at **50 Hz**.
- Minimizes noise without affecting neighboring EEG components.

Data Acquisition and Monitoring

- Digitizes EEG signals via ADC for visualization and analysis.
- Enables **real-time monitoring** or offline analysis using software tools.

Instrumentation Amplifier



Why we are using Instrumentation Amplifier :

1. **High Common-Mode Rejection Ratio (CMRR):** Reduces noise and interference.
2. **Adjustable Gain:** Set by a single resistor Rg.
3. **Low Power Consumption:** Suitable for battery-powered applications.
4. **Differential Measurement:** Effectively amplifies small signals while rejecting common-mode noise.

Working :

First Stage (Two Op-Amps in Buffer Configuration)

- The two input op-amps buffer V1 and V2, ensuring **high input impedance**.
- The gain of this stage is determined by R1 and Rg.

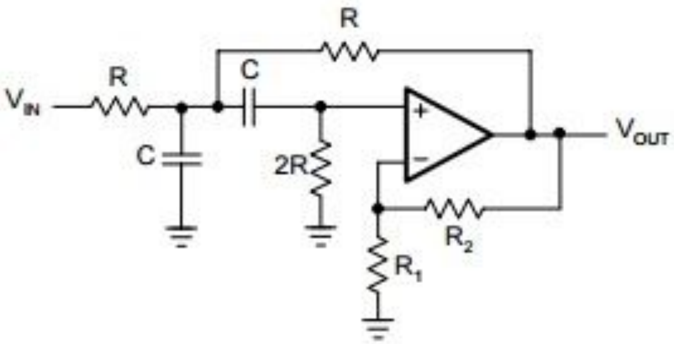
Second Stage (Differential Amplifier)

- The third op-amp amplifies the difference between the outputs of the first stage.
- R2 and R3 set the differential gain.

GAIN OF IA:

$$G = \left(1 + \frac{2R_1}{R_{gain}}\right) \times \frac{R_3}{R_2}$$

Sallen Key Bandpass Filter



Why we use Sallen Key Bandpass Filter:

- Suitable for low frequency devices
- Uses only Resistors and Capacitors

Working :

Only frequencies around the resonant frequency (f0) pass through, making it a **bandpass filter**.

Center Frequency :

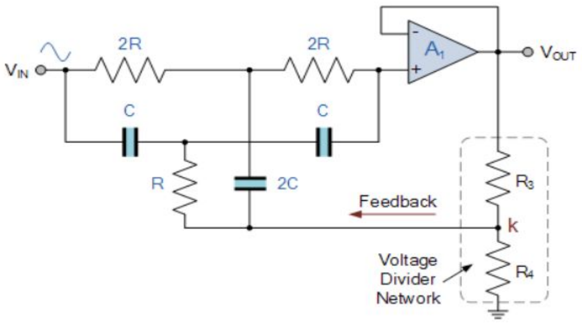
Bandwidth :

$$f_0 = \frac{1}{2\pi\sqrt{R1R2C1C2}}$$

$$BW = \frac{f_0}{Q}$$

Twin -T Notch filter

Single Op-amp Twin-T Notch Filter



Why we are using Twin-T Notch Filter

1. Eliminates power-line interference (50 Hz).
2. Deep Notch Depth – Effectively attenuates unwanted frequency components.
3. Higher Q-Factor – Provides sharp frequency rejection.

A **Twin-T Notch Filter** is a design consisting of **two RC networks** (one in series, one in parallel) to create a deep notch at the target frequency.

Purpose :

A **50 Hz notch filter** is used in **power line interference rejection of AC mains supply which is operating at 50Hz**

Working :

A **single op-amp Twin-T notch filter** consists of:

- **A Twin-T network**
- **An op-amp in a negative feedback configuration** to improve the depth of the notch and stability.

Twin-T Filter Equation:

$$f_N = \frac{1}{4\pi RC}$$

Generating Synthetic EEG Signals in MATLAB for Sensor Testing

Objective

Generate synthetic EEG signals using EEG function in MATLAB.

Test and validate EEG sensor performance in Cadence.

Why Synthetic EEG?

1. Provides ground-truth data for validation.

2. Customizable parameters (e.g., noise, activation functions).

3. Enables controlled testing of EEG sensors.

Key Features of EEG function :

Activation Functions: Sinusoidal waves or real EEG-derived ICA components.

Noise Control: Add white Gaussian noise and background brain activity.

Lead Field Support: Use custom or precomputed head models (16/32/64/128 channels).

Steps to Generate Synthetic EEG in MATLAB

Step 1:
Download EEG function
Access the EEG MATLAB function
Ensure MATLAB and FieldTrip toolbox are installed.

Step 2: Configure Parameters

```
Fs = 512;             % Sampling frequency (Hz)
n_channel = 64;       % Number of EEG electrodes
t_end = 20;           % Duration (seconds)
na = 5;               % Main active sources
nb = 20;              % Background noise sources
att = 50;             % Attenuation for noise
af = 'sin';           % Activation function ('sin' or 'ICA')
NOISE_SNR = 10 % Signal-to-noise ratio
```

Step 3: Generate and Export EEG

Observing and Analyzing the Signal

Analog Output:

- The sensor provides an **analog output** signal, which is then connected to the oscilloscope input channel. Ensure the output signal is within the oscilloscope's acceptable voltage range, typically **±50mV or ±250V**.

Voltage Range Considerations:

- The EEG signal after amplification will still be in the **millivolt (mV) range**, so the oscilloscope's **vertical scale** should be adjusted to 1 mV/div or similar.

Oscilloscope Settings:

- **Time Base**: Set to 10 ms/div to observe the EEG waveform at an appropriate time scale. Adjust based on the frequency of the brain waves being observed.
- **Triggering**: Set to trigger on the **rising edge** of the signal for a stable, continuous waveform display. This ensures the signal remains locked in phase with the oscilloscope sampling.

Observing and Analyzing the Signal

Real-Time Visualization:

- The oscilloscope displays the EEG signal in real-time, showing the brainwave activities such as **alpha, beta, theta, and delta** waves, depending on the subject's state (e.g., relaxed or alert).

Initial Calibration:

- Verify the signal's quality: Ensure the EEG signal is amplified appropriately and free from distortion. If noise or interference is visible, check the system's **grounding** and **shielding**.
- Adjust settings on the oscilloscope for optimal signal clarity.

Signal Analysis:

- Use the oscilloscope's built-in measurement tools to analyze key signal properties such as **frequency** and **peak-to-peak voltage**.
- **FFT (Fast Fourier Transform)** can be employed to analyse the waves too.

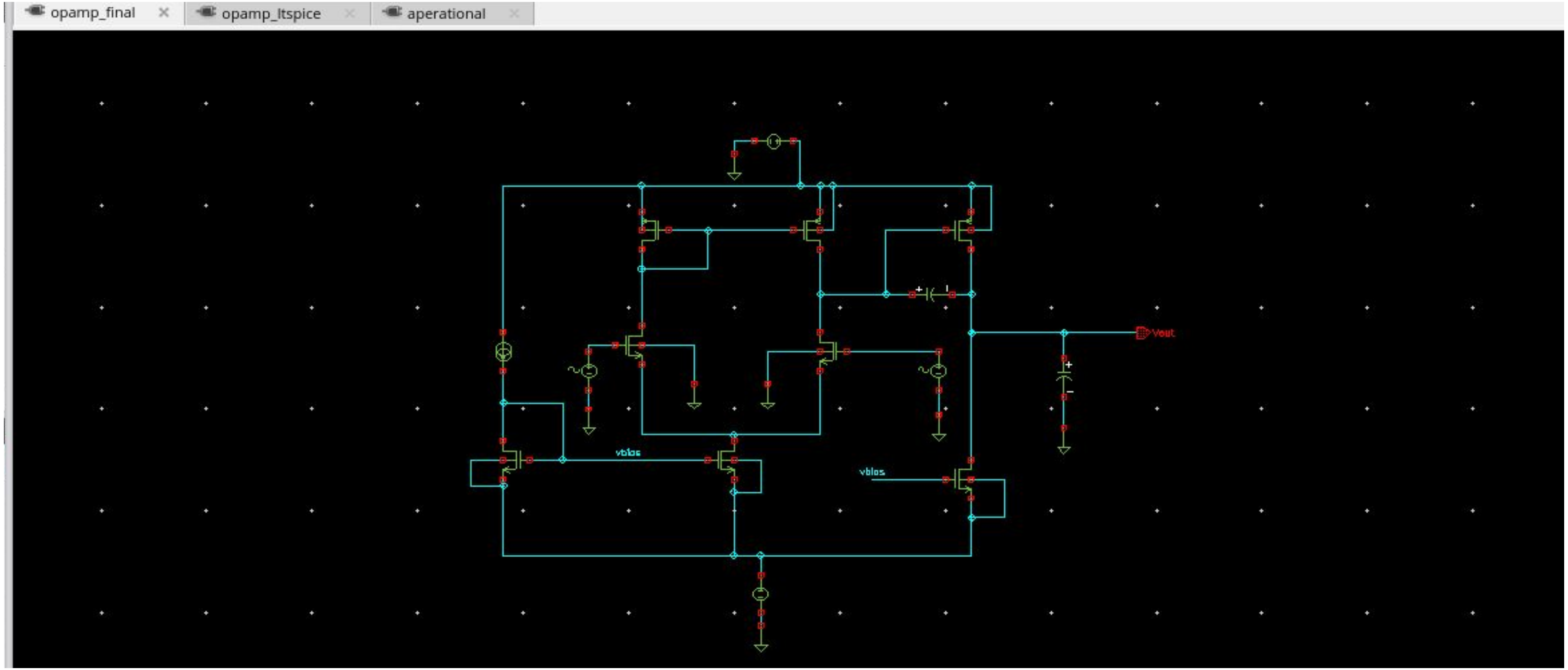
Comparison of all Literature Survey papers

