# Bilkent University Department Of Electrical and Electronics Engineering

# EEE212 Circuit Theory

# Lab 5

# Band Pass Filter Design

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## Purpose:

This lab aimed to design a bandpass filter with a center frequency between 1MHz and 4MHz and source/load resistors of 50 ohms.

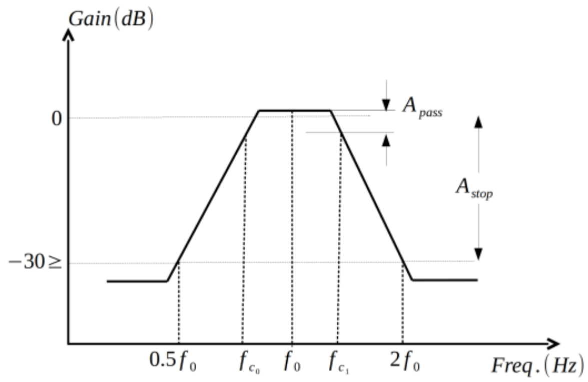



*Figure 1 – Lab Task*

## Methodology:

The bandpass filter is designed with passive circuit components in this lab assignment. The selected bandpass filter is a 3rd order Butterworth filter. The order of the filter is determined by taking the complexity and the accuracy of the filter into consideration. A generic design for the 3rd order Butterworth filter can be seen in Figure 2.

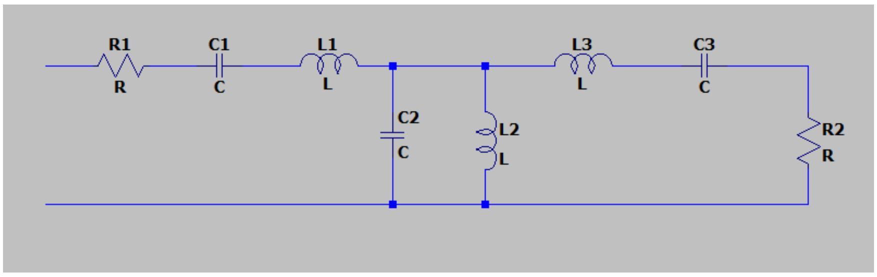



*Figure 2 – 3rd Order Butterworth BPF*

The bandpass filter will be designed in two steps:

1- Design a Butterworth LPF with a 3dB cut-off frequency equal to the bandwidth of the BPF.
2- Replace every series and parallel element with a tuned LC circuit at f_0.

A generic 3rd order Butterworth LPF can be seen in Figure 3.

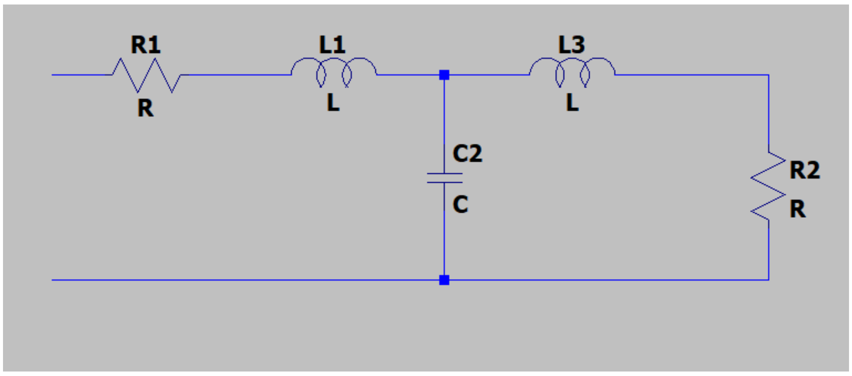



*Figure 3 – 3rd Order Butterworth LPF*

The calculations to find the capacitor and inductor values are as follows.

