Bandpass Filter using Sallen-Key Second-Order Filters

- **Second order High Pass Filter**
- **Second order Low Pass Filter**
- **Band Pass Filter**

Indian Institute of Technology Hyderabad

Lab Assignment : 06

EE1200: Electrical Circuits Lab

Harshil Rathan Y	**EE24BTECH11064**
Y Akhilesh	**EE24BTECH11066**

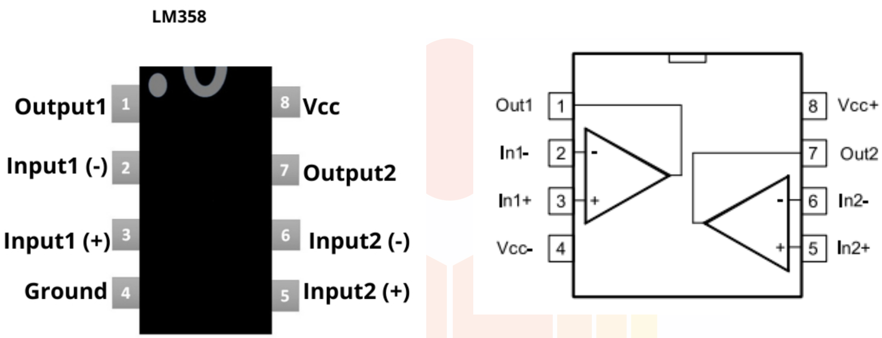
Contents

1 Experiment Objectives

- 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.
- Measure the gain at different frequencies to observe the filter's behavior and compare its frequency response with theoretical calculations.

2 LM358

The LM358 is a low-power, dual-operational amplifier (op-amp) IC designed for general-purpose applications. It consists of two independent, high-gain op-amps that operate from a single power supply.



The pin-out diagram for LM358 is give above

3 Sallen-Key Second-Order Filters

The Sallen-Key topology is a widely used active filter configuration that employs an operational amplifier (op-amp) along with resistors and capacitors to create a second-order filter response. It is commonly used for designing low-pass, high-pass, bandpass, and notch filters. This topology is preferred for its simplicity, stability, and ease of implementation.

Basic Structure

A typical Sallen-Key filter consists of:

- An op-amp configured as a voltage follower or with a fixed gain.
- Two resistors and two capacitors that determine the frequency response.
- A feedback loop that enhances the filter's performance and stability.

The general transfer function for a second-order Sallen-Key filter is given by:

$$H(s) = \frac{A}{s^2 + \frac{\omega_c}{Q} s + \omega_c^2} \tag{0.1}$$

where:

- ω_c is the cutoff frequency.
- Q is the quality factor, which determines the filter's selectivity.
- A is the gain of the system.

4 High-Pass Filter

4.1 Theory

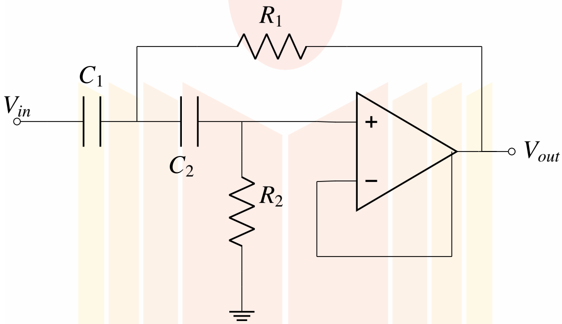
A high-pass filter allows higher frequency signals to pass through while blocking lower frequency components. The frequency at which the filter starts allowing signals through is called the cutoff frequency, given by:

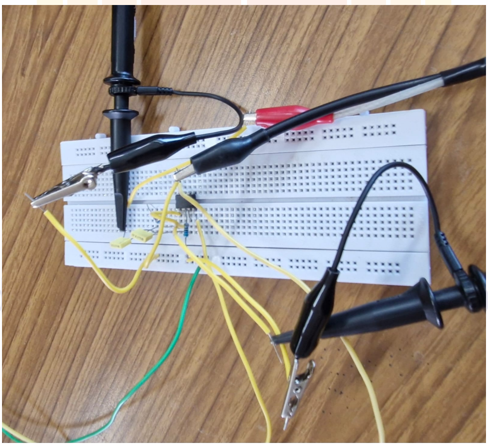
$$f_{c1} = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

This type of filter is useful for removing low-frequency noise.