EEGg: Generating Synthetic EEG Signals in Matlab Environment	Provides ground-truth EEG data; Open-source and user-friendly tool; Versatile configurations for noise and sensor setups.	High computational requirements for complex configurations.	Limited to the MATLAB environment; Limited datasets for ICA components.	To develop an advanced MATLAB tool for generating synthetic EEG signals to mimic real data.
Design and Implementation of Two-Stage CMOS Operational Amplifier (IRJET)	High gain and phase margin; Low power consumption; Simple architecture for Cadence Virtuoso.	Performance degradation with increasing load capacitance.	Designed for 180nm technology; May not be scalable to advanced nodes.	To design and implement a CMOS op-amp with improved gain and bandwidth using 180nm technology.

Analog Portable EEG Signal Extraction System Implementation	Portable and cost-effective; High gain amplifier and noise rejection filters; Compatible with Arduino for real-time processing.	Limited electrode count reduces signal fidelity.	Prototype tested only with basic EEG signals; Accuracy not compared to commercial systems.	To develop a low-cost, portable EEG system with data logging for patient-friendly monitoring.
Two Stage CMOS Operational Amplifier Using Cadence 180nm Technology (IJIRSET)	High gain (72.56 dB); Wide bandwidth (34 MHz); Low power consumption with efficient design.	Possible instability due to phase margin challenges.	Restricted to academic research on 180nm CMOS technology.	To design, simulate, and analyze a CMOS two-stage op-amp optimized for gain and bandwidth in Cadence.

Op Amp Design

The following schematic is of the Operational Amplifier which has been implemented on Cadence



About this Op Amp and why we chose it

This is a **two-stage operational amplifier (opamp)** with a differential input pair, a gain stage(common source stage), and a compensation capacitor for stability.

1. **Power Supply:**

- We are using dual power supply ,this means the op amp operates with a **3.6 V supply range**.

2. **Differential Input Stage:**

i . **M1 (0.54/0.2) and M2 (0.54/0.2):**

- These are **NMOS transistors** forming the differential input pair.
- They receive differential input signals (Vin+ and Vin−).
- The current source **M8** provides the tail current, which splits between M1and M2

ii. **M3 (2.7/0.5) and M4 (2.7/0.5):**

- These **PMOS transistors** act as active load current mirrors.
- They ensure proper differential-to-single-ended conversion.

iii. **Gain for this stage :** $Av1 = gm1 \cdot (ro3 \| ro1)$ = **40 dB or 100 V/V**

3. Gain Stage :

- **M5 (0.81/ 0.18)   :** Acts as a current source to bias the second stage.
- **M6 (10.92/ 0.18) :**
    - This **PMOS transistor** provides gain in the second stage.
    - It drives the output Vout while being loaded by M7.

Gain for this stage : Av2 = gm6 $\cdot$ (ro6 $||$ ro7) **= 30 dB or 30 V/V**

4. Output Stage :

- **M7 (2.52/ 0.18):** Acts are common source amplifier providing additional gain and drives the load

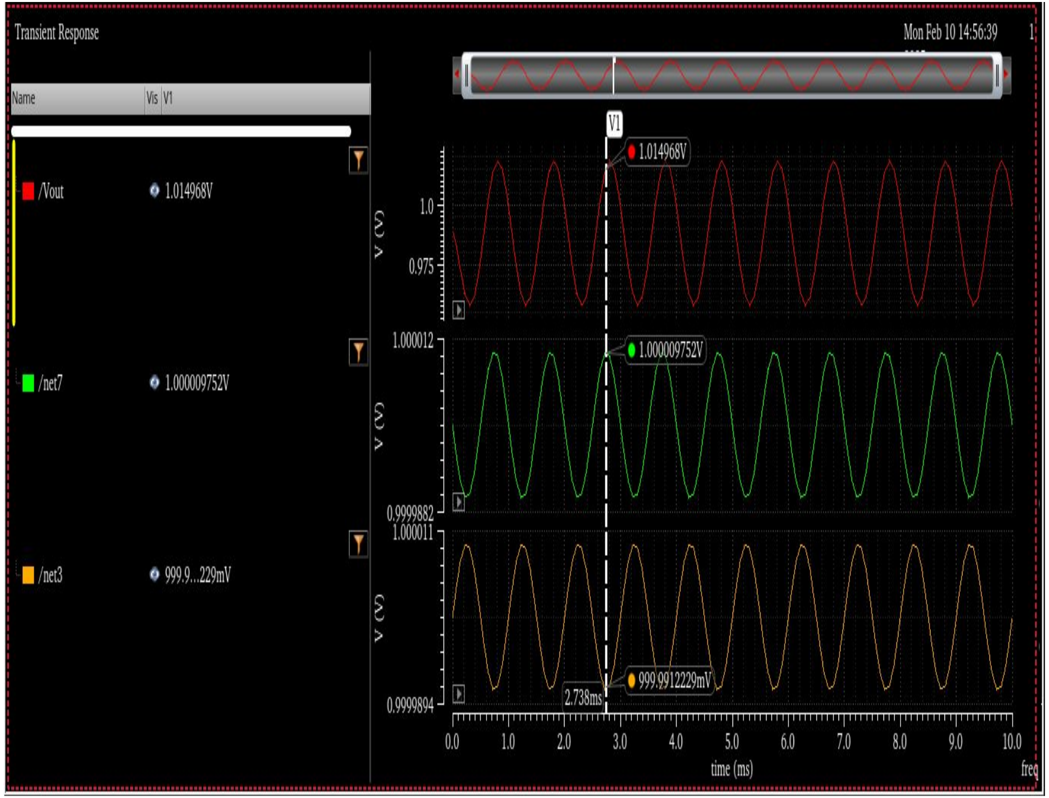
5. Compensation :

- **CL** = 10pF : Load capacitance
- **Cc** = 3pF   : Miller compensation capacitor, used to ensure stability and avoid oscillations.

6. Why we use this particular opamp?

This two-stage CMOS operational amplifier is chosen for its balance between **high gain and stable frequency**. It is widely used in **low-power, low-voltage applications.**

