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Section: 1

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Bilkent University Electrical and Electronics Engineering

EE202-Circuit Theory

Lab 5:

Bandpass Filter Design

Introduction:

The purpose of this lab is to design a band pass filter with central frquency (f_o) between 2MHz and 5MHz, 30dB stopband attenuation, at least 3dB gain variation in the passband, 0.05f_o passpand width. In order to satisfy the lab requirements I used second order butterworth pandpass filter. I chose f_o to be 3MHz. Lab requirements are given below (Figure 1).

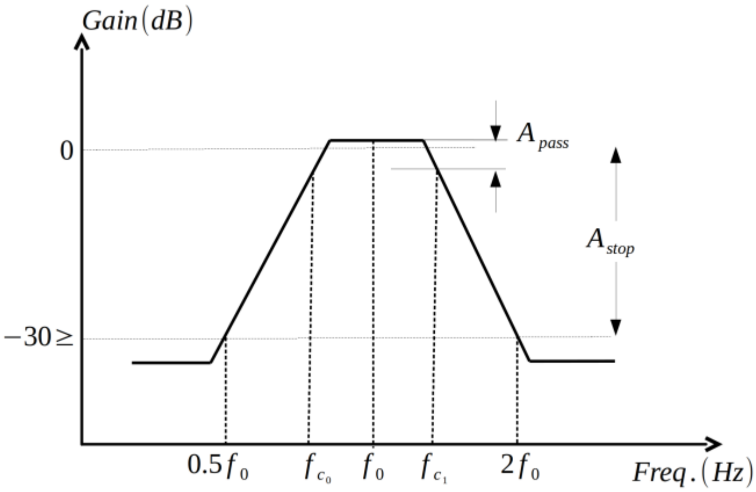


Figure 1: Frequency response of the filter

Central frequency: $2Mhz \leq f_0 \leq 5Mhz$
Passband width: $f_{c_1} - f_{c_0} = 0.05 f_0$
Gain variation in the passband: $A_{pass} \leq 3dB$
Stopband attenuation: $A_{stop} \geq 30dB$

Part 1: Software Implementation

Analysis:

In order the decide the order of the filter below equations are solved (eq. 1).

$$\frac{P_L}{P_A} = \frac{1}{1+\left(\frac{f_o}{\Delta f}\right)^{2n}\left(\frac{f}{f_o}-\frac{f_o}{f}\right)^{2n}} \quad \text{(eq. 1)}$$

After I take the logarithm below function appears:

At 3 MHz:

$$\left(\frac{3\times 10^6}{0.15\ \times\ 10^6}\right)^{2n}\left(\frac{6\times 10^6}{3\times 10^6}-\frac{3\times 10^6}{4\times 10^6}\right)^{2n} = 999$$

$$3^{2n} = 999 \Rightarrow \mathrm{n} \approx 1.015$$

The minimum integer n can be given is n=2. For the low-pass filter circuit, n is chosen as 2.

Given that the frequency deviation is Δf = $0.05 f_o$where f_o is chosen as 3 MHz, and the bandwidth is determined to be 150 kHz. For simplicity in the design, a logarithmic calculation with n=2 is chosen.

To design a bandpass filter, a Butterworth lowpass filter is initially designed with a -3dB cutoff frequency set equal to Δf. Subsequently, the filter elements are tuned using LC circuits to achieve the desired center frequency (f_o). Initial lowpass filter is below (Figure 2).

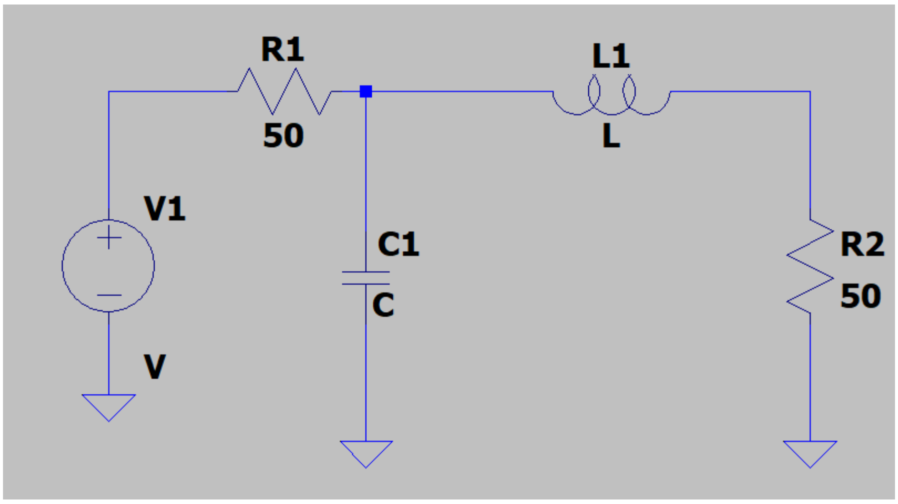


Figure 2: Schematic of the Lowpass Filter

To create a bandpass filter :

1. Have to create a low pass filter which has 150 kHz bandwidth at -3dB cut-off frequency. We need to equal ω_C (center frequency) to $\Delta\omega$ (bandwidth) (eq 2.1 and 2.2).
2. Tune the capacitors with grounded inductors and tune the inductors with series capacitors.