The first step is to insert filter coefficients from the table(Figure 4).

| $n$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ | $b_6$ | $b_7$ | $b_8$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.000 | | | | | | | |
| 2 | 1.4142 | 1.4142 | | | | | | |
| 3 | 1.0000 | 2.0000 | 1.0000 | | | | | |
| 4 | 0.7654 | 1.8478 | 1.8478 | 0.7654 | | | | |
| 5 | 0.6180 | 1.6180 | 2.0000 | 1.6180 | 0. 6180 | | | |
| 6 | 0.5176 | 1.4142 | 1.9319 | 1.9319 | 1.4142 | 0.5176 | | |
| 7 | 0.4450 | 1.2470 | 1.8019 | 2.0000 | 1.8019 | 1.2470 | 0.4450 | |
| 8 | 0.3902 | 1.1111 | 1.6629 | 1.9616 | 1.9616 | 1.6629 | 1.1111 | 0.3902 |

*Figure 4 – Butterworth filter coefficients*

$$L_1 = b_1, C_2 = b_2, L_3 = b_3$$

$$L_1 = 1, C_2 = 2, L_3 = 1$$

Divide the L&C values by frequency.

$$L_1 = \frac{1}{w}, C_2 = \frac{2}{w}, L_3 = \frac{1}{w}$$

In this experiment, the center frequency is selected as f=2.34Mhz. Thus the bandwidth is 117kHz

$$L_1 = \frac{1}{2 * \pi * 117k}, C_2 = \frac{2}{2 * \pi * 117\mathrm{k}}, L_3 = \frac{1}{2 * \pi * 117\mathrm{k}}$$

Multiply L values by R, and divide C values by R.

$$L_1 = \frac{R}{2 * \pi * 117\mathrm{k} * R}, C_2 = \frac{2}{2 * \pi * 117\mathrm{k} * \mathrm{R}}, L_3 = \frac{R}{2 * \pi * 117\mathrm{k}}$$

In this experiment, the R is selected as 50Ω.

$$L_1 = \frac{50}{2 * \pi * 117\mathrm{k}}, C_2 = \frac{2}{2 * \pi * 117\mathrm{k} * 50}, L_3 = \frac{50}{2 * \pi * 117\mathrm{k}}$$

After the calculations, the component values of the LPF are as follows.

$$L_1 = 68.01\mu\mathrm{H}, C_2 = 54.4\mathrm{nF}, L_3 = 68.01\mu\mathrm{H}$$

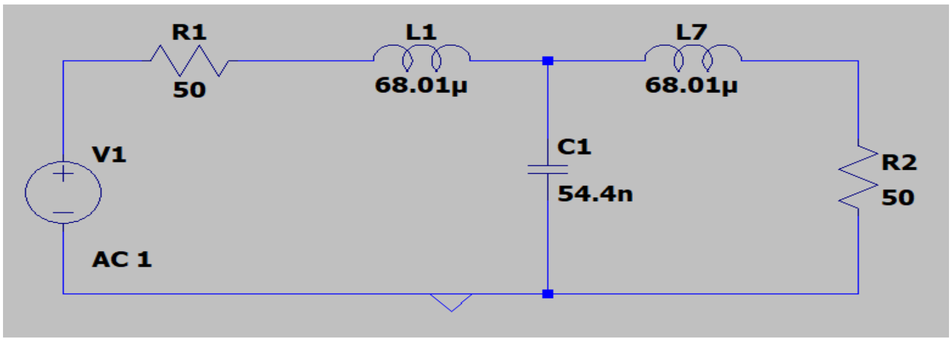



*Figure 5 – The designed Butterworth LPF*

In the second step, the L&C values are tuned at f=2.34Mhz.

$$C_1 = \frac{1}{w_0^2 * L_1}, L_2 = \frac{1}{w_0^2 * C_2}, C_3 = \frac{1}{w_0^2 * L_3}$$

$$C_1 = \frac{1}{2.16 * 10^{14} * 68.01\mu}, L_2 = \frac{1}{2.16 * 10^{14} * 68.01\mu}, C_3 = \frac{1}{2.16 * 10^{14} * 54.4n}$$

$$C_1 = 68.0\text{pF}, L_2 = 85\text{nH}, C_3 = 68.0\text{pF}$$

The overall circuit can be seen in Figure 6.