4.2 Connections

Below is the circuit diagram for a second order sallen key high pass filter





The connections are as shown in the above figure

4.3 Procedure

1. Make connections according to the circuit diagram and LM358 pinout diagram
2. Connect the input function across the first capacitor (Pin 3)
3. Measure the output across the first pin (Pin 1)
4. The values of the resistors and capacitors are
   - $R_1 = R_2 = 56K\Omega$
   - $C_1 = C_2 = 4.7nF$
5. Power the LM358 by connecting V_{cc} (PIN 8) to +15V and GND (PIN 4) to -15V
6. Connect the COM to other end of R_2 GND

4.4 Calculating cutoff frequency

The cutoff frequency (f_c) for a Sallen-Key High-Pass Filter is given by:

$$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$$

Given values,

$$\begin{aligned} R_1 &= 56K\Omega = 56 \times 10^3\Omega, \\ R_2 &= 56K\Omega = 56 \times 10^3\Omega, \\ C_1 &= 4.7nF = 4.7 \times 10^{-9} \text{ F}, \\ C_2 &= 4.7nF = 4.7 \times 10^{-9} \text{ F} \end{aligned}$$

On Substituting the values,

$$f_c = \frac{1}{2\pi\sqrt{(56 \times 10^3) \times (56 \times 10^3) \times (4.7 \times 10^{-9}) \times (4.7 \times 10^{-9})}}$$

Performing step-by-step calculation,

$$\begin{aligned} R_1R_2 &= (56 \times 10^3) \times (56 \times 10^3) = 3.136 \times 10^9, \\ C_1C_2 &= (4.7 \times 10^{-9}) \times (4.7 \times 10^{-9}) = 2.209 \times 10^{-17}, \\ \sqrt{(3.136 \times 10^9) \times (2.209 \times 10^{-17})} &= \sqrt{6.929 \times 10^{-8}}, \\ &= 8.322 \times 10^{-4}, \\ 2\pi \times 8.322 \times 10^{-4} &= 5.23 \times 10^{-3}, \\ f_c &= \frac{1}{5.23 \times 10^{-3}} = 604.69 \text{ Hz}. \end{aligned}$$

Final Answer:

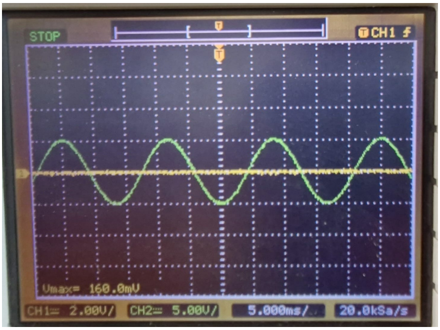
$$\mathbf{f_c \approx 604.69} \text{ Hz}$$

This is the calculated cutoff frequency for the given high-pass filter.

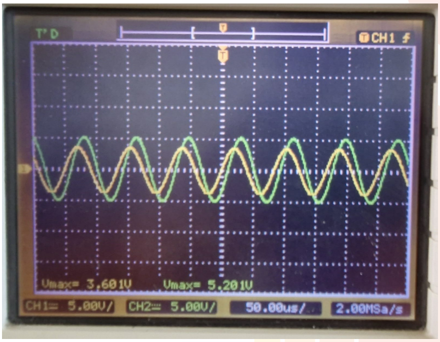
4.5 Observations

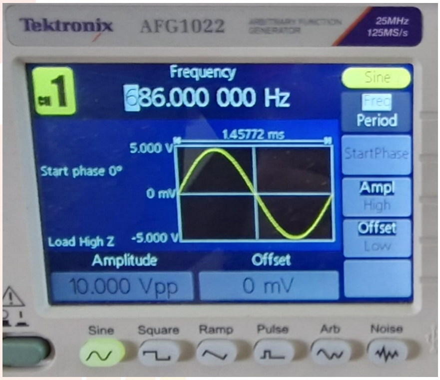
We observed how the gain changes w.r.t the frequency