In order to do that first, I designed a low pass filter with the desired values (Figure 3).

$$\omega_C = \Delta\omega = 2\pi \times 0.05 f_o \quad \text{(eq 2.1)}$$

$$\omega_C = 0.3\pi \times 10^6 \text{ Hz} \quad \text{(eq 2.2)}$$

Initially, I need to calculate the C1 and L1 in the low-pass filter for that, butterworth coefficients table is used (Table 1). Now, for the low pass filter, C and L values are calculated as below considering the coefficients from the table (eq. 3.1 and 3.2):

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7
1	2.0000	1.0000					
2	1.4142	1.4142	1.0000				
3	1.0000	2.0000	1.0000	1.0000			
4	0.7654	1.8478	1.8478	0.7654	1.0000		
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000	
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1

Table 1: Butterworth Coefficients

$$L_1 = \frac{g_1 R}{2\pi f_c} \quad , \quad L_1 = \frac{1.4142 \times 50}{2\pi \times 150kHz} = \ 75.03\ uH \qquad \text{(eq. 3.1)}$$

$$C_1 = \frac{g_1}{2\pi R f_c} \quad , \quad C_1 = \frac{1.4142}{2\pi \times 50 \times 150kHz} = 30.01\ nF \qquad \text{(eq. 3.2)}$$

Note: f_c stands for (f_{c1}- f_{c0}) (passband width)

Now, we needed to create a resonance at 3 MHz by tuning the inductor and capacitor. This is achieved by introducing a parallel inductor (L2) to capacitor (C1) and a series capacitor (C2) to inductor (L2) as mentioned in the steps of creating a bandpass filter (eq. 4.1 , 4.2 and 4.3).

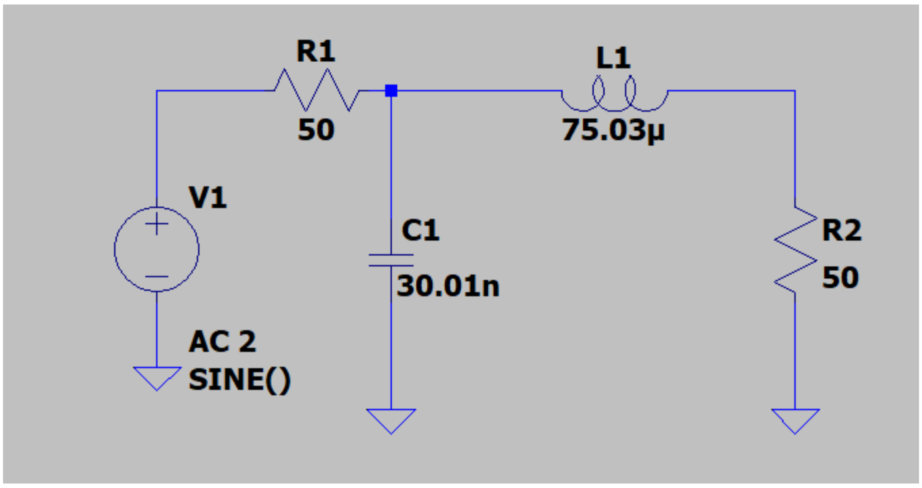


Figure 3: Schematic of the Lowpass Filter with Calculated Values

$$\omega = \sqrt{\frac{1}{L_1 C_1}} \quad \text{(eq. 4.1)}$$

$$L_2 = \frac{1}{(2\pi \times f_o)^2 \times C_1}\ , \quad L_2 = \frac{1}{(2\pi \times 3 \times 10^6)^2 \times 30 \times 10^{-9}} = 93.82\ nH \quad \text{(eq. 4.2)}$$

$$C_2 = \frac{1}{(2\pi \times f_o)^2 \times L_1}, \quad C_2 = \frac{1}{(2\pi \times 3 \times 10^6)^2 \times 75.03 \times 10^{-6}} = 37.51\ pF \quad \text{(eq. 4.3)}$$

Now, butterworth bandpass filter can be designed with these values (Figure 4):