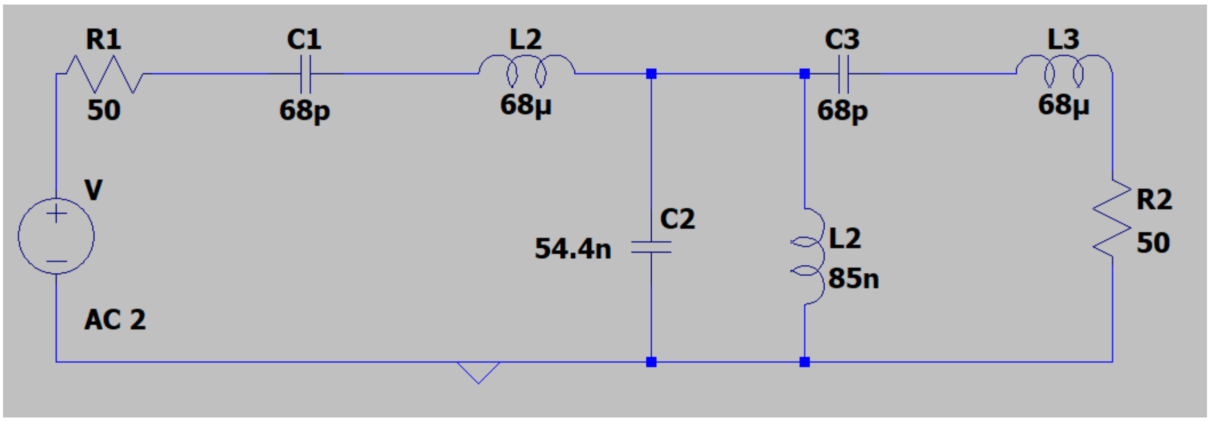



*Figure 6 – The designed Butterworth BPF*

The proposed circuit will be constructed with approximate components available in the hardware part at the lab. The gain will be calculated with the formula:

$$20 * \log(\frac{V_{out}}{V_{in}})$$

# Results:

## Simulation Results:

To evaluate the performance of the BPF, first, the LPF is tested.

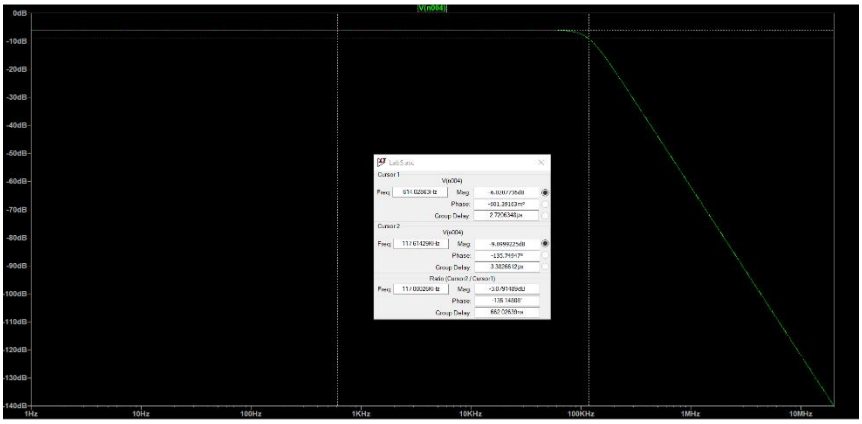



*Figure 7 – The Simulation Result of Butterworth LPF*

The cut-off frequency of the proposed LPF is 117.68kHz, which is quite close to the theoretical value of 117kHz, with an error of 0.58%.

The simulation results from the BPF are as follows.