- Frequency = 60Hz

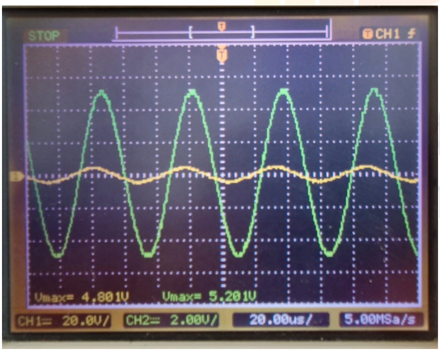


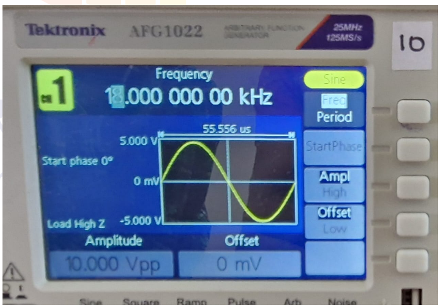
- Frequency = 686Hz



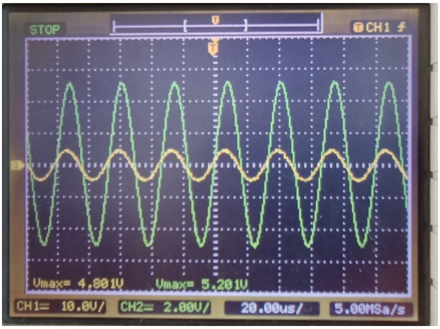


- Frequency = 18kHz

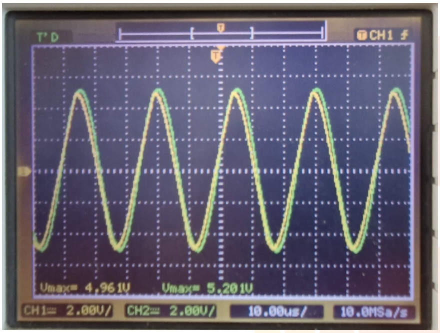




- Frequency = 30kHz



- Frequency = 40kHz



4.6 Bode Plot

The behavior of the high-pass filter was observed using an oscilloscope while varying the input frequency. The key observations are:

- When the input frequency was adjusted to a much lower value than the cutoff frequency, the output signal on the oscilloscope approached a straight-line response, indicating heavy attenuation of lower frequencies.
- As the input frequency increased and reached the cutoff frequency, the output amplitude gradually increased.
- When the input frequency was much higher than the cutoff frequency, the output signal closely followed the input sinusoidal waveform, meaning minimal attenuation at higher frequencies.

The theoretical cutoff frequency calculated using the formula was:

$$f_{c,\text{calculated}} = 604.69 \text{ Hz}$$

However, during practical measurements, it was observed that the expected attenuation of 70% of the maximum output occurred at an input frequency of:

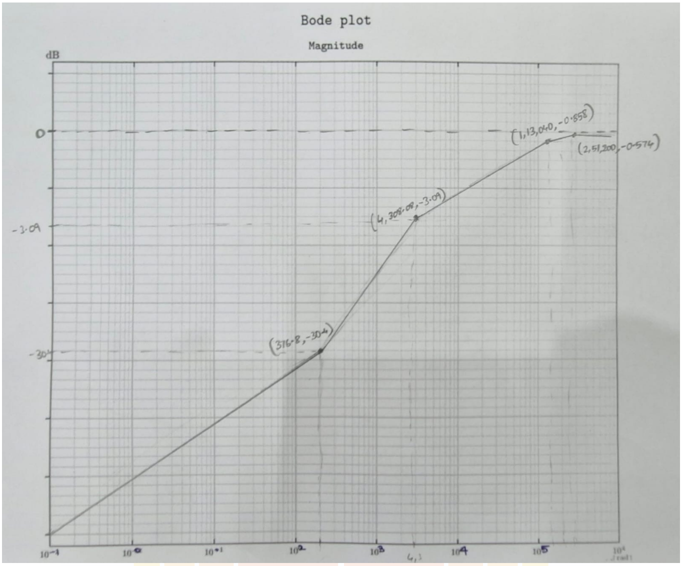
$$f_{c,\text{measured}} = 686 \text{ Hz}$$

This small discrepancy can be attributed to minor experimental errors such as:

- Tolerances in resistor and capacitor values.
- Parasitic effects in the breadboard connections.
- Non-ideal characteristics of the operational amplifier.
- Measurement variations in the oscilloscope and function generator settings.