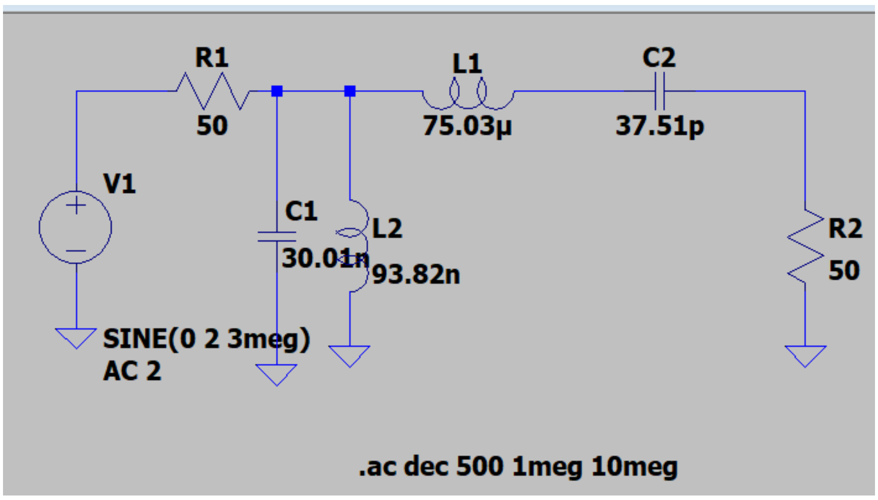


Figure 4: Schematic of the Bandpass Filter

Simulations:

In the simulation iti is seen that the maximum gain point has the frequency of 3.0069MhZ which is very close to actual central frequency (f_o) selected (Figure 5).

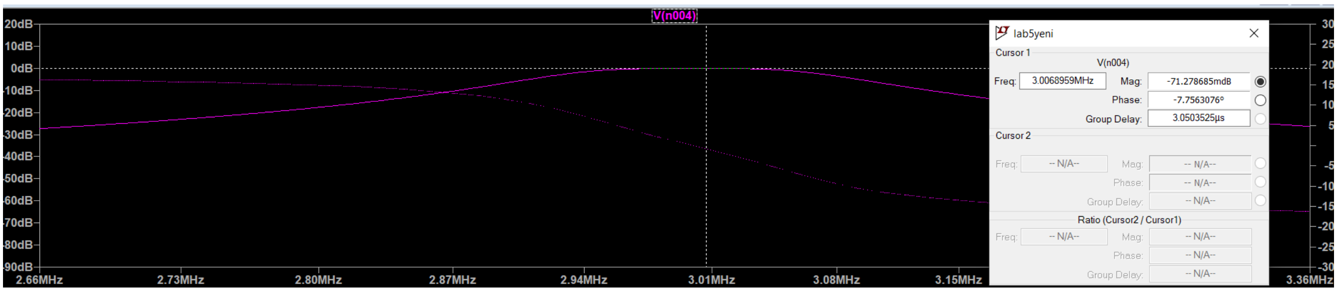


Figure 5: Simulation Result of Butterworth Bandpass Filter, central frequency = of 3.0069MhZ

Bandwidth is observed 148.84 kHZ at the points -3dB (cut off frequencies) (Figure 6).

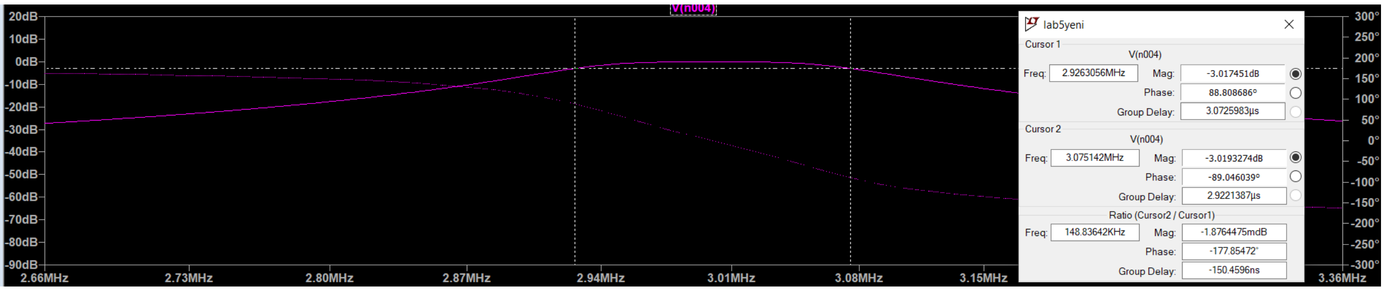


Figure 6: Simulation Result of Butterworth Bandpass Filter, Bandwidth = 148.84 kHz

I examined the points at 0.5f_o= 1.5 MHz I got -59.085dB and at 2f_o= 6MHz I got -59.093dB on the plot to assess the stopband gain (Figure 7).

