Second order filters

Sai Akhila - EE24BTECH11055
Sai Akshita - EE24BTECH11054

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1 Objective:

- To design and implement a bandpass filter using separate Sallen-Key Low Pass Filter (LPF) and High Pass Filter (HPF).
- To analyze and compare the frequency response of LPF, HPF, and the final bandpass filter.
- To plot the magnitude response (gain vs. frequency) of all three filters.

2 Components and Equipment Required:

- Operational Amplifiers (e.g., TL074, TL081, or LM358)
- Resistors: R1, R2, R3, R4 (in kΩ)
- Capacitors: C1, C2, C3, C4 (in nF)
- Function Generator
- Oscilloscope or Spectrum Analyzer
- DC Power Supply (±12V)
- Breadboard and connecting wires

3 Role of Op-Amp in Sallen-Key Filters:

- Helps in Amplification of the output signal.
- The high input impedance and low output impedance of an op-amp prevent loading effects.
- Allows better control over cutoff frequency, Q-factor, and bandwidth compared to passive filters.
- Op-amps ensure better linearity and stable frequency response, reducing signal distortion.

4 Types of Filter Designs:

- **Butterworth Filter:** Maximally flat frequency response ()
- **Chebyshev Filter:** Faster roll-off than Butterworth but introduces ripples.
- **Bessel Filter:** Best for preserving waveform shape (constant group delay).

5 Types of Filters

5.1 Sallen-Key Low Pass Filter

The Sallen-Key low-pass filter is a second-order active filter that allows low-frequency signals to pass while attenuating higher-frequency signals. It consists of an op-amp, two resistors, and two capacitors arranged in the given specific topology.

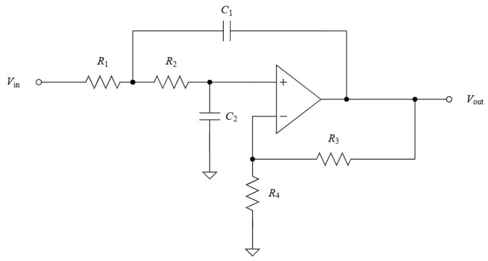

Figure 1: Sallen-Key Low pass filter

Working Principle:

- When low-frequency signals are given as input to the circuit, the impedance of the capacitors ($\frac{1}{\omega C}$) is high, resulting in open- wire behaviour of the capacitor branch. This ensures that the signal is passed that with minimal attenuation.

- When high-frequency signals are given as input to the circuit, the impedance of the capacitors ($\frac{1}{\omega C}$) is low, resuiting in lower impedance behaviour of the capacitor branch. Thus, more amount of current flows in to the branch and hence, the signal is not reached to V_{out}.

- The input signal (Vin) passes through R1 and C1, forming the first stage of filtering.

- R2 and C2 create a second filtering stage before the op-amp.

- The op-amp acts as a buffer to prevent loading effects and maintain stability.

- The resistors R1 and R2 form a voltage divider with C1 and C2 and define the cutoff frequency.

- R3 and R4 allow gain adjustment.

- C1, also known as Feedback capacitor, Works with R1 and R2 to determine the filter's frequency response and provides negative feedback to the op-amp, improving stability.

- C2 Forms a low-pass network with R2.

- Transfer function of the filter is $H(s) = \frac{K}{s^2 + \frac{\omega_c}{Q}s + \omega_c^2}$, where K is the gain.

- Quality factor is $Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 + R_2}$

- At cutoff-frequency, the output voltage drops to 70.7%(-3dB) of the input voltage if r1=r2=r and c1=c2=c.(optional)
- The cutoff Frequency is given by$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$

5.2 Sallen-Key High Pass Filter

The Sallen-Key high-pass filter is a second-order active filter that allows high-frequency signals to pass while attenuating lower-frequency signals. It consists of an op-amp, two resistors, and two capacitors arranged in the given specific topology.

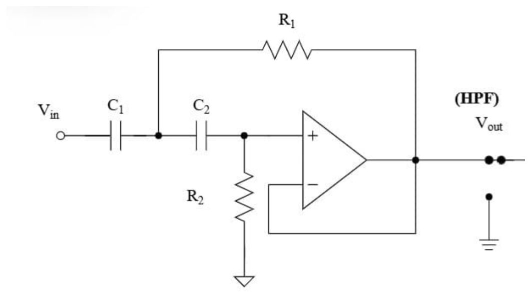

Figure 2: Sallen-Key High pass filter

Working Principle:

- When high-frequency signals are given as input to the circuit, the impedance of the capacitors ($\frac{1}{\omega C}$) is low, resulting in lower impedance behaviour of the capacitor branch. This ensures that the signal is passed that with minimal attenuation.
- When low-frequency signals are given as input to the circuit, the impedance of the capacitors ($\frac{1}{\omega C}$) is high, resuiting in open-wire behaviour of the capacitor branch. Thus, less amount of current flows in to the branch and hence, the signal is not reached to V_{out}.
- C1 (Input Capacitor) blocks low frequencies and allows high frequencies to pass.

- C2 (Feedback Capacitor) Shapes the frequency response by interacting with the op-amp's feedback loop.
- The cutoff frequency is given by $f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$
- gain is given by $K = 1 + \frac{R_3}{R_4}$
- At cutoff-frequency, the output voltage drops to 70.7%(-3dB) of the input voltage if r1=r2=r and c1=c2=c.

subsectionSallen-Key Band Pass Filter A Butter-worth band-pass filter is a type of electronic filter that passes frequencies within a certain range and attenuates frequencies outside that range. The Butterworth bandpass filter is typically constructed by cascading a low-pass and a high-pass filter.