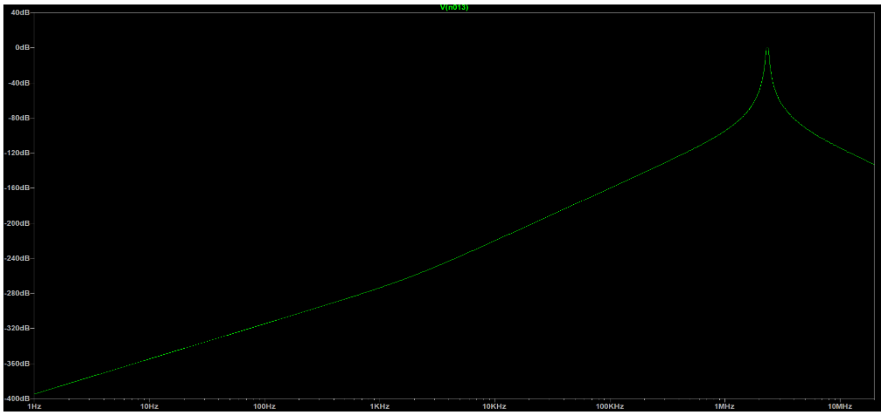



*Figure 8 – The Simulation Result of Butterworth BPF*

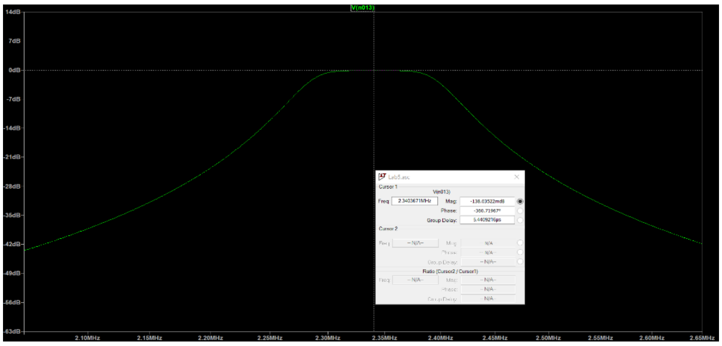


*Figure 9 – The Gain at the Center Frequency*

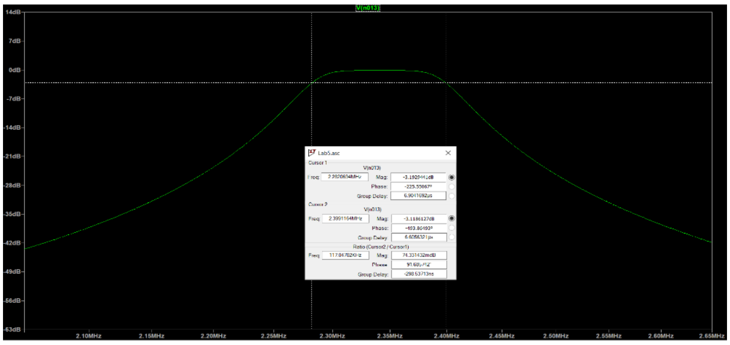


*Figure 10 – The Bandwidth of the BPF*

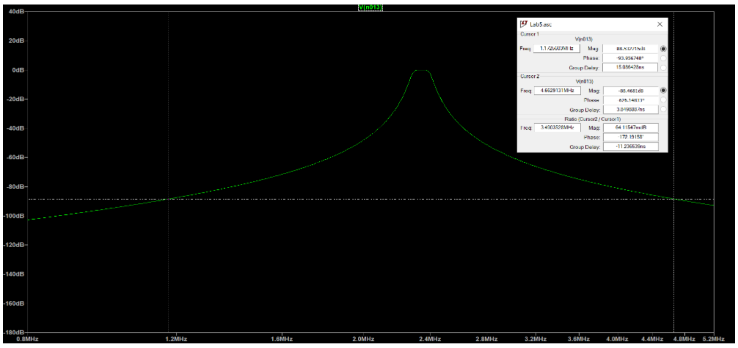


*Figure 11 – The Gain at $f_0 * \frac{1}{2}$ and $f_0 * 2$*

*Table I – The Simulation Results*

| | |
|---|---|
| **Gain at $\mathbf{f_0}$** | -0.138dB |
| **Bandwidth** | 117.04kHz |
| **Gain at $\mathbf{\frac{f_0}{2}}$** | -88.53dB |
| **Gain at $\mathbf{f_0 * 2}$** | -88.53dB |
| **Gain Variation in the Passband** | A_pass <= 3dB |