Transient Response of the Operational Amplifier



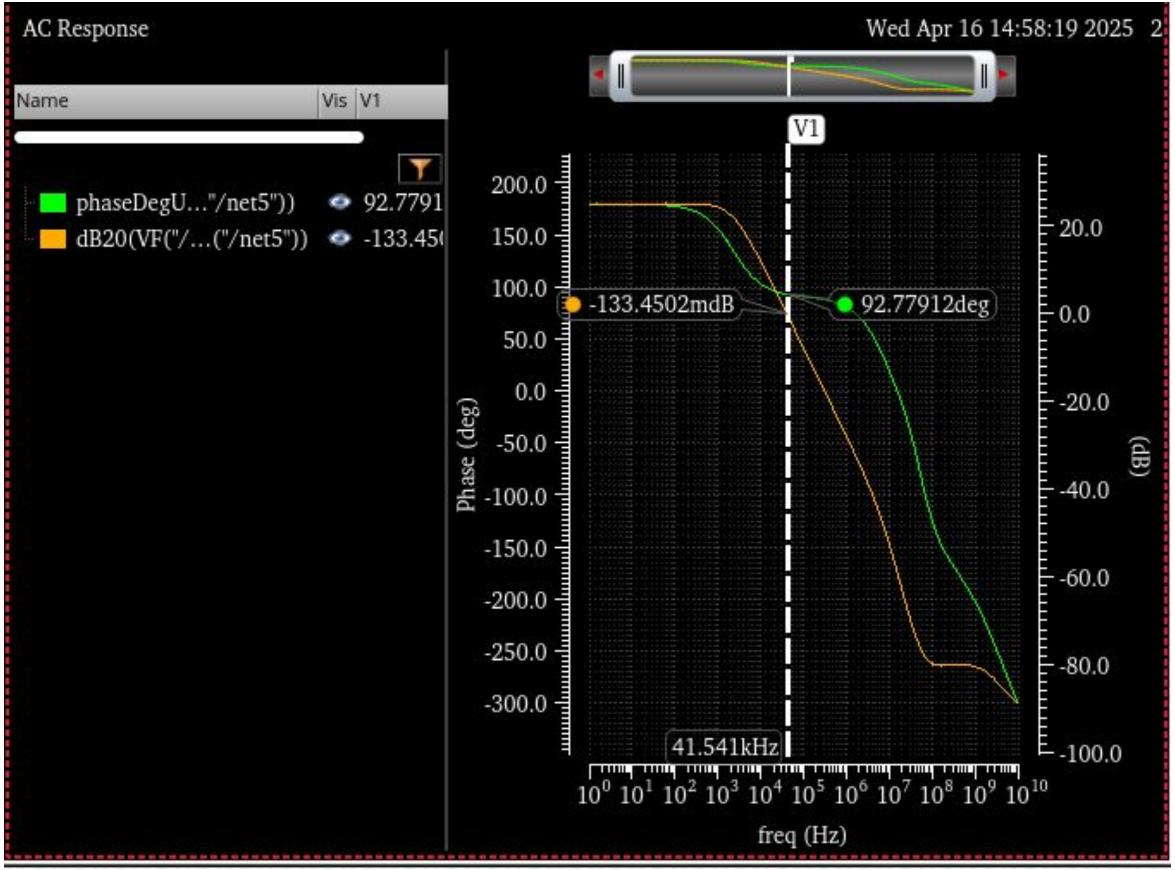
Vin (+) = AC = 1V , DC = 1V

Vin (-) = AC = -1V , DC = 1V

Amplitude = 10uV

Frequency sweep range - 1KHz

Gain and Phase Plot of the Operational Amplifier



1. Gain of the circuit = 70dB
2. Phase Margin = 60°
3. Frequency range = 1 - 100 Hz

SPECIFIC PARAMETERS	DESIGNED VALUES
Technology	180 nm
Bias Voltage	1 V
DC Voltage	1.8 V
DC Current	2 uA
Gain Bandwidth	1 - 100 Hz
Gain	70 dB
Phase Margin	60°
Cc	100 pF
Load Capacitance	120 pF
Slew Rate	0.67 V/µs

Instrumentation Amplifier

Stage 1: Buffering and Gain Setting

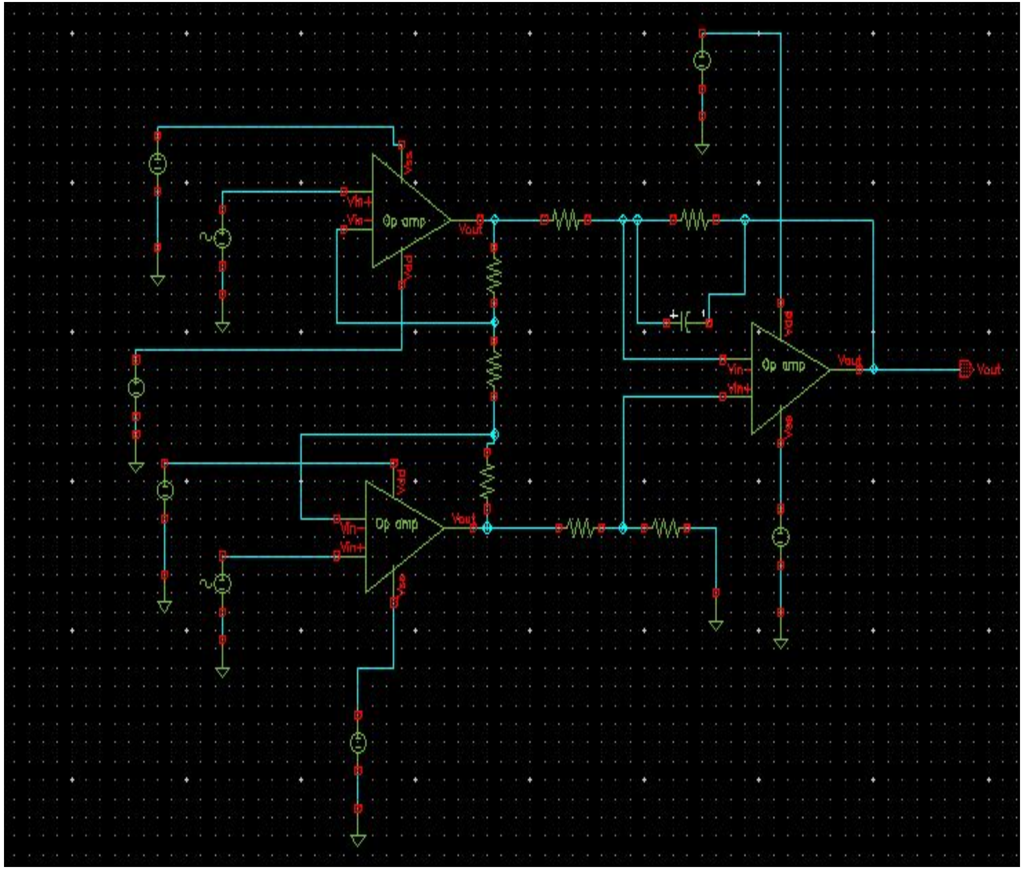
- Consists of 2 OpAmps and gain is controlled by single resistor (Rgain) between the 2 OpAmp.

$$\text{Gain}_1 = 1 + \frac{2R_1}{R_{\text{gain}}}$$

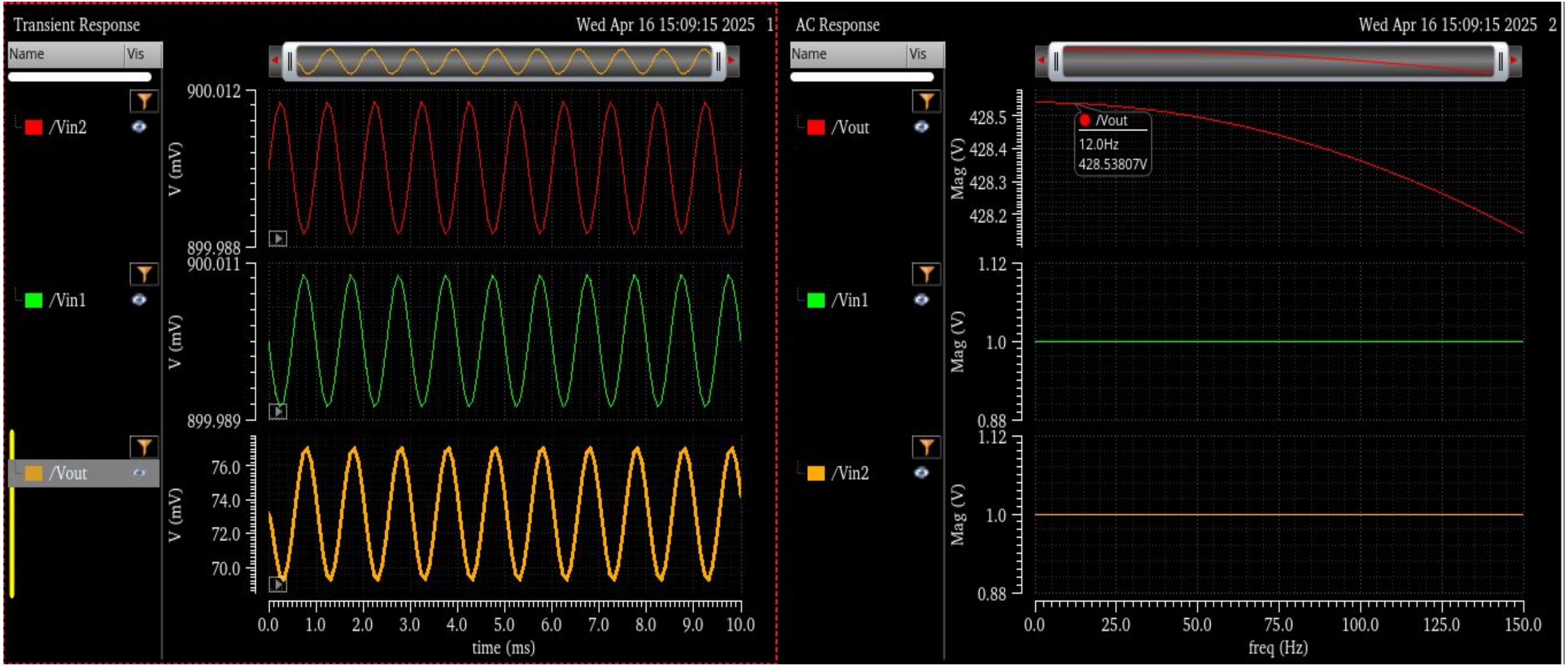
Stage 2: Differential Amplifier

- The output of the first stage feed into the **third op-amp**, which acts as a **differential amplifier**.
- This stage amplifies the **difference** between the two input voltages and **rejects common-mode signals**