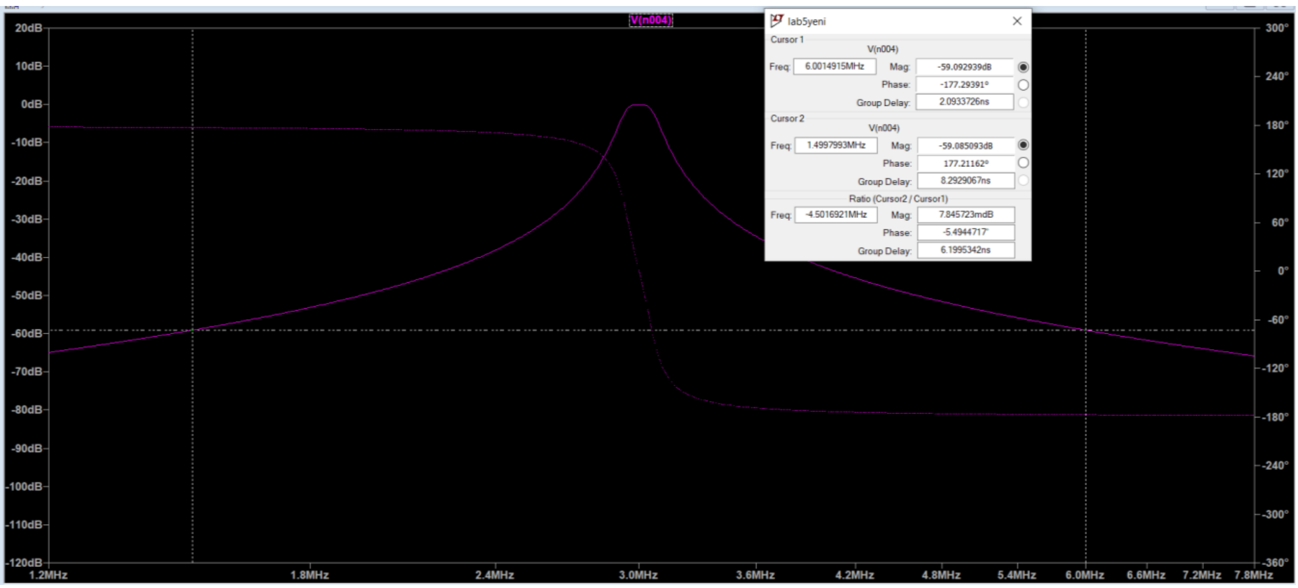


Figure 7: Simulation Result of Butterworth Bandpass Filter, Stopband Gain (A_{stop}≈ 59.09)

	Expected Value (Calculation Results)	Simulation Results	Error (%)
Central frequency	3MHz	3.0069MhZ	0.69
Bandwidth at -3dB (Δf)	150 kHz	148.84 kHz	0.773
Gain at 1.5 MHz point (0.5f_o)	$\geq 30\text{dB}$	|59.085 - 0.71|= 58.375 dB	Meets the expectations
Gain at 6 MHz point (2f_o)	$\geq 30\text{dB}$	|59.093 - 0.71|= 58.383 dB	Meets the expectations
Gain variation in the passband	$\leq 3\text{dB}$	|3.017-0.71|= 2.307 dB	Meets the expectations

Table 2: Simulation Results and Error

Note: Consider that in Figure 7, we assumed A_{stop} is observed from the starting of the 0dB point. However, since there is a slight derivation from 0dB in the central frequency correct calculation should be as in Table 2.

Table 2 demonstrates that all requirements have been met with an error rate of less than 10%.

Part 2: Hardware Implementation

Due to the unavailability of specific capacitors and inductor values in the laboratory for hardware implementation, I opted to utilize the nearest available components. To meet the required specifications, I configured new components by connecting them in series and parallel. I observed the highest gain at 2.93MHz, so continued my calculations as my central frequency is 2.93MHz.