**Hardware Results:**

For the hardware implementation, the inductor core is chosen as T50 with Al = 4.3nH/t^2. The inductor and capacitor values are as follows: L1: 67uH, C1: 68pF, L2: 85nH, C2: 56nF, L3: 67uH, C3: 68pF. Since the signal generator has 50ohm internal resistance, only the load resistor is connected to the circuit. The 50ohm load resistor is obtained by connecting two 100ohm resistors in parallel. The inductors other than L2 are obtained by connecting 2 10uH with one 47uH inductor. The L2 is obtained by winding five times around the T50 core. The hardware implementation of the 3rd order circuit can be seen in Figure 12.

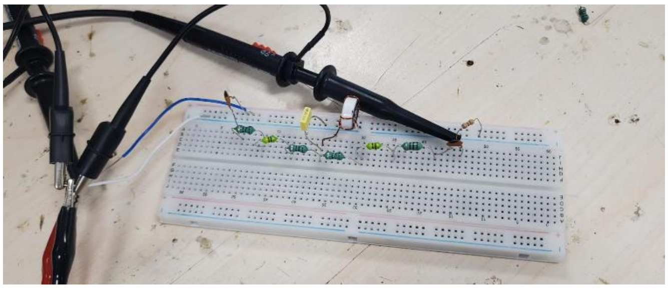


*Figure 12 – The Hardware Implementation*

The performance of the BPF has tested at least ten different frequencies. The results can be seen below.

First, the performance is tested in the bandwidth region.


*Figure 13 – The input-output at f =2.36Mhz and f=2.38Mhz*

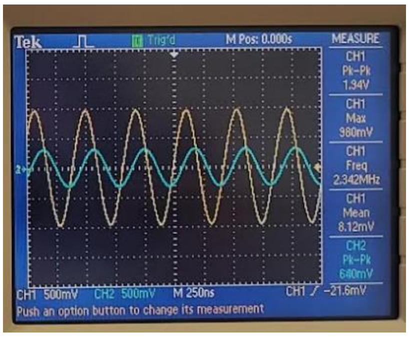
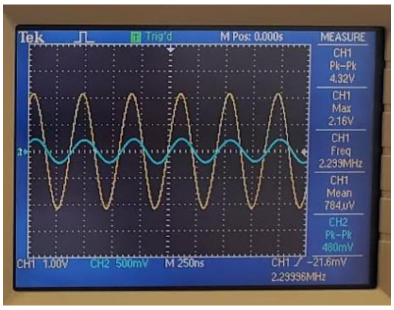



*Figure 14 – The input-output at f =2.34Mhz*



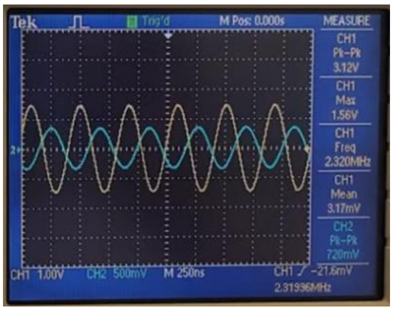




*Figure 15 – The input-output at f =2.3Mhz and f=2.32Mhz*

Then five frequency measurements are taken outside the bandwidth region.