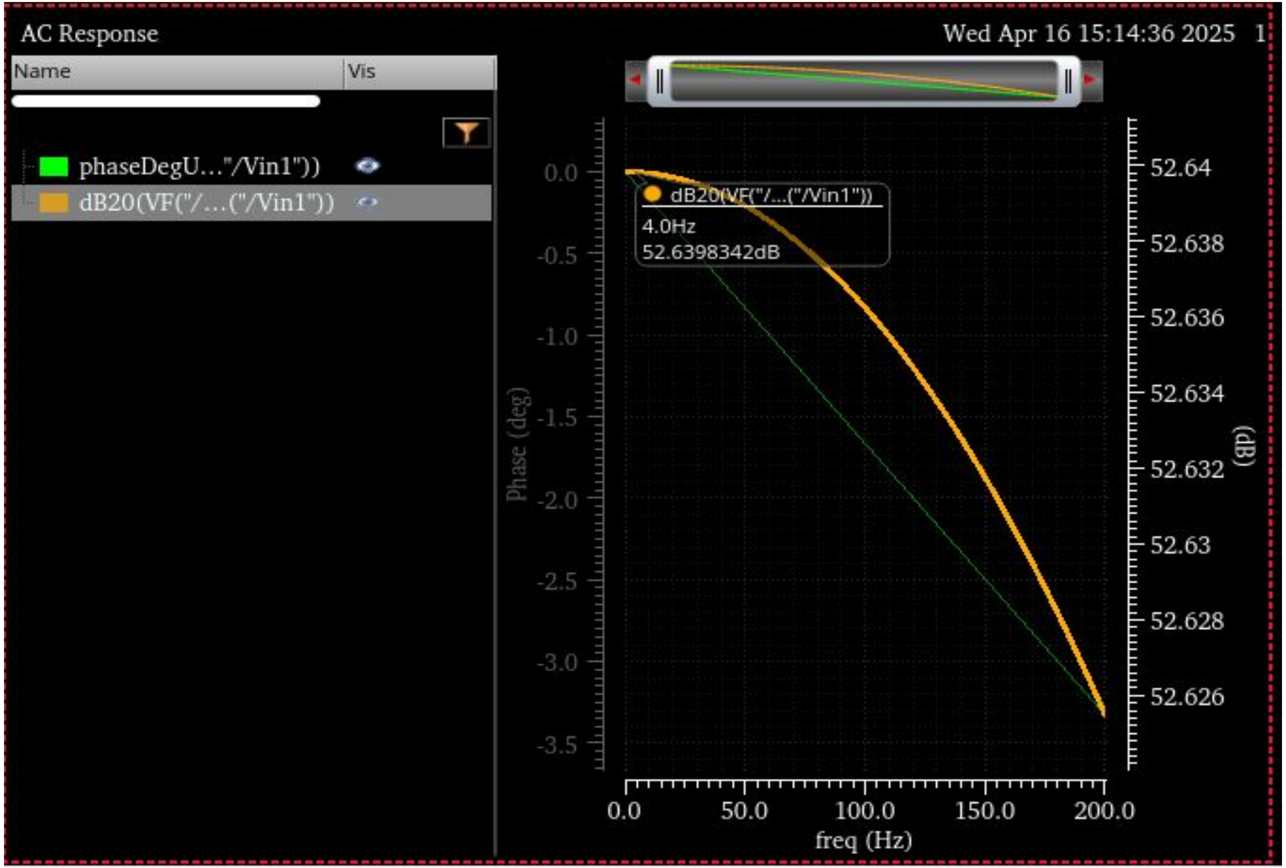
$$V_{\text{out}} = \left(1 + \frac{2R_1}{R_{\text{gain}}}\right) \cdot \left(\frac{R_3}{R_2}\right) \cdot (V_2 - V_1)$$



Transient Analysis of Instrumentation Amplifier

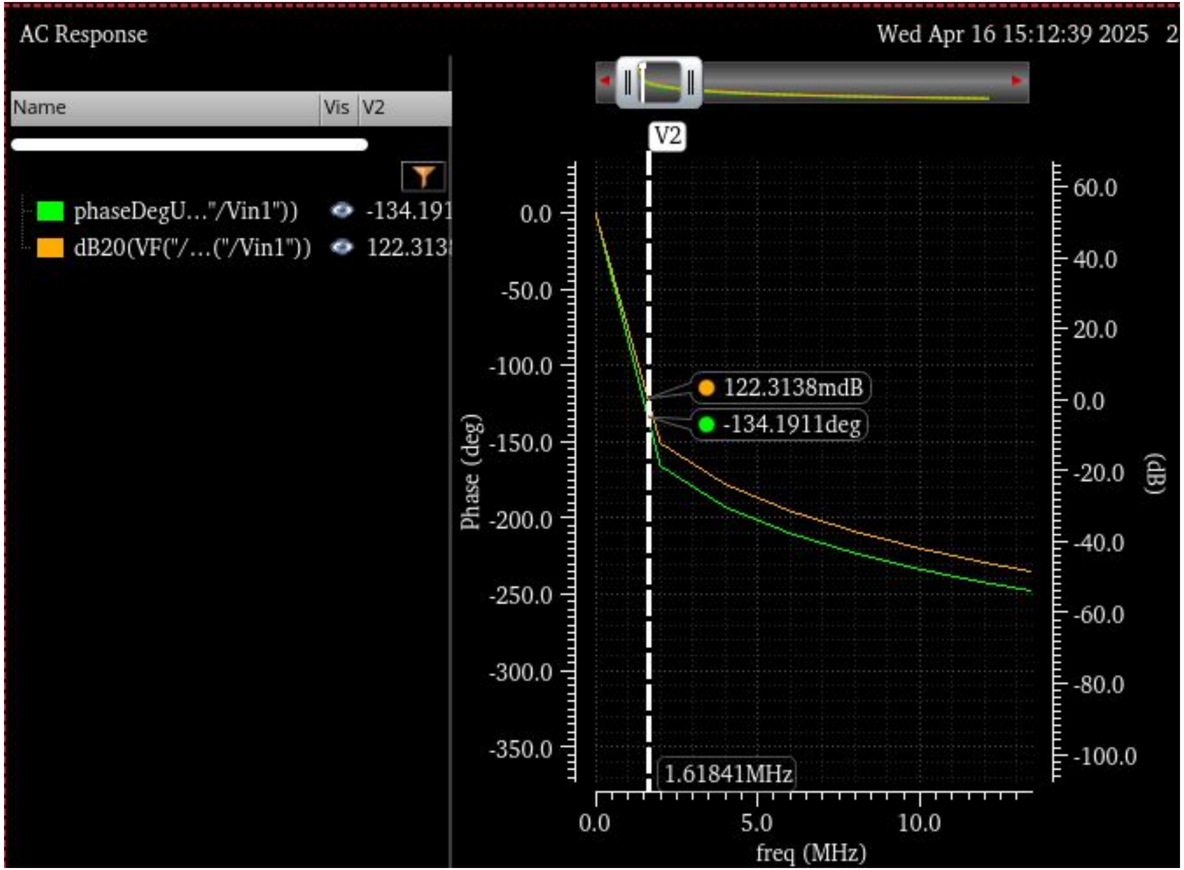


Gain Plot of Instrumentation Amplifier



Gain of IA : 52 dB

Phase Plot of Instrumentation Amplifier



Phase of IA : 45°

Instrumentation Amplifier Design Parameters

SPECIFIC PARAMETERS	DESIGNED VALUES
Gain	52dB
Gain Bandwidth	1 - 100 Hz
Phase Margin	45°
Gain Resistor	500 Ω
R1	10 KΩ
Zin	10 MΩ
Zout	100 Ω

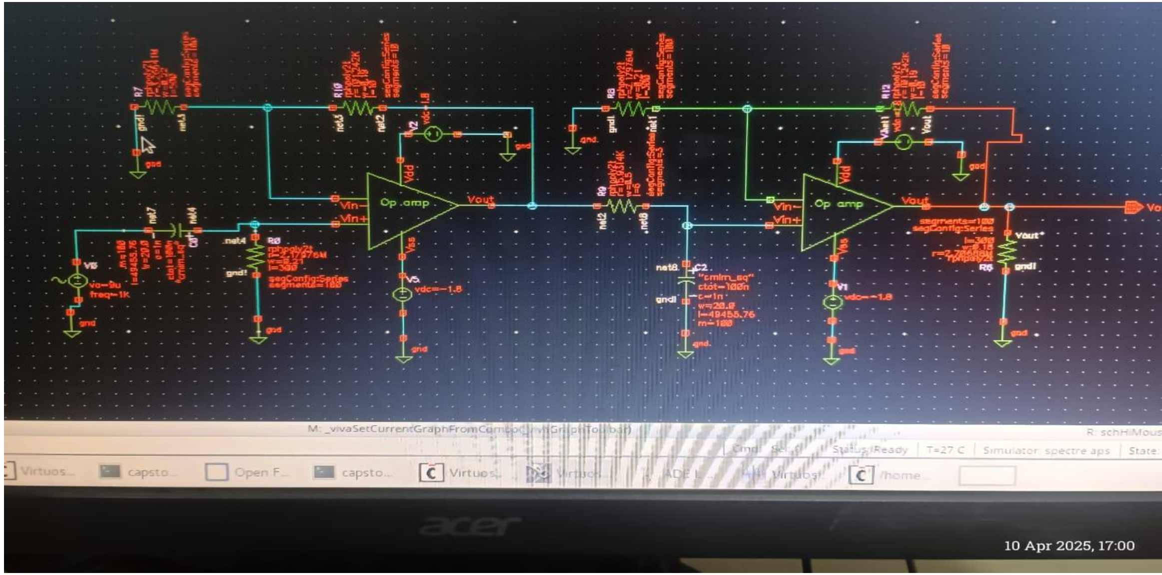
Bandpass Filter

A **bandpass filter** is created by **combining a low-pass filter and a high-pass filter** in series.