Figure 8: Hardware Implementation

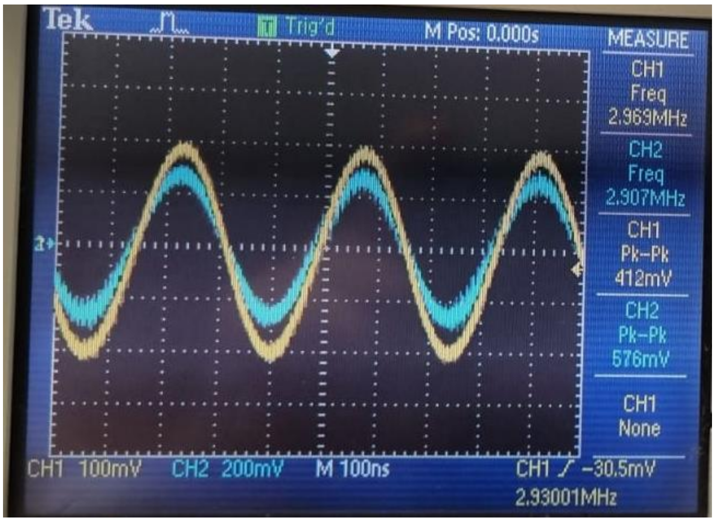


Figure 9: Central Frequency at 2.93MHz

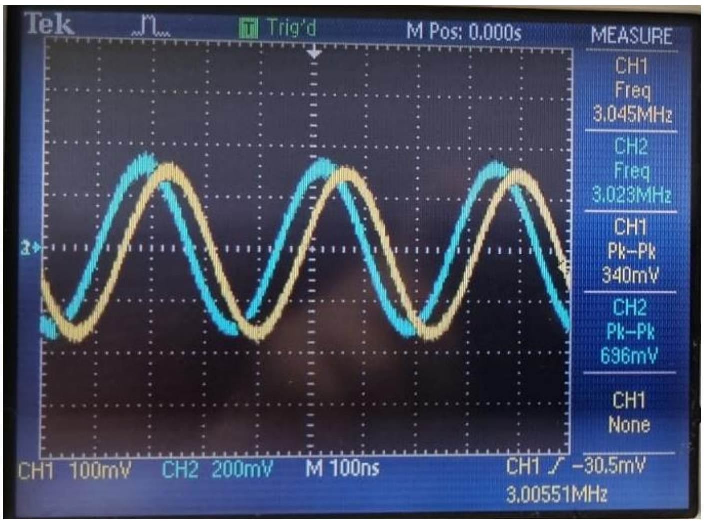


Figure 9: Cut-off Frequency at 3.0055MHz

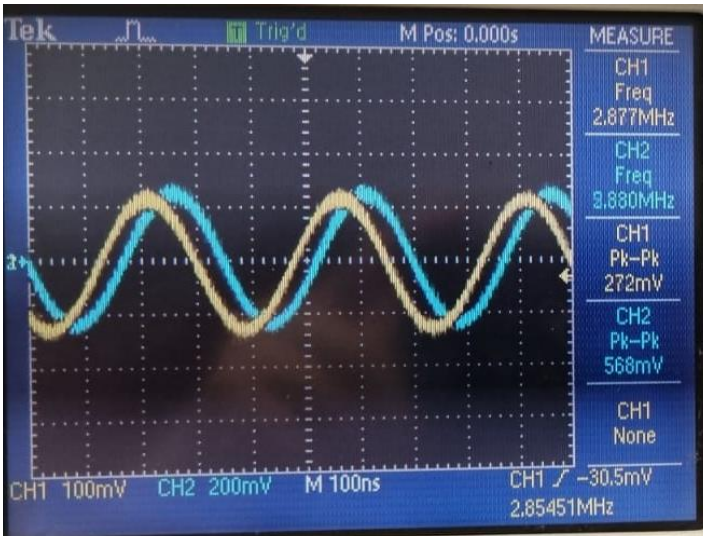


Figure 9: Cut-off Frequency at 2.8545MHz

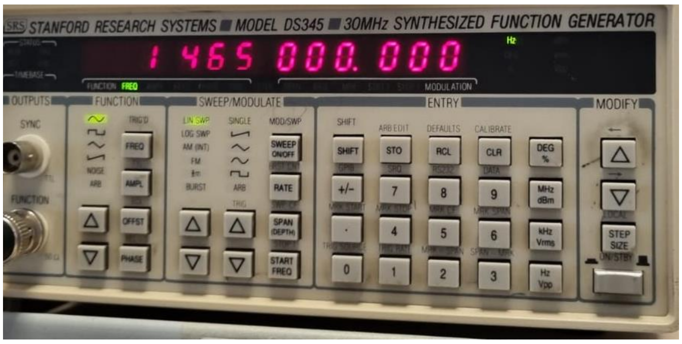