Despite this slight variation, the overall frequency response of the high-pass filter matched the expected theoretical behavior.

Figures displaying the oscilloscope waveforms for different frequency values have been attached for further analysis.



5 Low-Pass Filter

5.1 Theory

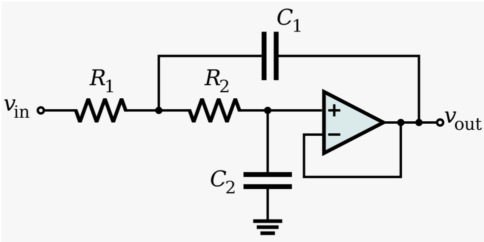
A low-pass filter does the opposite of a high-pass filter. It allows lower frequency signals to pass while blocking higher frequencies. The cutoff frequency for an LPF is given by:

$$f_{c2} = \frac{1}{2\pi\sqrt{R_3R_4C_3C_4}} \tag{0.2}$$

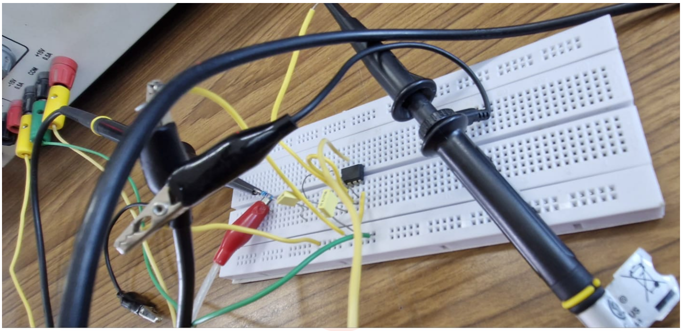
This type of filter is useful for reducing high-frequency noise.

5.2 Connections

Below is the circuit diagram for a second order sallen key high pass filter



Below is the connected circuit diagram on breadboard



5.3 Procedure

1. Make connections according to the circuit diagram and LM358 pinout diagram
2. Connect the input function across the first resistor (Pin 3)
3. Measure the output across the first pin (Pin 1)
4. The values of the resistors and capacitors are
   - $R_1 = R_2 = 56K\Omega$
   - $C_1 = C_2 = 4.7nF$
5. Power the LM358 by connecting V_{cc} (PIN 8) to +15V and GND (PIN 4) to -15V
6. Connect the COM to other end of R_2 GND

The cutoff frequency (f_c) for a Sallen-Key Low-Pass Filter follows the same formula:

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

Given values,

$$\begin{aligned} R_1 &= 56K\Omega = 56 \times 10^3\ \Omega, \\ R_2 &= 56K\Omega = 56 \times 10^3\Omega, \\ C_1 &= 4.7nF = 4.7 \times 10^{-9}\ \text{F}, \\ C_2 &= 4.7nF = 4.7 \times 10^{-9}\ \text{F} \end{aligned}$$

On substituting the values,

$$f_c = \frac{1}{2\pi\sqrt{(56\times 10^3)\times(56\times 10^3)\times(4.7\times 10^{-9})\times(4.7\times 10^{-9})}}$$

Performing step-by-step calculation,

$$\begin{aligned}
R_1R_2 &= (56\times 10^3)\times(56\times 10^3) = 3.136\times 10^9,\\
C_1C_2 &= (4.7\times 10^{-9})\times(4.7\times 10^{-9}) = 2.209\times 10^{-17},\\
\sqrt{(3.136\times 10^9)\times(2.209\times 10^{-17})} &= \sqrt{6.929\times 10^{-8}},\\
&= 8.322\times 10^{-4},\\
2\pi\times 8.322\times 10^{-4} &= 5.23\times 10^{-3},\\
f_c &= \frac{1}{5.23\times 10^{-3}} = 604.69 \text{ Hz}.
\end{aligned}$$

Final Answer:

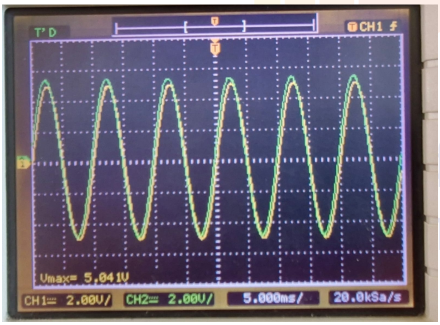
$$\mathbf{f_c} \approx \mathbf{604.69} \text{ Hz}$$