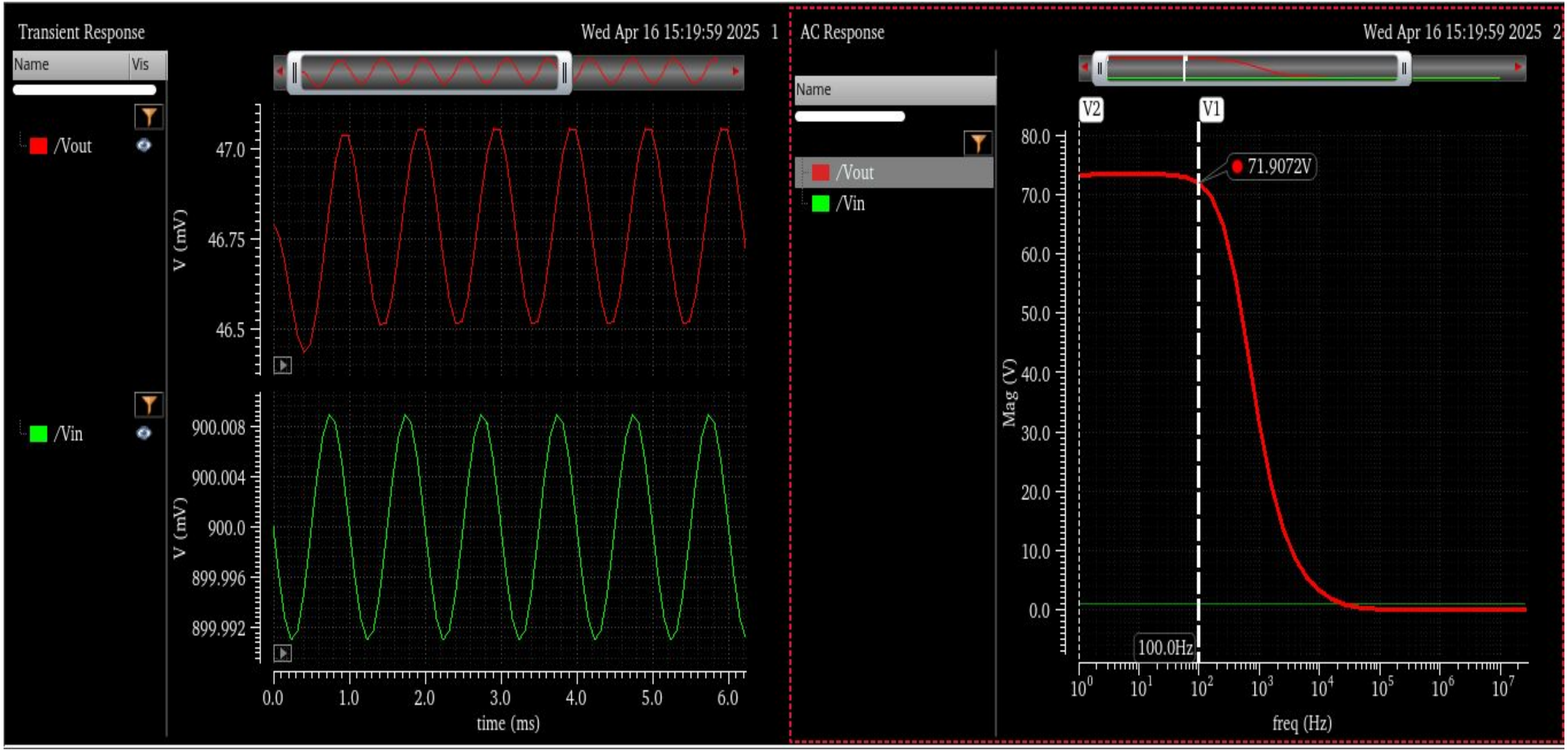
- The **high-pass filter** removes low-frequency signals **below** a certain cutoff frequency (`f_low`).

- The **low-pass filter** removes high-frequency signals **above** a certain cutoff frequency (`f_high`).

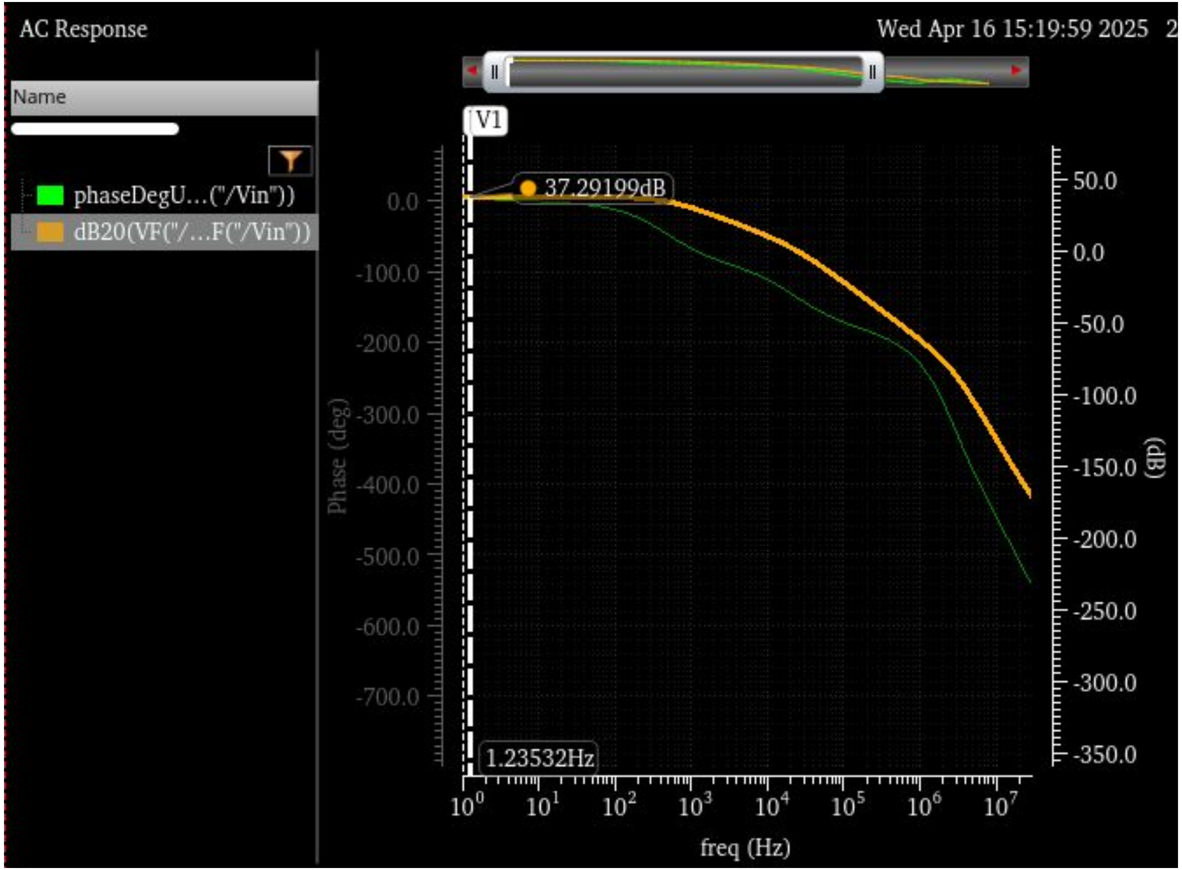
- The resulting filter only **passes signals between `f_low` and `f_high`**, which is the **bandwidth** of the filter.