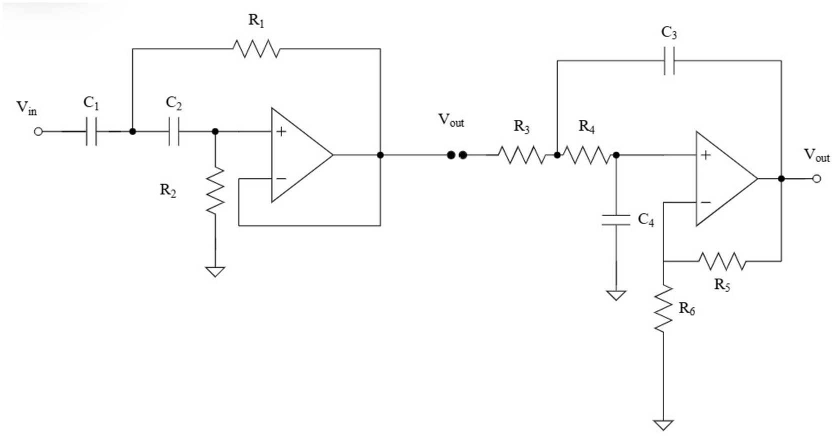

Figure 3: Circuit Diagram

Working Principle:

- The bandpass filter is typically constructed by cascading a high-pass and a low-pass Sallen-Key filter stage.
- The lower cutoff frequency (f_L) is determined by the high-pass section, while the upper cutoff frequency (f_H) is set by the low-pass section.
- When input frequencies are between f_L and f_H, the filter allows them to pass with minimal attenuation.
- For frequencies below f_L, the high-pass section attenuates the signal, while the low-pass section has little effect.

- For frequencies above f_H, the low-pass section attenuates the signal, while the high-pass section has minimal impact.
- The center frequency (f_c) of the bandpass filter is the geometric mean of f_L and f_H, given by: $f_c = \sqrt{(f_L \times f_H)}$
- The bandwidth (BW) is defined as the difference between the upper and lower cutoff frequencies: $BW = f_H - f_L$
- The quality factor (Q) of the bandpass filter is given by: $Q = f_c/BW$
- The transfer function of the bandpass filter is the product of the high-pass and low-pass transfer functions:

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

  , where K is the gain, ω_c is the center frequency in radians/second, and Q is the quality factor.
- The gain at the center frequency is determined by the Q factor and cannot be set independently as in low-pass or high-pass filters.

6 Procedure and Observations

6.1 Low-Pass Filter

1. Assemble the Sallen-key LPF circuit on the breadboard.
2. Use the function Generator to apply a sine wave.
3. Vary the input frequency and measure the output voltage.
4. Record gain values for different frequencies.
5. Plot gain vs. frequency (Bode plot).