Figure 10: First Stopband Frequency $0.5f_o$= 1.465 MHz

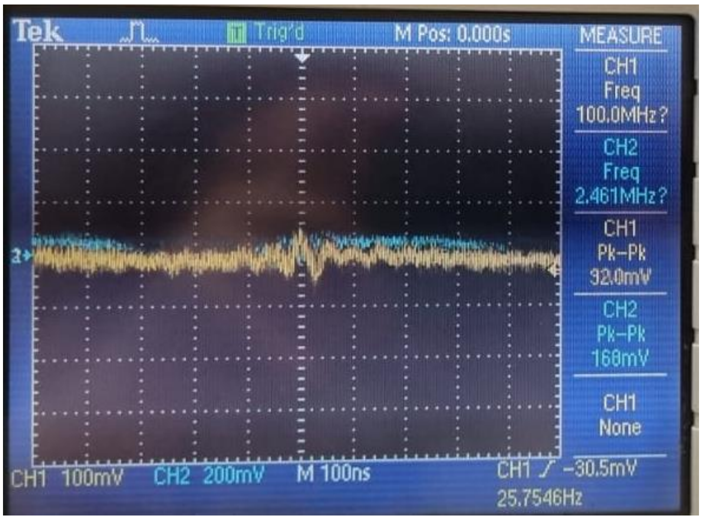


Figure 11: The Response of the Circuit, First Stopband Frequency (at $0.5f_o$= 1.465 MHz)

Figure 12:Second Stopband Frequency $2f_o$= 5.86 MHz

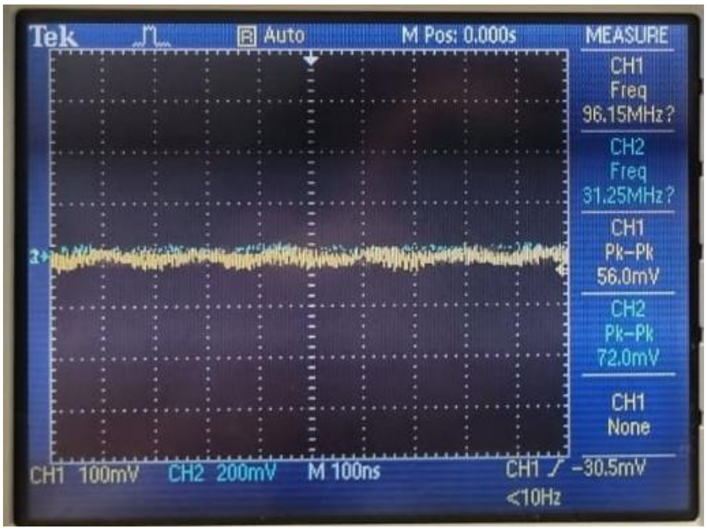


Figure 13: The Response of the Circuit, Second Stopband Frequency (at $2f_o$= 5.86 MHz)