Transient Response of Bandpass Filter



Gain and Phase of Bandpass Filter



Gain : 37 dB

Bandpass Design Parameters

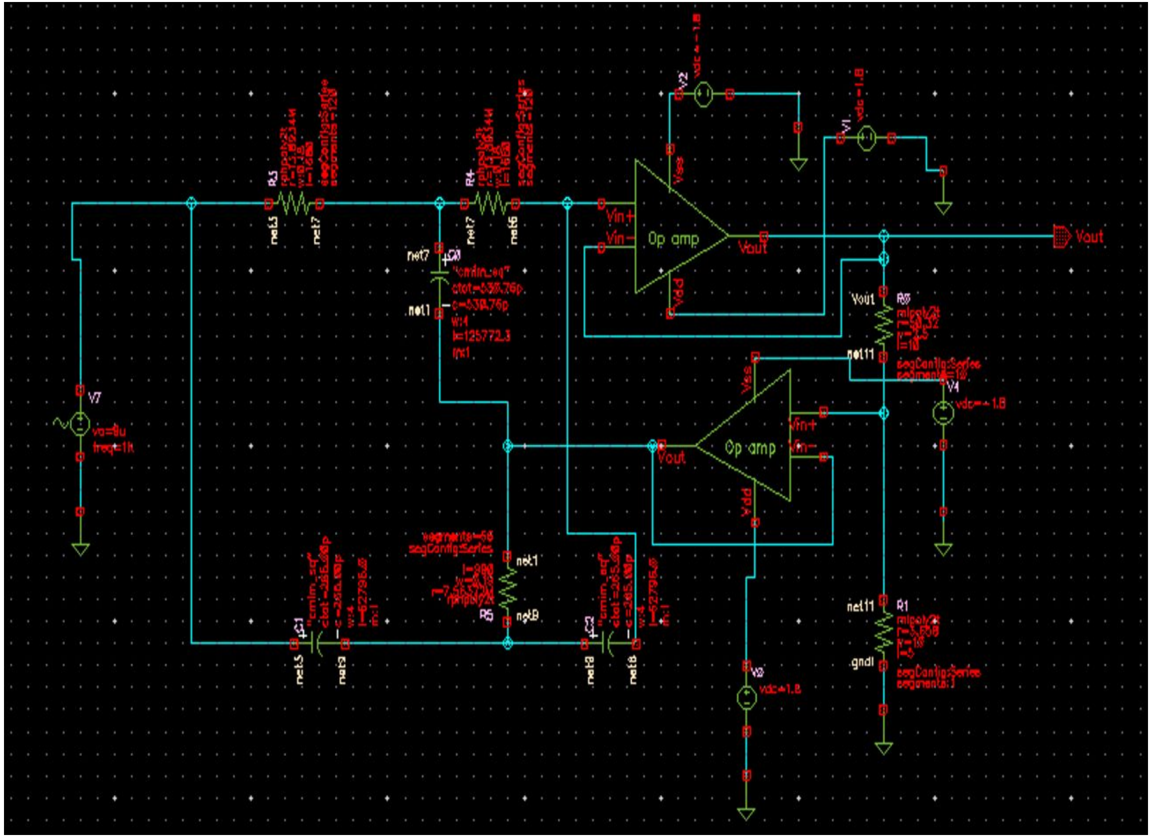
SPECIFIC PARAMETERS	DESIGNED VALUES
Lower Cutoff Frequency	1Hz
Upper Cutoff Frequency	100 Hz
Bandwidth	1- 100 Hz
Quality Factor	100
Gain	37 dB
Filter Order	2
Type	Active Bandpass Filter

Notch Filter

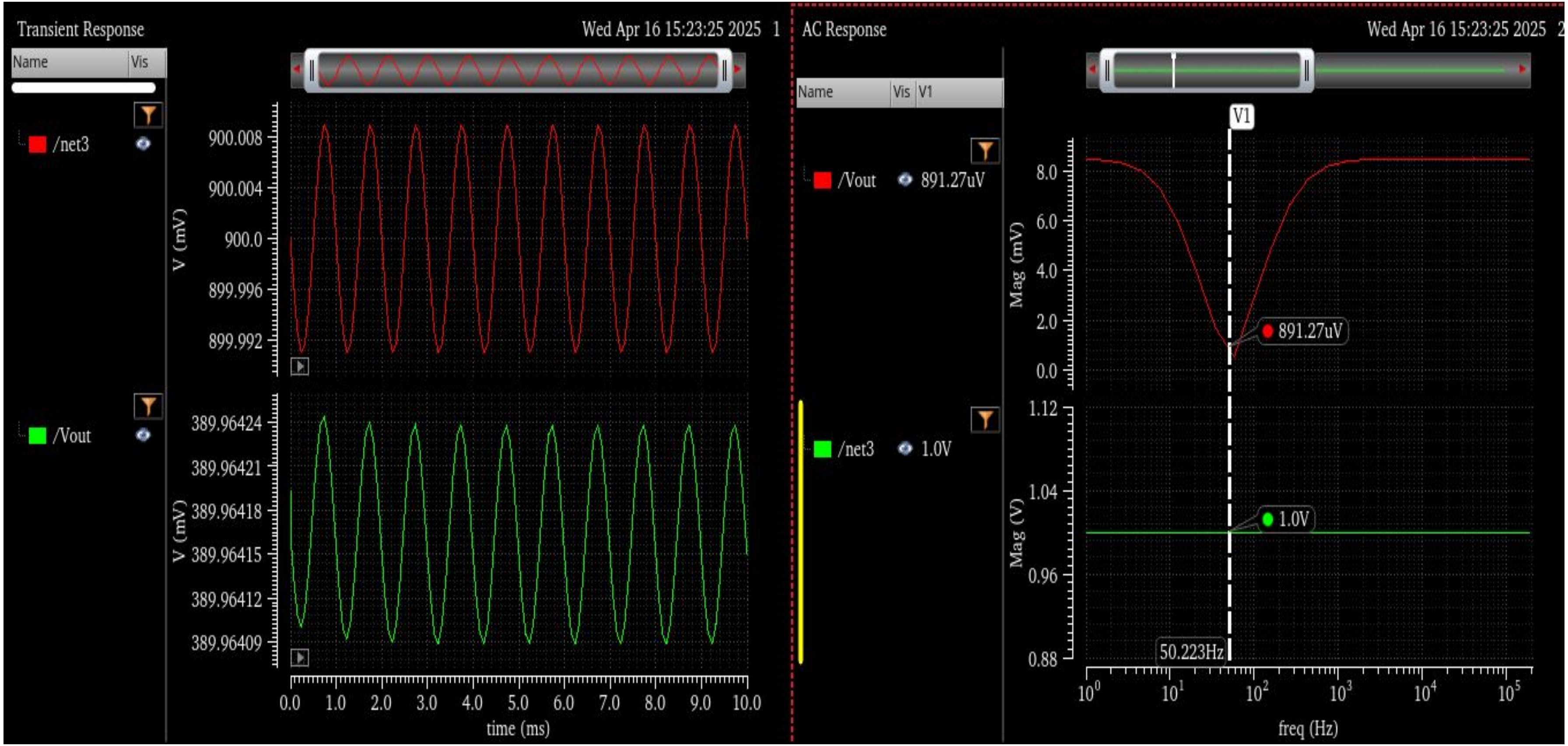
Notch band: The specific frequency that the filter is designed to eliminate. In this region, the signal’s amplitude is significantly reduced, creating the "notch".

second-order bandstop filter (analog) transfer function is given as:

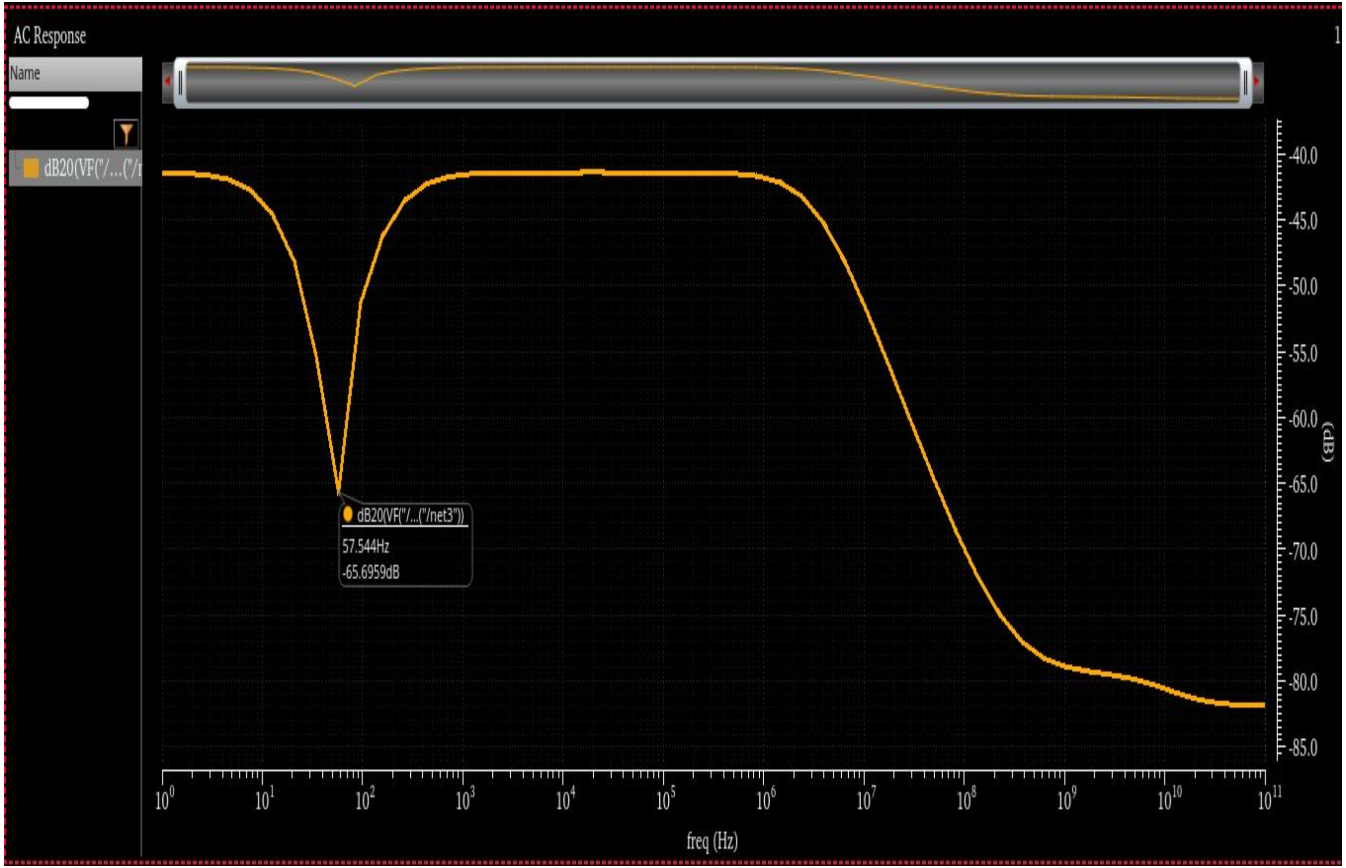
$$H(s) = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$



Transient Analysis of Notch Filter



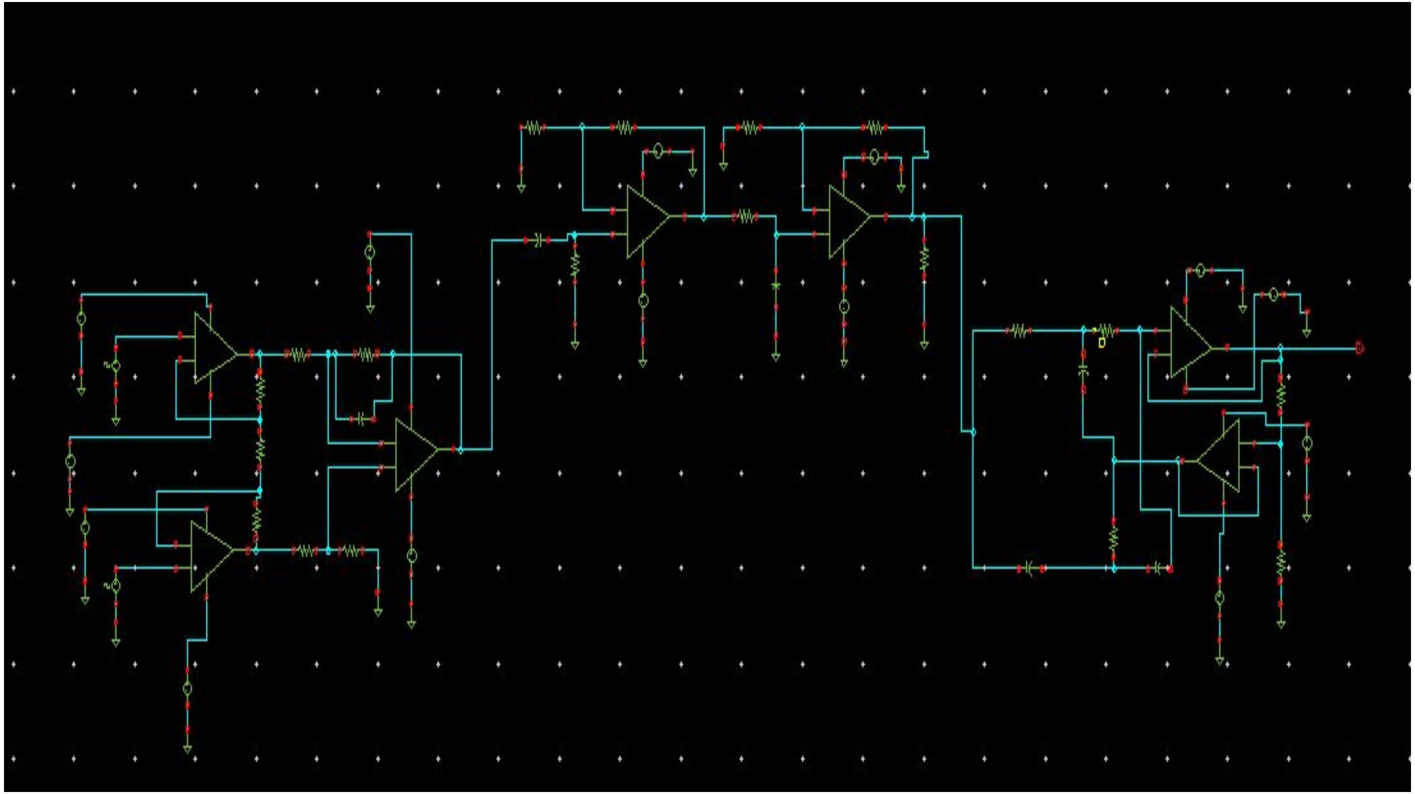
Gain Plot of Notch Filter



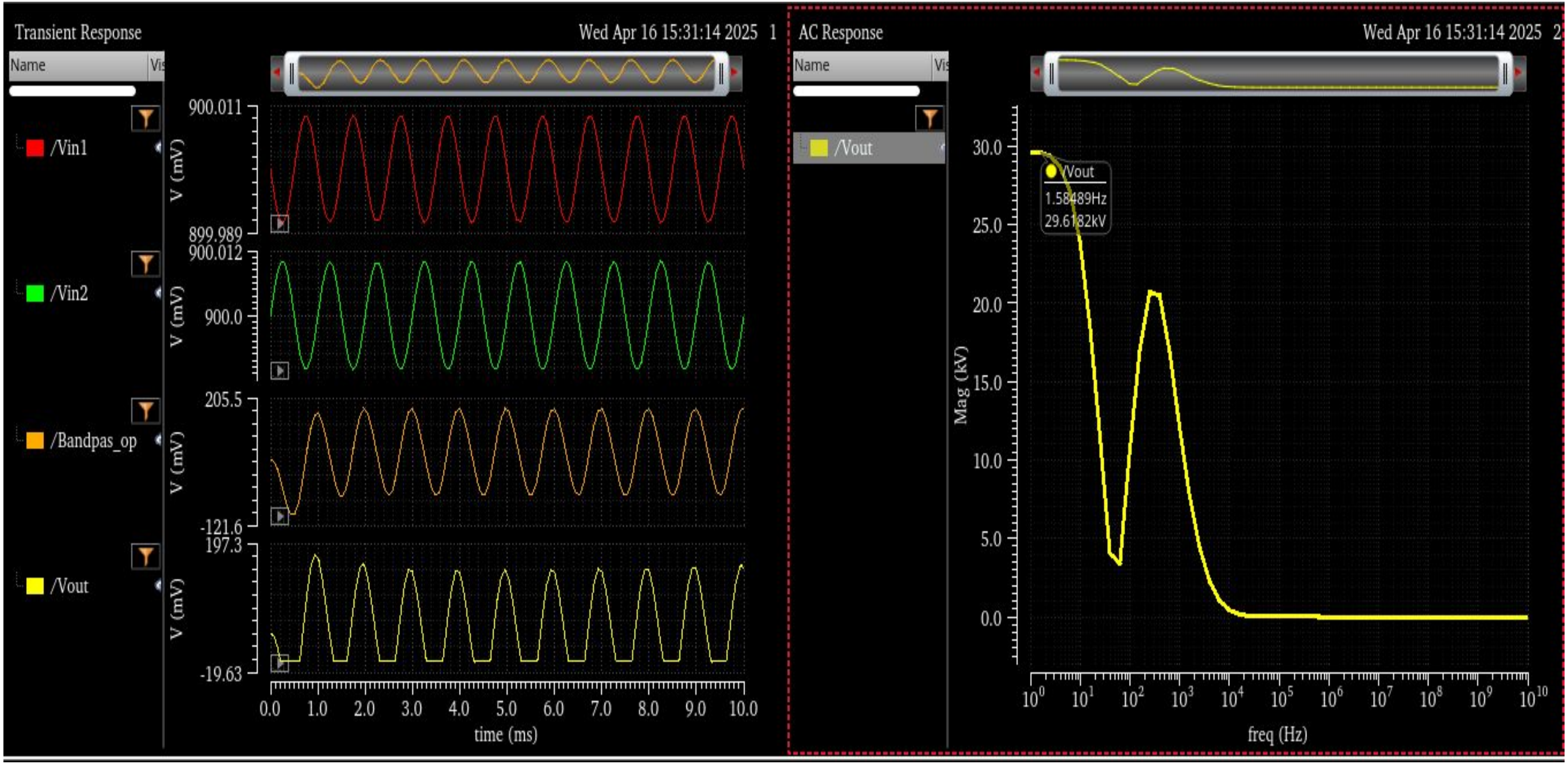
Notch Filter Design Parameters

SPECIFIC PARAMETERS	**DESIGNED VALUES**
Center Frequency (fc)	50 Hz
Gain Bandwidth	1 - 100 Hz
Quality Factor (Q)	100
Capacitance (C)	500 pF
Filter Type	Two op-amp notch filter design