6.1.1 Observations

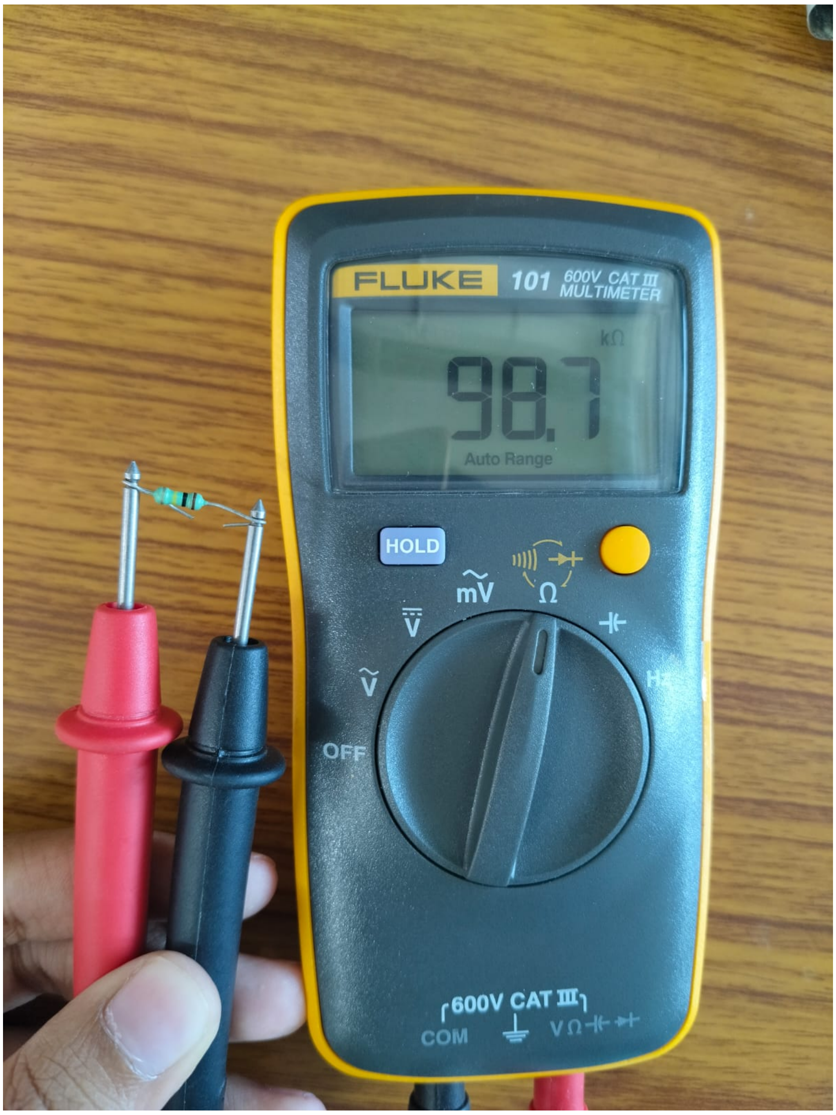

Figure 4: Resistance

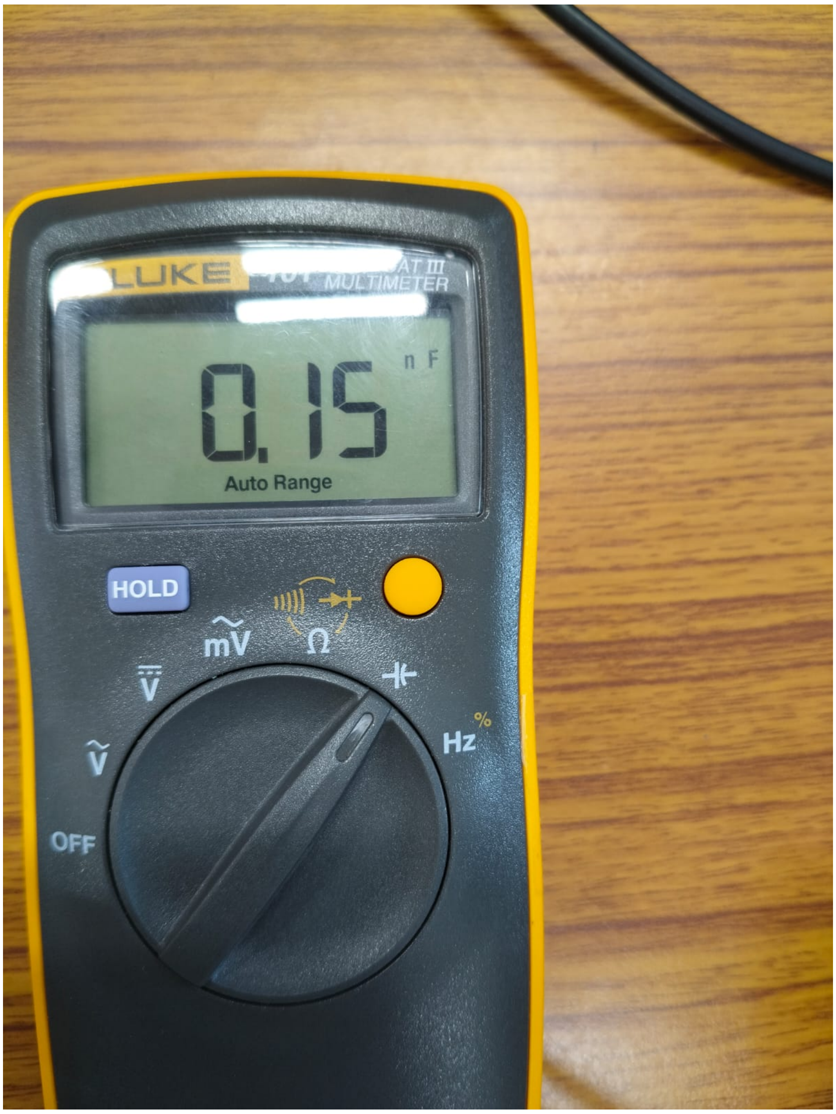

Figure 5: Resistance

The table below shows a comparison between measured values of V_{pp} and Theoretically expected ones.

Frequency(in Hz)	Measured Value
10	11.2
200	11.8
300	11.6
1894	8.321
2000	22.20
3000	10.4
5000	4.96
6000	3.04
7000	2.08
8000	1.58
9000	1.201
10000	0.96