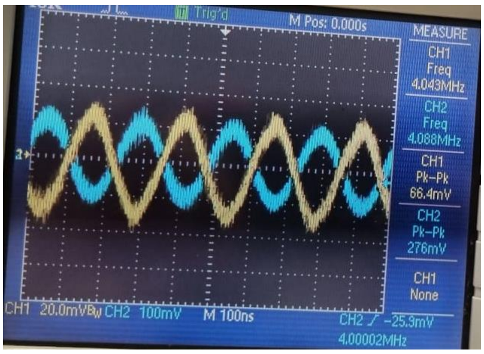


Figure 14: Response at 4MHz

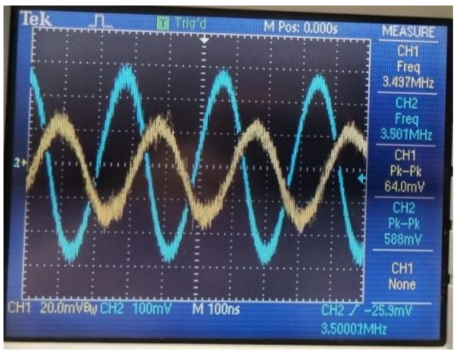


Figure 15: Response at 3.5MHz

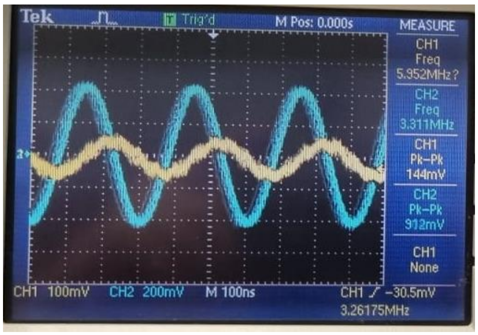


Figure 16: Response at 3.26MHz

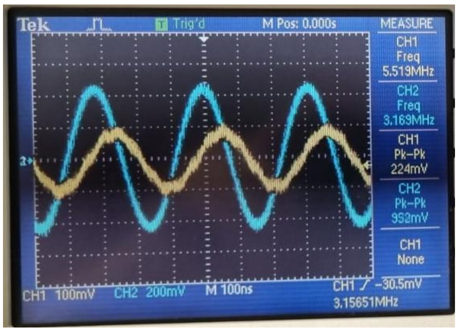


Figure 17: Response at 3.16MHz

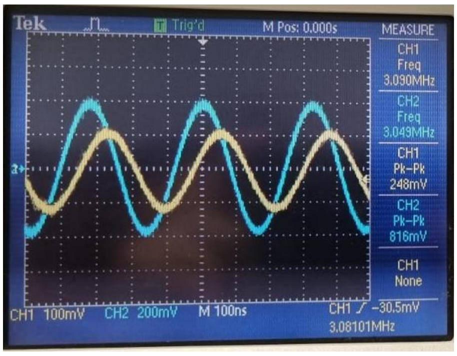


Figure 18: Response at 3.08MHz

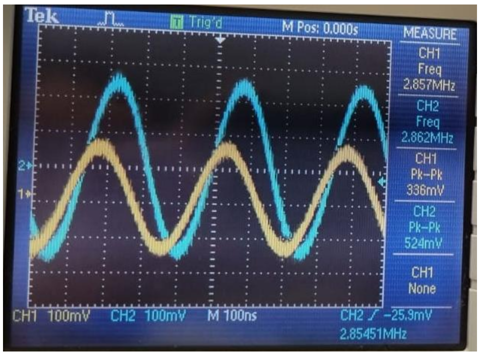


Figure 19: Response at 2.8545MHz (cut-off)

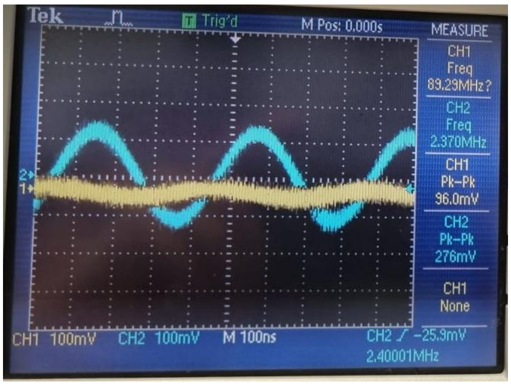


Figure 20: Response at 2.4MHz

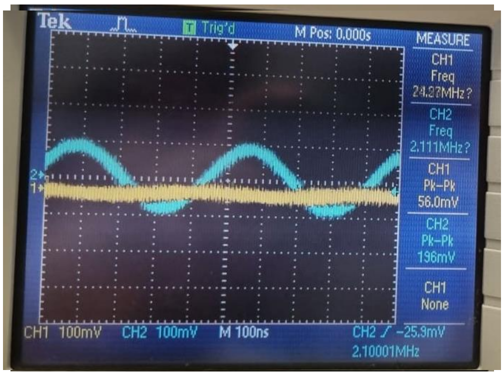


Figure 21: Response at 2.1MHz

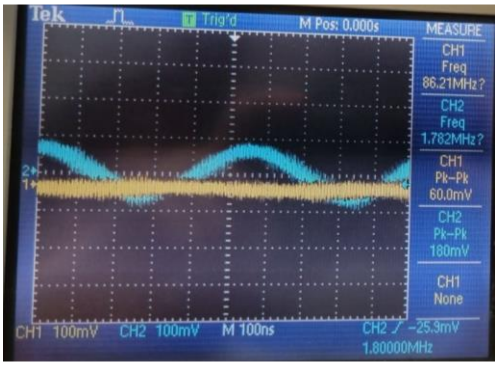


Figure 22: Response at 1.8MHz

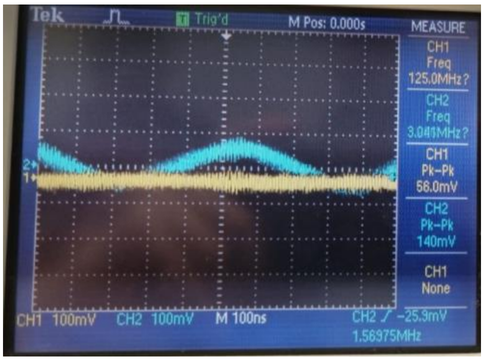


Figure 23: Response at 1.57MHz

Voltage gain is calculated as below:

$$\text{Voltage gain} = 20log_{10}\left(\frac{V_{out}}{V_{in}}\right) \quad \text{(eq. 5)}$$

	Software result (MHz)	Hardware result (MHz)	Software Gain (dB)	Hardware result (dB)
Central frequency	3.0069	2.97	-0.71	-2.91
First cutoff frequency	3.075	3.0055	-3.0175	-6.22
Second cutoff frequency	2.926	2.855	-3.019	-6.4
First Stopband ($0.5f_o$)	1.499	Since there is almost no waveform, we can't observe the frequency	58.375	-5.23
Second Stopband ($2f_o$)	6.001	Since there is almost no waveform, we can't observe the frequency	58.383	-2.183

Table 3: Hardware Results of Some Critical Points

Since even the oscilloscope couldn't measure the frequency at the stopband points, since there is almost no signal at these points our gain couldn't be measured correctly. However, we know that from the software part, this value has to be very close to -59 dB absolutely bigger than 30 dB. Therefore, I plot the graph (Graph 1) considering this fact.