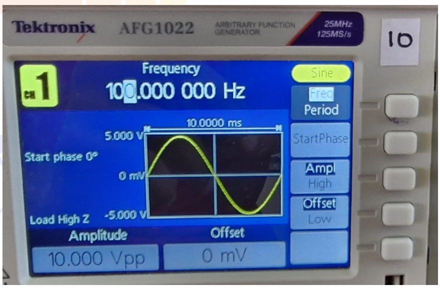
This is the calculated cutoff frequency for the given low-pass filter.

5.4 Observations

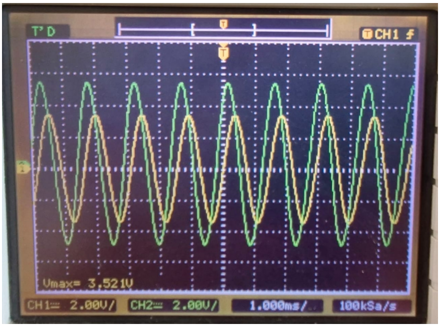
We observed how the gain changes w.r.t the frequency for a low pass filter

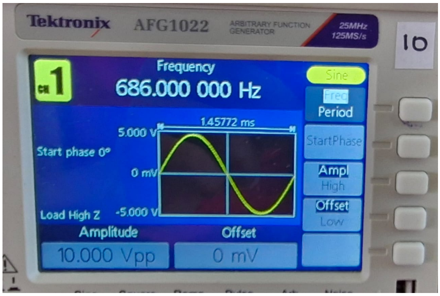
- Frequency = 100Hz



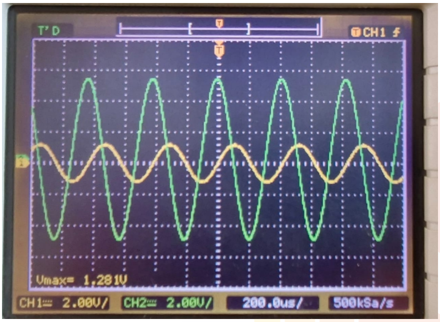


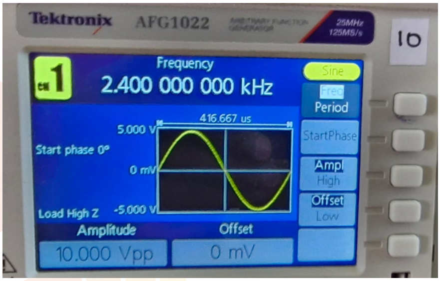
- Frequency = 686Hz



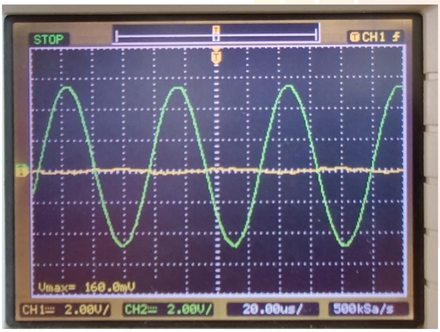


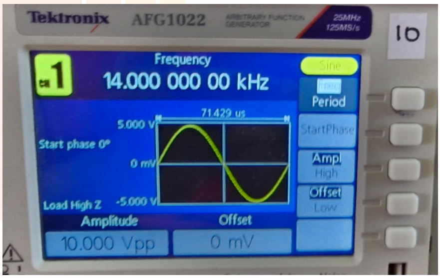
- Frequency = 2.4kHz



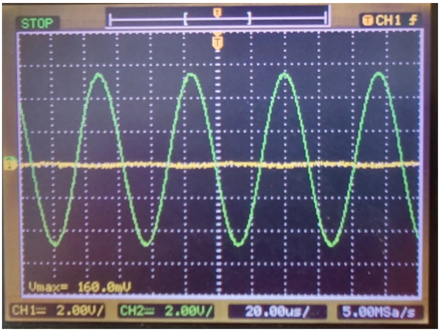


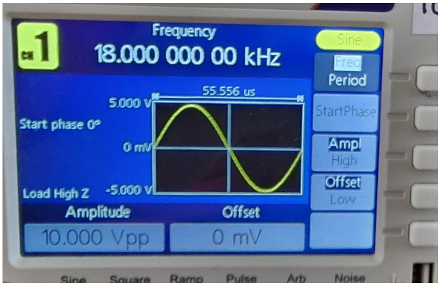
- Frequency = 14kHz





- Frequency = 18kHz





5.5 Low-Pass Filter Response

The behavior of the low-pass filter was observed using an oscilloscope while varying the input frequency. The key observations are:

- When the input frequency was much lower than the cutoff frequency, the output signal closely followed the input sinusoidal waveform, indicating minimal reduction at low frequencies.
- As the input frequency increased and approached the cutoff frequency, the output amplitude started decreasing gradually.
- When the input frequency was much higher than the cutoff frequency, the output signal on the oscilloscope became nearly a straight line, indicating significant reduction of higher frequencies.

The theoretical cutoff frequency calculated using the formula was:

$$f_{c,\text{calculated}} = 604.69 \text{ Hz}$$

However, during practical measurements, it was observed that the expected reduction to 70% of the maximum output occurred at an input frequency of:

$$f_{c,\text{measured}} = 686 \text{ Hz}$$

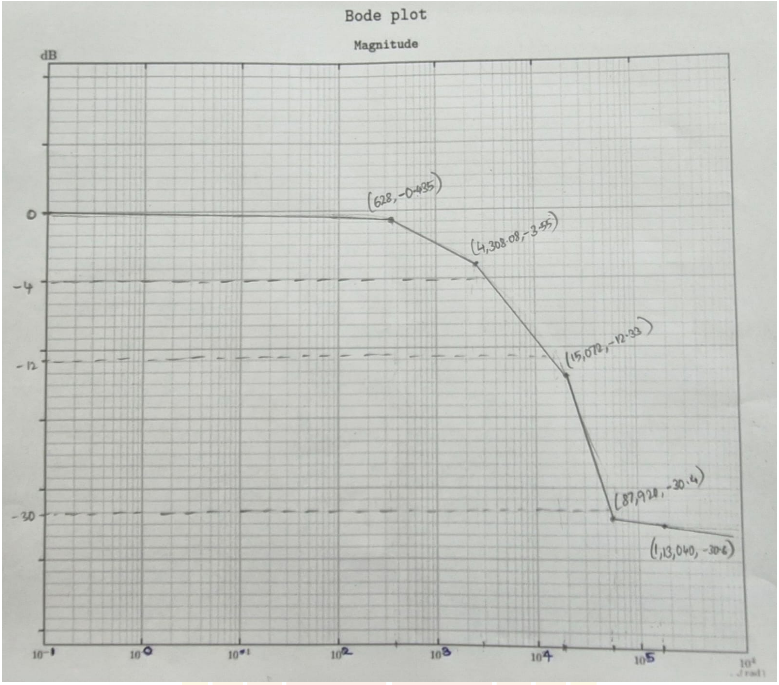
This small discrepancy can be attributed to minor experimental errors such as:

- Tolerances in resistor and capacitor values.
- Parasitic effects in the breadboard connections.
- Non-ideal characteristics of the operational amplifier.
- Measurement variations in the oscilloscope and function generator settings.

Despite this slight variation, the overall frequency response of the low-pass filter matched the expected theoretical behavior.

Figures displaying the oscilloscope waveforms for different frequency values have been attached for further analysis.

5.6 Bode Plot



6 Band-Pass Filter

6.1 Theory

By cascading the HPF and LPF, we create a bandpass filter that only allows frequencies within a specific range to pass. The important parameters of the bandpass filter are:

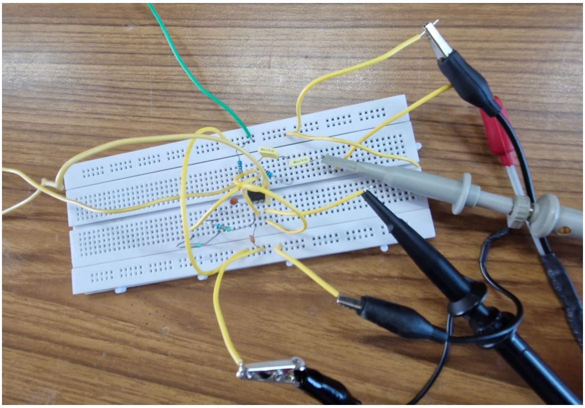
- **Lower cutoff frequency** (f_{c1}) - Determined by the HPF.
- **Upper cutoff frequency** (f_{c2}) - Determined by the LPF.
- **Center frequency** (f_0) - The midpoint frequency where the filter has the highest gain:

$$f_0 = \sqrt{f_{c1} f_{c2}} \tag{0.3}$$

- **Bandwidth** (BW) - The range of frequencies that the filter allows:

$$BW = f_{c2} - f_{c1} \tag{0.4}$$

6.2 Connections



6.3 Procedure

- Connect both the LPF and HPF across 2 op-amps of LM358
- Connect the HPF's output to the LPF's input
- Connect V_{in} to the HPF's input
- Connect V_{out} to the LPF's output
- The values of resistors and capacitors are
  - LPF
    - $R_1 = R_2 = 68k\Omega$
    - $C = 1nF$
  - HPF
    - $R_3 = R_4 = 56K\Omega$
    - C $= 4.7nF$
- Make the following connections according the circuit diagram and LM358 pinout diagram

6.4 LPF Cutoff Frequency

The cutoff frequency (f_c) for a first-order Low-Pass Filter is given by:

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

Given values,

$$R_1 = R_2 = 68K\Omega = 68 \times 10^3\ \Omega,$$
$$C_1 = C_2 = 1nF = 1 \times 10^{-9}\ \text{F}$$

On substituting the values,

$$f_{c,\text{LPF}} = \frac{1}{2\pi \times (68 \times 10^3) \times (1 \times 10^{-9})}$$

Performing the calculation,

$$\begin{aligned} f_{c,\text{LPF}} &= \frac{1}{2\pi \times 68 \times 10^{-6}} \\ &= \frac{1}{4.274 \times 10^{-4}} \\ &= 2340.51 \text{ Hz} \end{aligned}$$

Final Answer:

$$\mathbf{f_{c,\text{LPF}}} \approx \mathbf{2340.51} \text{ Hz}$$

6.5 HPF Cutoff Frequency

The cutoff frequency (f_c) for a first-order High-Pass Filter is given by:

$$f_c = \frac{1}{2\pi\sqrt{R_3 R_4 C_3 C_4}}$$

Given values,

$$\begin{aligned} R_3 = R_4 &= 56K\Omega = 56 \times 10^3 \ \Omega, \\ C_3 = C_4 &= 4.7nF = 4.7 \times 10^{-9} \text{ F} \end{aligned}$$

On substituting the values,

$$f_{c,\text{HPF}} = \frac{1}{2\pi \times (56 \times 10^3) \times (4.7 \times 10^{-9})}$$

Performing the calculation,

$$\begin{aligned} f_{c,\text{HPF}} &= \frac{1}{2\pi \times 2.632 \times 10^{-4}} \\ &= \frac{1}{1.653 \times 10^{-3}} \\ &= 604.69 \text{ Hz} \end{aligned}$$

Final Answer:

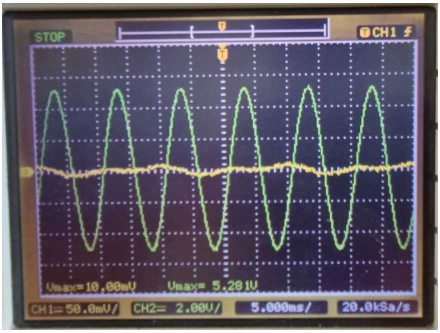
$$\mathbf{f_{c,\text{HPF}}} \approx \mathbf{604.69} \text{ Hz}$$

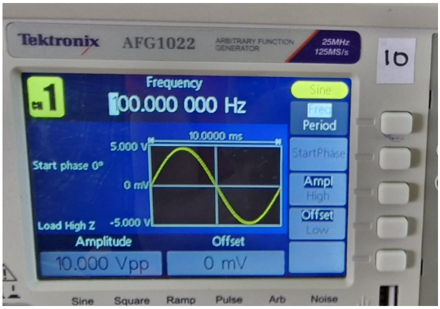
Thus, the calculated cutoff frequencies for the bandpass filter components are:

- Low-Pass Filter Cutoff Frequency: **2340.51 Hz**
- High-Pass Filter Cutoff Frequency: **604.69 Hz**

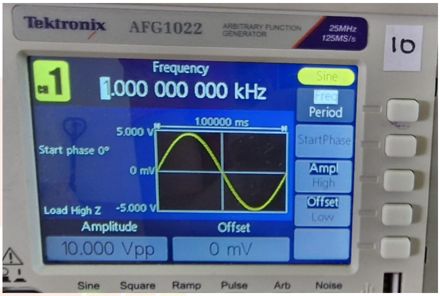
6.6 Observations

- Frequency = 100Hz

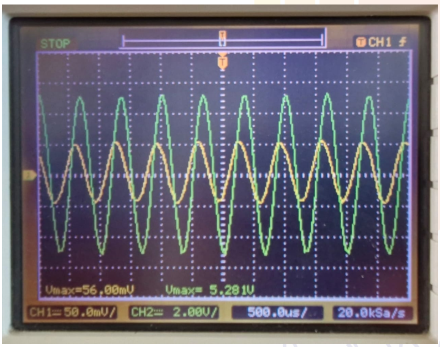


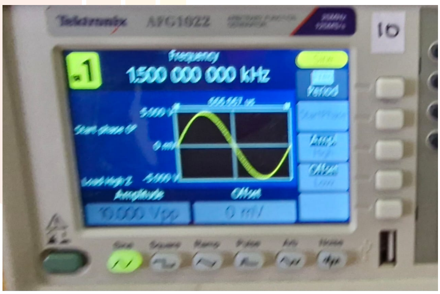


- Frequency = 1kHz

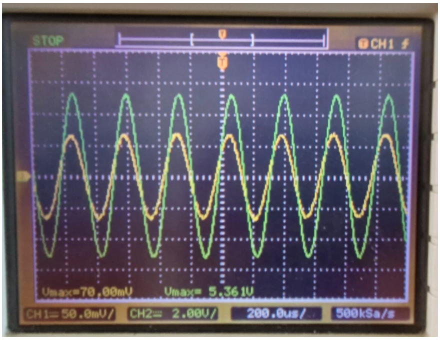


- Frequency = 1.5kHz

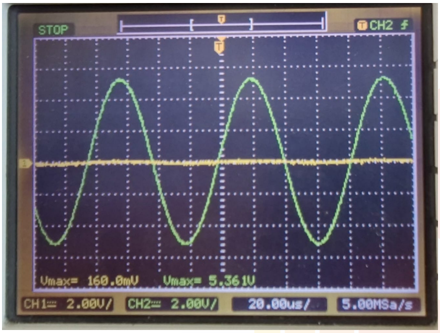




- Frequency = 3kHz



- Frequency = 40kHz



The behavior of the bandpass filter was observed using an oscilloscope while varying the input frequency. The key observations are:

- **For frequencies below the high-pass cutoff frequency ($f_{c,\mathbf{HPF}}$):**
  - The waveform appears highly diminished, approaching a straight-line response on the oscilloscope.
- **For frequencies between the high-pass and low-pass cutoff frequencies ($f_{c,\mathbf{HPF}} < f < f_{c,\mathbf{LPF}}$):**
  - The output waveform closely follows the input sinusoidal signal, maintaining a strong amplitude.
  - The gain remains relatively stable within this passband region.
- **For frequencies above the low-pass cutoff frequency ($f > f_{c,\mathbf{LPF}}$):**
  - The low-pass filter attenuates these high-frequency components, causing the output signal amplitude to decrease.
  - As the frequency increases further, the waveform diminishes significantly, eventually approaching a near-straight-line response.

A bandpass filter is formed by cascading a High-Pass Filter (HPF) and a Low-Pass Filter (LPF). The key parameters are:

- **Lower cutoff frequency** (f_{c1}) = 604.69 Hz (HPF)

- **Upper cutoff frequency** (f_{c2}) = 2340.51 Hz (LPF)
- **Center frequency** (f_0) = $\sqrt{f_{c1} f_{c2}}$ = 1189.66 Hz
- **Bandwidth** (BW) = $f_{c2} - f_{c1}$ = 1735.82 Hz

These values define the operating range of the bandpass filter.

6.7 Bode Plot