Table 1: Measured vs Theoretical Values

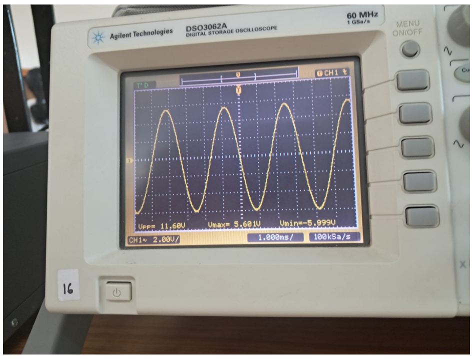

Figure 6: Oscilloscope reading for frequency 300Hz

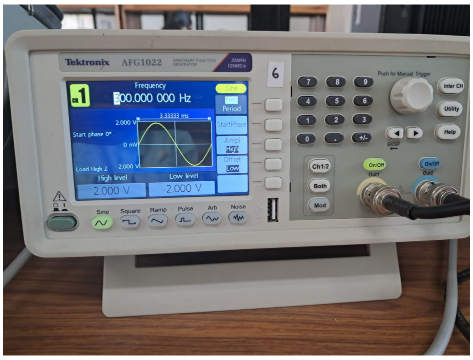

Figure 7: FG

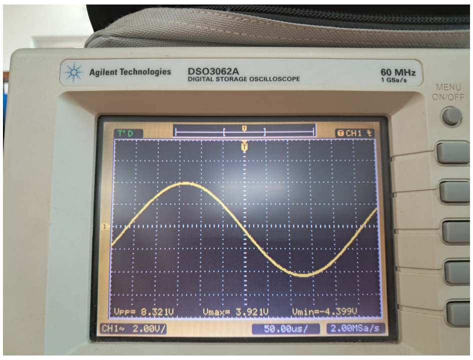

Figure 8: Oscilloscope reading for frequency 1.8kHz

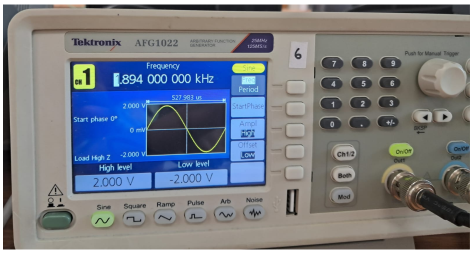

Figure 9: FG

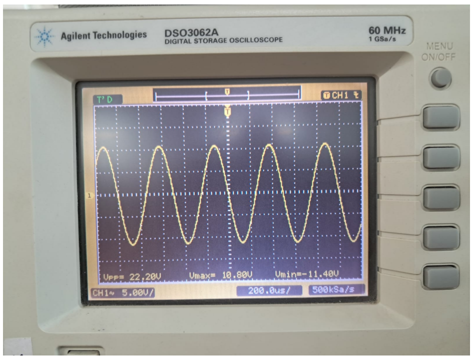

Figure 10: Oscilloscope reading for frequency 2kHz

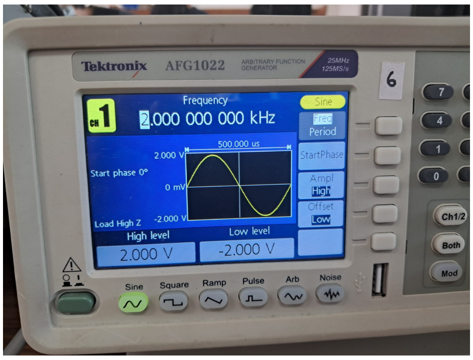

Figure 11: FG

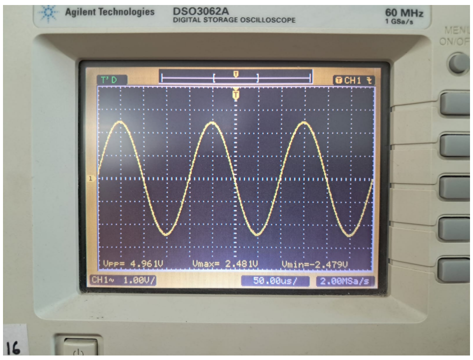

Figure 12: Oscilloscope reading for frequency 5kHz

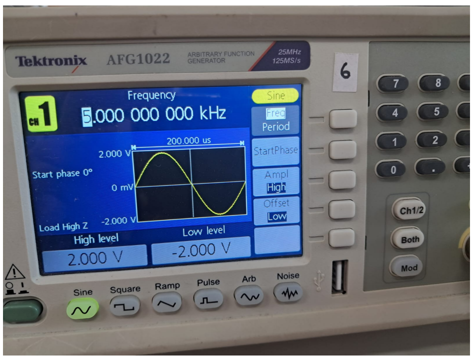

Figure 13: FG

6.1.2 Bode plot

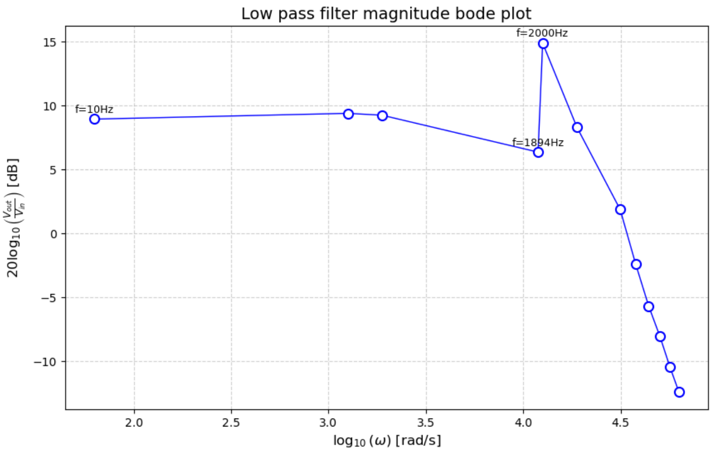

Figure 14: Low pass BP- Measured

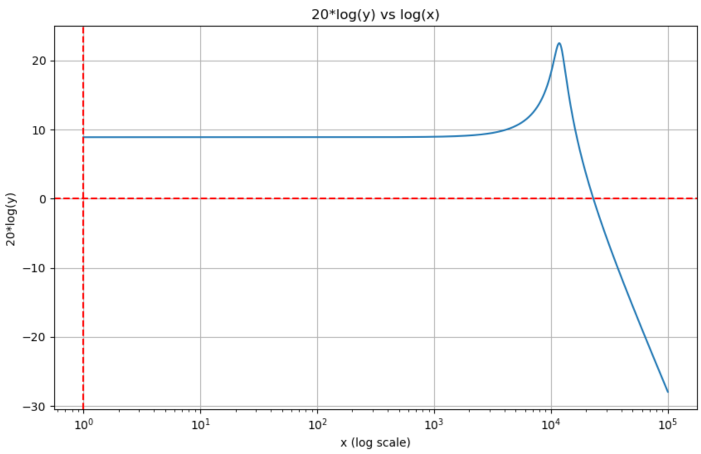

Figure 15: Low pass BP- Theoretical

6.2 High-Pass Filter

1. Assemble the Sallen-key HPF circuit on the breadboard.
2. Use the function Generator to apply a sine wave.
3. Vary the input frequency and measure the output voltage.