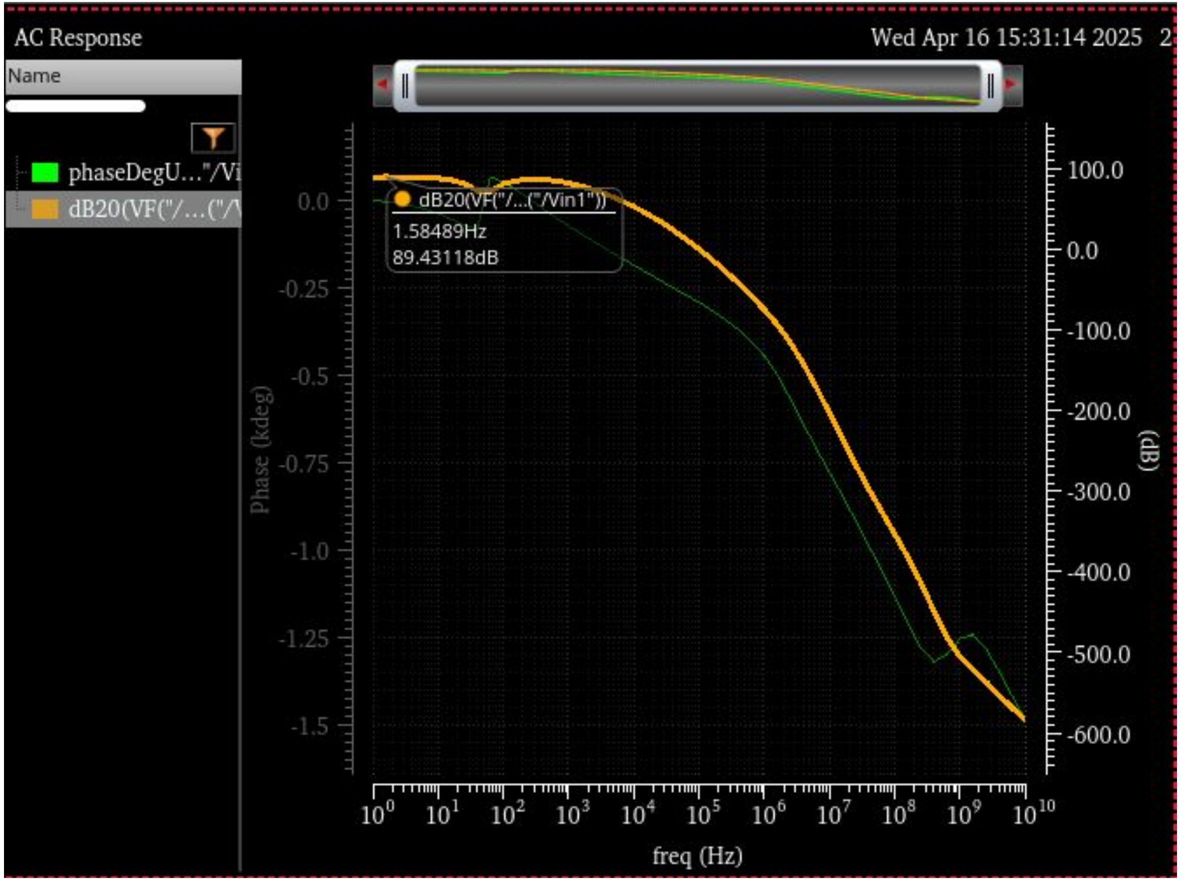
EEG Sensor Schematic



Transient Response of EEG Sensor

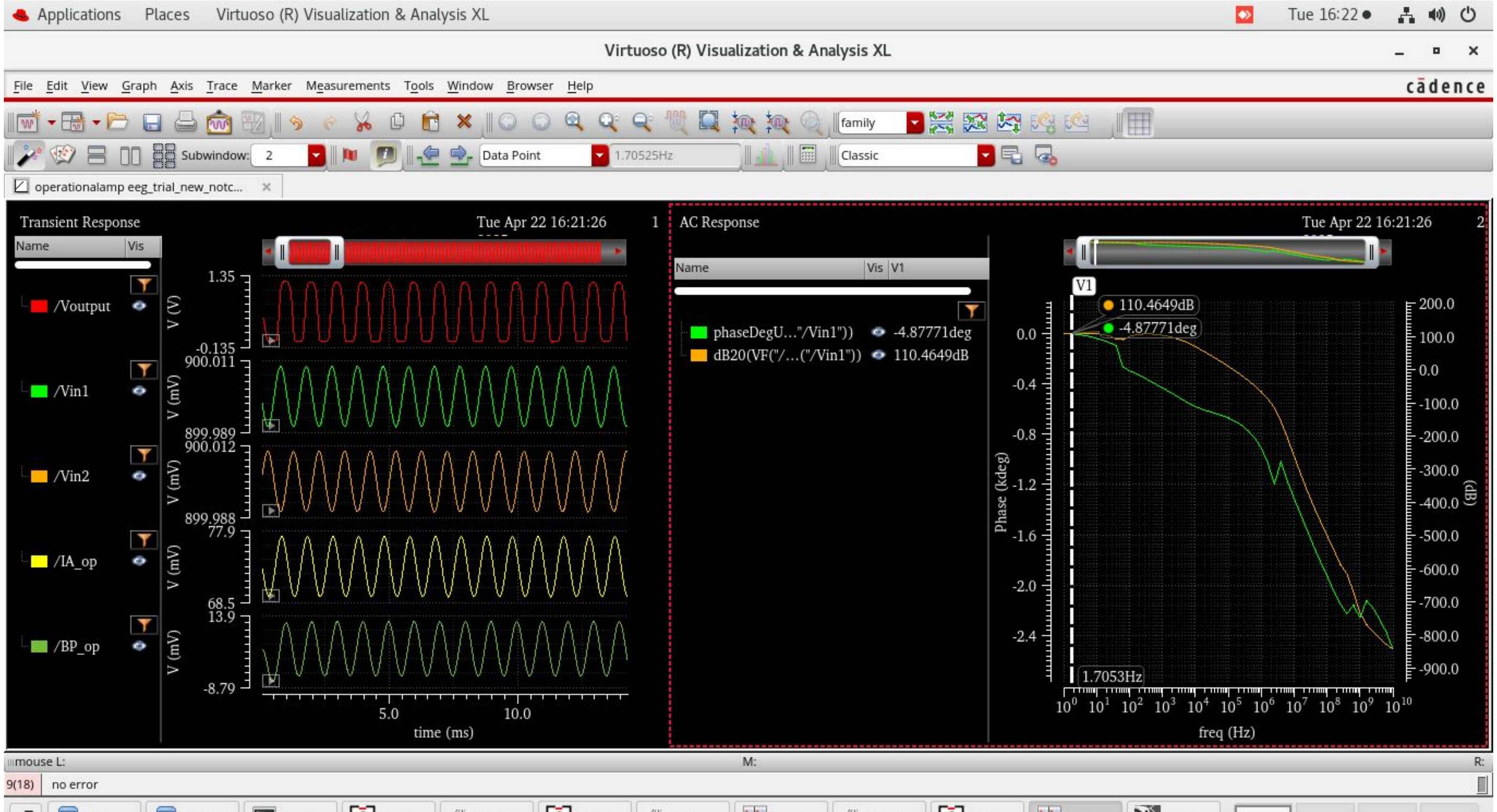


Gain and Phase Plot of EEG Sensor



EEG Sensor Schematic

Gain and Phase Plot of EEG Sensor



Project Timeline

Literature Survey

Conduction of Literature survey and decided Problem statement.

2024

Jan - April 2025

Circuit design and analyses

Designing and analyzing operational amplifier,IA,Bandpass filter,Notch filter.

June - Sep 2025

Layout implementation and Testing

Layout implementation for all circuits.

References

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Thank You