*Figure 16 – The input-output at f =5Mhz and f=10Mhz*

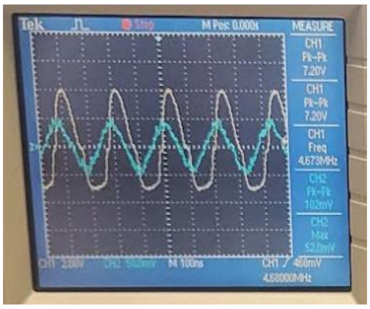
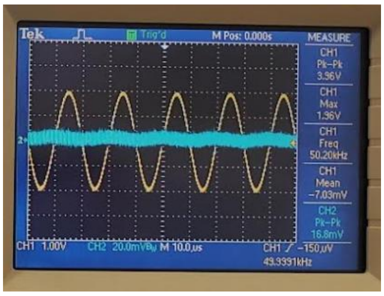



*Figure 17 – The input-output at f =4.68Mhz*



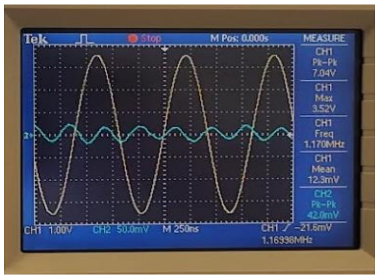




*Figure 18 – The input-output at f =0.05Mhz f=1.17Mhz*

*Table II – The Frequency-Gain Table*

| Frequency | Gain |
|---|---|
| **2.3Mhz** | −14.07dB |
| **2.32Mhz** | -12.73dB |
| **2.34Mhz** | −9.63dB |
| **2.36Mhz** | −9.19dB |
| **2.38Mhz** | −12.13dB |

| Frequency | Gain |
|---|---|
| **50khz** | −52.81dB |
| **1.17Mhz** | −44.43dB |
| **4.68Mhz** | −42.58dB |
| **5Mhz** | −44.86dB |
| **10Mhz** | −50.881dB |

*Table III – The Hardware Results*

| | |
|---|---|
| **Gain at $f_0$** | -9.63dB |
| **Bandwidth** | 71.23kHz |
| **Gain at $\frac{f_0}{2}$** | −44.43dB |
| **Gain at $f_0 * 2$** | −42.58dB |
| **Gain Variation in the Passband** | A_pass <= 3dB |

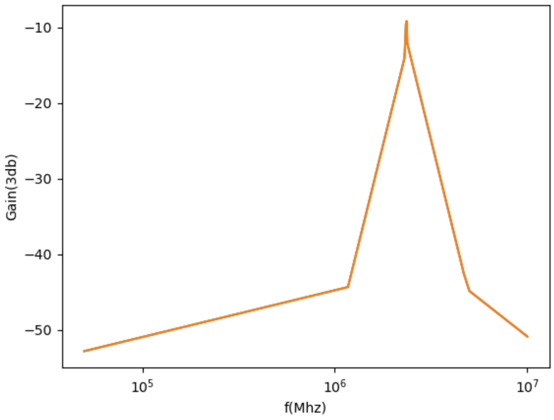



*Figure 19 The Gain vs Frequency Graph*

## Conclusion:

This lab task aims to design a bandpass filter with the given specifications. The selected bandpass filter is a Butterworth filter. In the previous course, EEE211 Analog Electronics, we get familiar with the design of a bandpass filter. Furthermore, the calculations are easy to follow since the constants have a lookup table. The filter is designed as a 3rd order BPF. Initially, due to hardware complexities, the filter is intended to be 2nd order. Although the simulation results were promising, the hardware results had significant errors. Thus, I changed it to a 3rd order BPF for better accuracy. The simulation results of the 3rd order were promising, such that all of them complied with the specifications. In the hardware lab, the results were not excellent but satisfactory. The center frequency was 2.34Mhz, but the results showed the most significant gain at 2.36Mhz(0.85% error) in the hardware design. Overall, the circuit successfully stopped frequencies beyond the passband. However, the width of the passband was not quite close to the proposed value of 117kHz. The passband measured in the hardware lab was 71.23kHz(37.4% error). Furthermore, the gain was lower than the expected values. This was expected since energy loss is inevitable with every component added. To compensate for this, the sinusoidal input could be amplified. The amplification should be applied before filtering, not after filtering, because the noise can also be amplified if the amplification is made after the filtration. Moreover, I used approximate values in the hardware lab. If the exact values are used, the results would be much better. I learned to design a Butterworth bandpass filter in both LTSpice and real life in this lab.