4. Record gain values for different frequencies.
5. Plot gain vs. frequency (Bode plot).

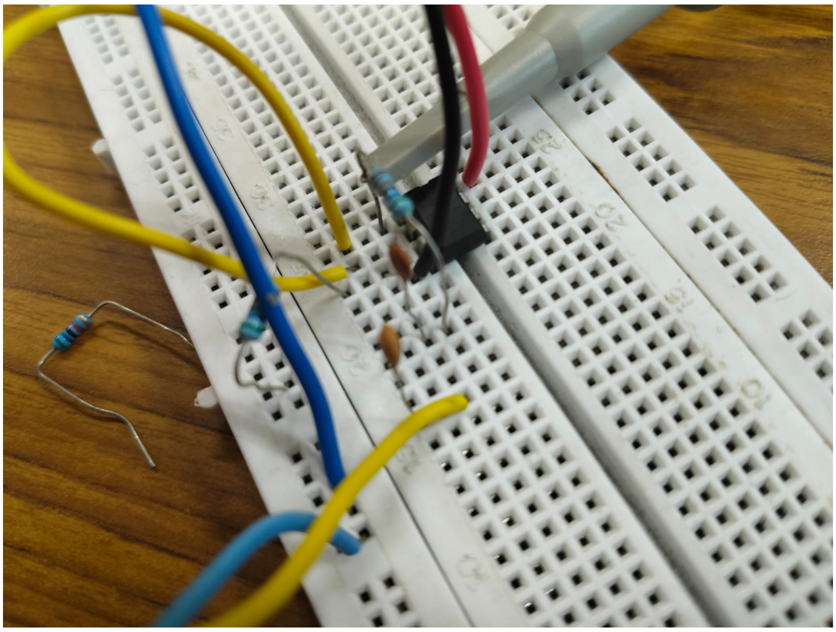

Figure 16: Circuit Diagram

6.2.1 Observations

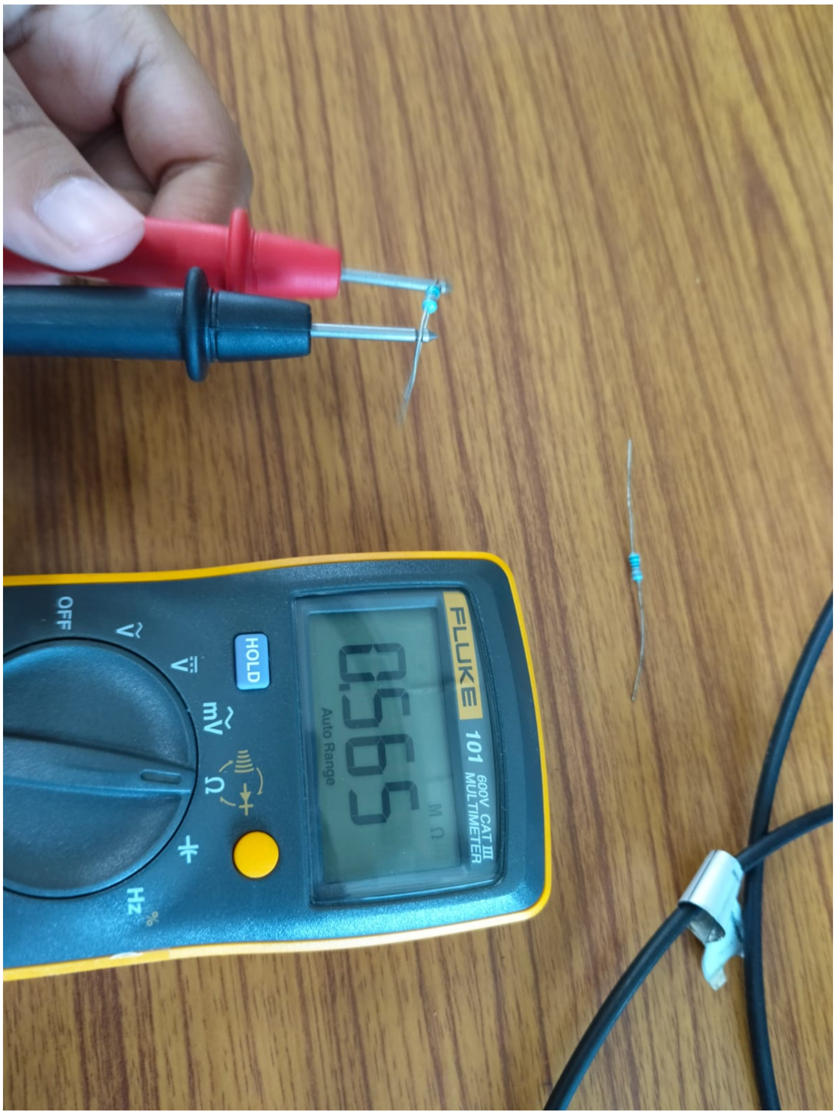

Figure 17: Resistance

Frequency(in Hz)	Measured Values
500	1.001
900	1.201
7000	4.001
10000	4.201
11904	4.201
20000	4.601
50000	4.401