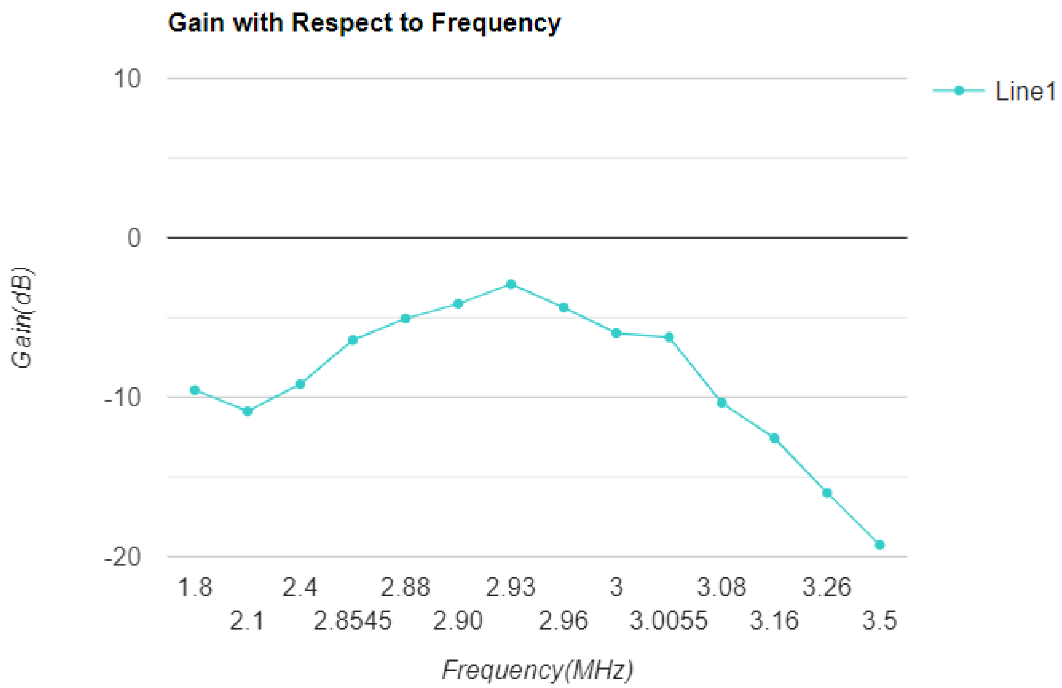
Frequency (MHz)	Gain (dB)
5.86 $(2f_o)$	-2.183
3.5	-19.26
3.26	-16
3.16	-12.57
3.08	-10.35
3.0055 (cut-off)	-6.22
2.8545 (cut-off)	-6.4
2.4	-9.173
2.1	-10.88
1.8	-9.54
1.465 $(0.5f_o)$	-5.23

Table 4: Gains of Some Other Frequencies in Hardware

These values fall within the acceptable 20% range. Subsequently, I some other frequencies within the passband too rather than out of the passband.

Frequency	Gain
2.88 MHz	-5.06 dB
2.90 MHz	-4.14 dB
2.93 MHz (central)	-2.91 dB
2.96 MHz	-4.36 dB
3 MHz	-5.97 dB

Table 5: Gains of Frequencies within the passband in Hardware



Graph 1: Gain With Respect to Frequency

Conclusion:

I designed a second-order Butterworth bandpass filter. Initially, I designed a low-pass filter using a single capacitor and one inductor, adjusting them for resonance at 3MHz. After creating the circuit, I ran a computer simulation to confirm its functionality. Additionally, I brought the design to life in hardware. In this part, I could get the highest gain at 2.93MHz so I shifted all my values according to this value. Also, I had issues with the breadboard so, I continued implementing my work manually with soldering. Then my error decreased. After that, both simulated and real-world results showed error rates within acceptable limits, and they were quite close to what I expected except for the stopband values. Because the oscilloscope couldn't measure the frequency at the stopband points, since there is almost no signal at these points our gain couldn't be measured correctly, there were way out of range. Any slight deviations in the error rates could potentially be attributed to measurement errors or inherent inaccuracies in the equipment.

REFERENCES

Book-Electric-Circuits-9th-ed-J.-Nilsson-S.-Riedel-Prentice-Hall-2011.pdf

https://www.semanticscholar.org/paper/Design-and-development-of-band-pass-filter-for-Jijesh-Shivashankar/b75fe731917fb8d6beb62594781c4f41bf3d136f