Table 2: Measured vs Theoretical Values

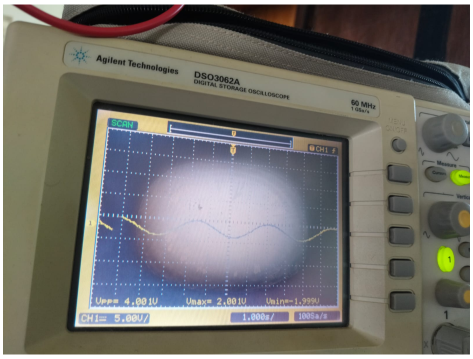

Figure 18: Oscilloscope reading for frequency 7kHz

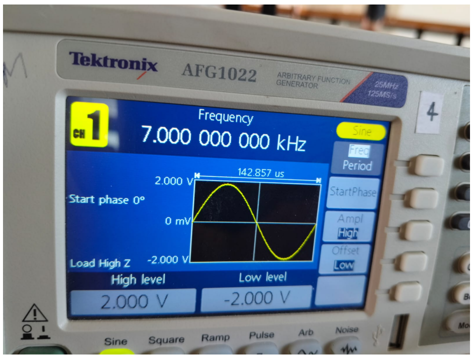

Figure 19: FG

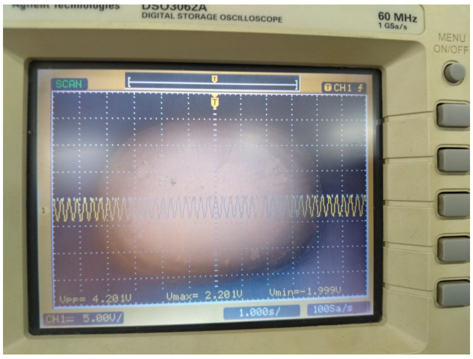

Figure 20: Oscilloscope reading for frequency 11.904kHz

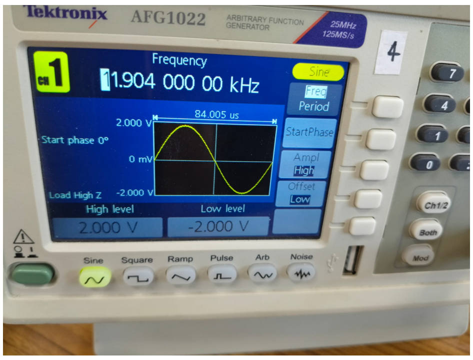

Figure 21: FG

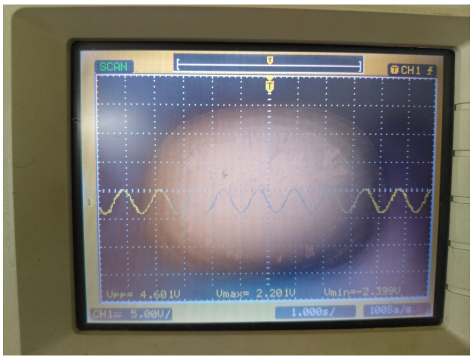

Figure 22: Oscilloscope reading for frequency 20kHz

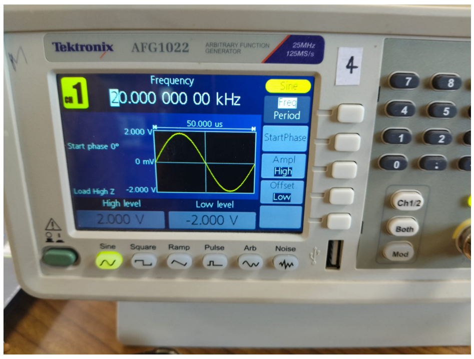

Figure 23: FG

6.2.2 Bode plot

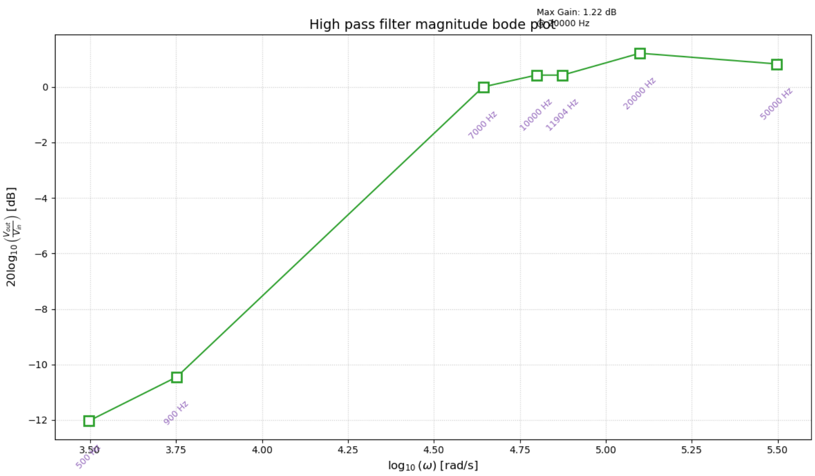

Figure 24: High pass BP- Measured

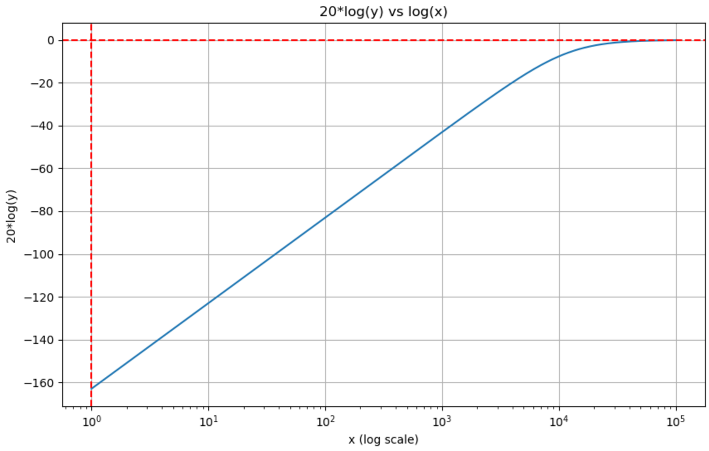

Figure 25: High pass BP- Theoretical

6.3 Band-Pass fiter

1. Assemble the Sallen-key BPF circuit on the breadboard.
2. Use the function Generator to apply a sine wave.
3. Vary the input frequency and measure the output voltage.
4. Record gain values for different frequencies.
5. Plot gain vs. frequency (Bode plot).

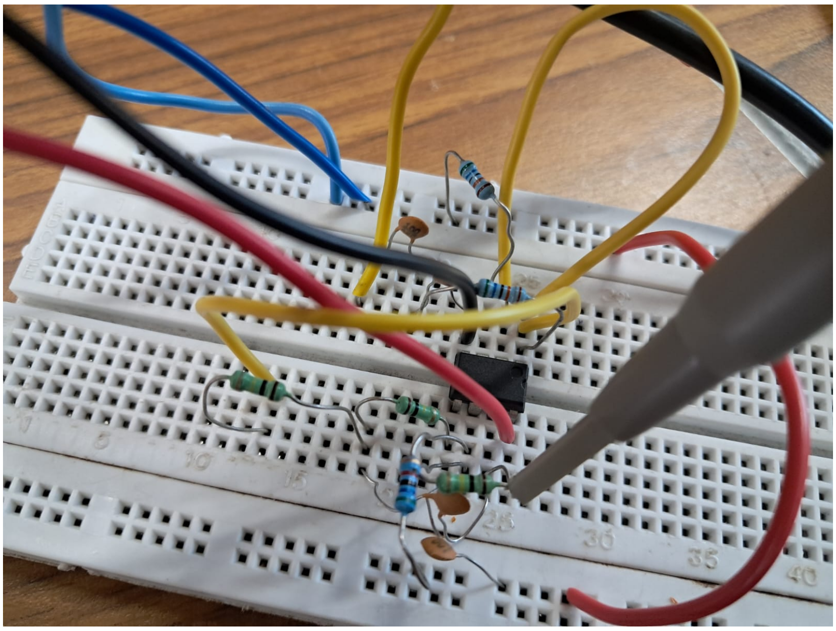

Figure 26: Circuit Diagram

6.3.1 Observations

Frequency(in Hz)	Measured Value
2000	3.801
3000	5.801
5000	7.801
6000	8.001
8000	7.601
10000	7.201
20000	4.601

Table 3: Measured vs Theoretical Values

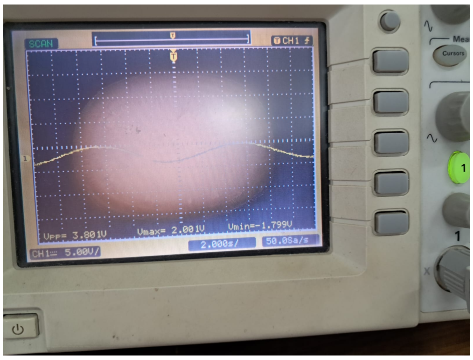

Figure 27: Oscilloscope reading for frequency 2kHz

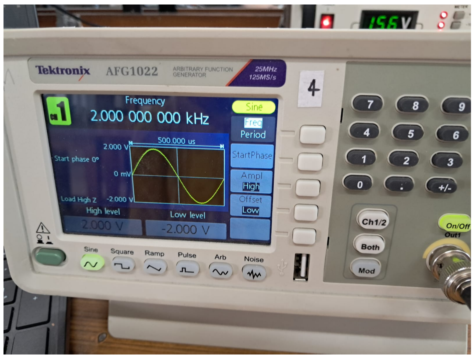

Figure 28: FG

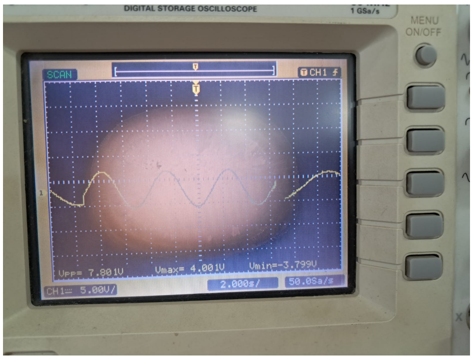

Figure 29: Oscilloscope reading for frequency 5kHz

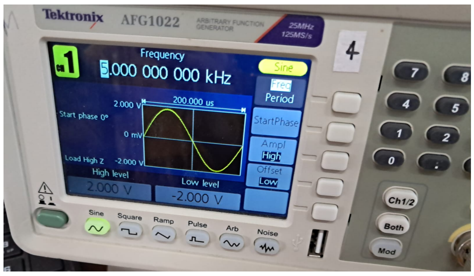

Figure 30: FG

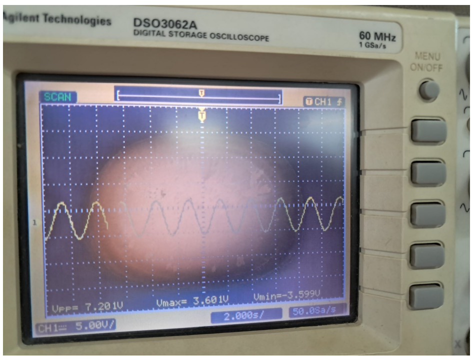

Figure 31: Oscilloscope reading for frequency 10kHz

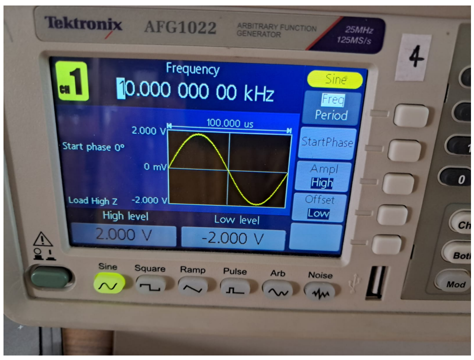

Figure 32: FG

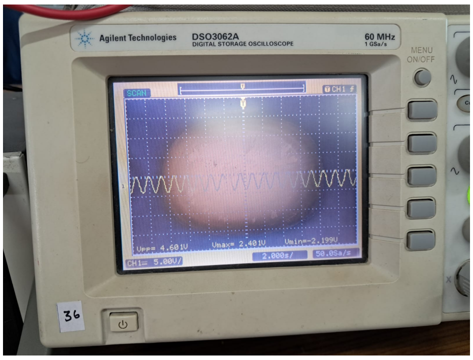

Figure 33: Oscilloscope reading for frequency 20kHz

Figure 34: FG

7 Conclusion

- The experiment verifies the cascading method to form a bandpass filter.
- The experimental results match the theoretical calculations.
- Sallen-Key topology provide good stability and response.

7.0.1 Bode plot

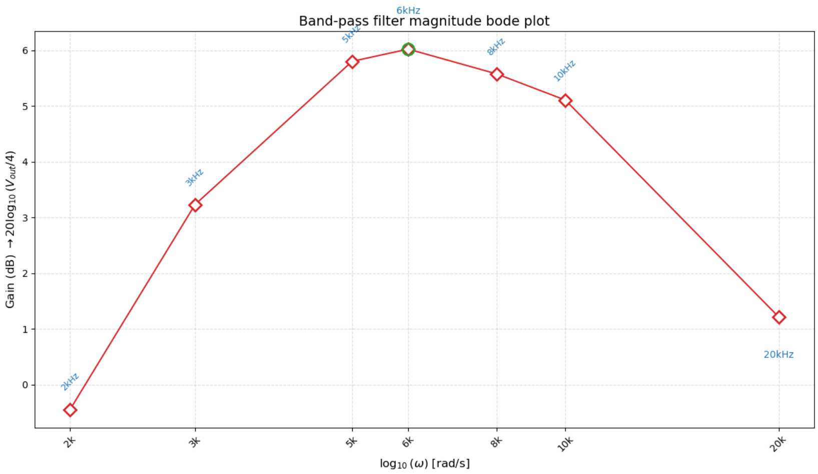

Figure 35: Band pass BP- Measured

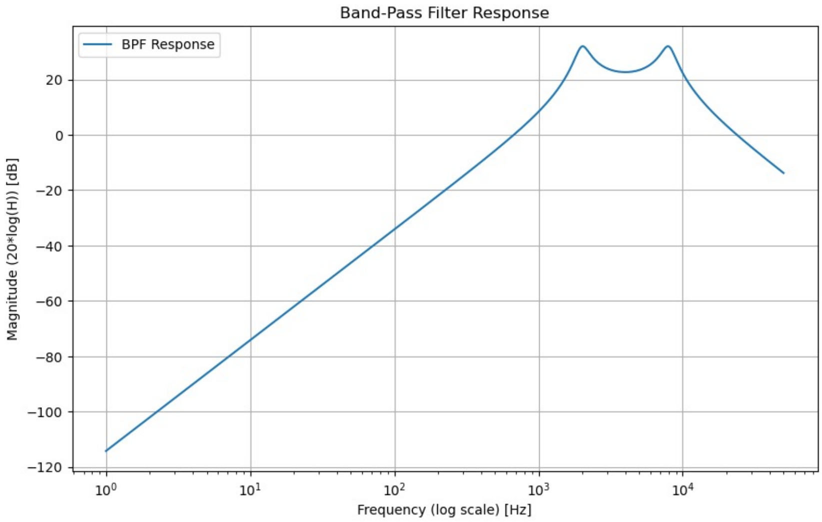

Figure 36: Band pass BP- Theoretical