Hardware Report Lab 5
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Hardware Lab 5

Introduction

This lab assignment consisted of designing a band pass filter. It was given that our band-pass filters should have a center frequency (f_0) between 1MHz and 6MHz. The load resistor should be 50Ω. Furthermore, the 3-dB bandwidth should be equal to 0.05*f_0. The pass-band loss of the filter should be less than 6dB. The rejection of the output of the filter should at least 30dB for 0 < f < 0.5f_0 and 2f_0< f < 5f_0. The expected output can be seen below.

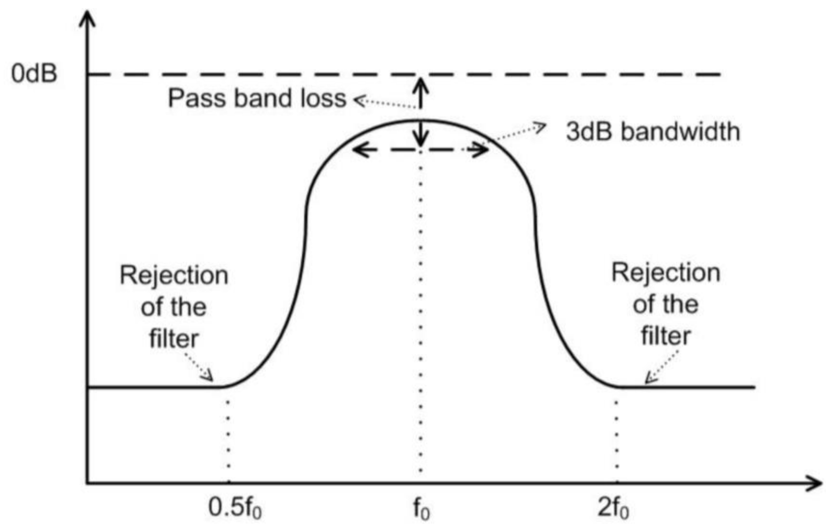

Figure 1: Filter Response

This software report investigates a way to obtain the desired band-pass filter, which will be abbreviated as BPF throughout the report. Then the concluded design will be simulated on LTSpice and the results will be discussed. Then, the designed circuit will be built and tested.

Hence, the first process is to select the center frequency that we will be working with. The center frequency (f_0) is chosen as 2Mhz. Hence, the 3-dB bandwidth (Δf) becomes;

$$\Delta f = 0.05 * 2MHz = 100kHz$$

However, there are some important concepts that must be investigated before starting on the structural process. In order to design a BPF, we need to understand how to design Butterworth Filters. One significant detail, I have decided to build a second order Butterworth filter as it is the optimal number when efficiency is concerned. Furthermore, there are two main steps of designing a Butterworth BPF.

1. First, we design a second order low pass filter (LPF), which consists of a serial inductor and a parallel capacitor. Note that the low-pass filter's 3dB cutoff frequency should be equal to Δf.
2. Then, we need to match the capacitor with inductor and vice versa. The capacitor should be in series with the inductor and the capacitor should be in parallel with the inductor. The inductance and capacitance values of these components van be found with the equations below

$$C_1 = \frac{1}{(2\pi f_0)^2 . L_1}$$

$$L_2 = \frac{1}{(2\pi f_0)^2 . C_2}$$

Software Analysis

Design and Analysis

Now executing the first step, we need to design a Butterworth LPF. In order to, we need to use the following relations to find the needed inductance and capacitance values.

$$L_1 = \frac{b_1 R_L}{2\pi.\Delta f}$$

$$C_2 = \frac{b_2}{2\pi R_L.\Delta f}$$

We have knowledge of all of these unknowns except the coefficients b1 and b2. These values are to be found from the table that has already calculated values namely "Prototype Element Values in Butterworth LPF".

Order	R_S	C_1 a_1	L_2 a_2	C_3 a_3	L_4 a_4	C_5 a_5	L_6 a_6	C_7 a_7
1	1.0	2.0000						
2	1.0	1.4142	1.4142					
3	1.0	1.0000	2.0000	1.0000				
4	1.0	0.7654	1.8478	1.8478	0.7654			
5	1.0	0.6180	1.6180	2.0000	1.6180	0.6180		
6	1.0	0.5176	1.4142	1.9319	1.9319	1.4142	0.5176	
7	1.0	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450

As our aim is to build a second order LPF, b1 and b2 are both equal to 1.41421. Now we can calculate C1 and L2.

$$L_1 = \frac{b_1 R_L}{2\pi.\Delta f} = \frac{1.41421 * 50}{2\pi.100.10^3} \approx 113\mu H$$

$$C_2 = \frac{b_2}{2\pi R_L.\Delta f} = \frac{1.41421}{2\pi.50.100 * 10^3} \approx 45nF$$

Since we have obtained the required information on designing the LPF, we can implement it on LTSpice and see the results. The implemented circuit can be found below.

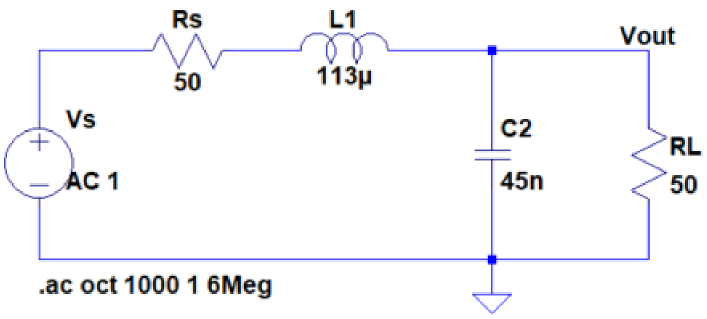

Figure 2 – The LPF Circuit Schematic

AC simulation of the circuit is also down below.

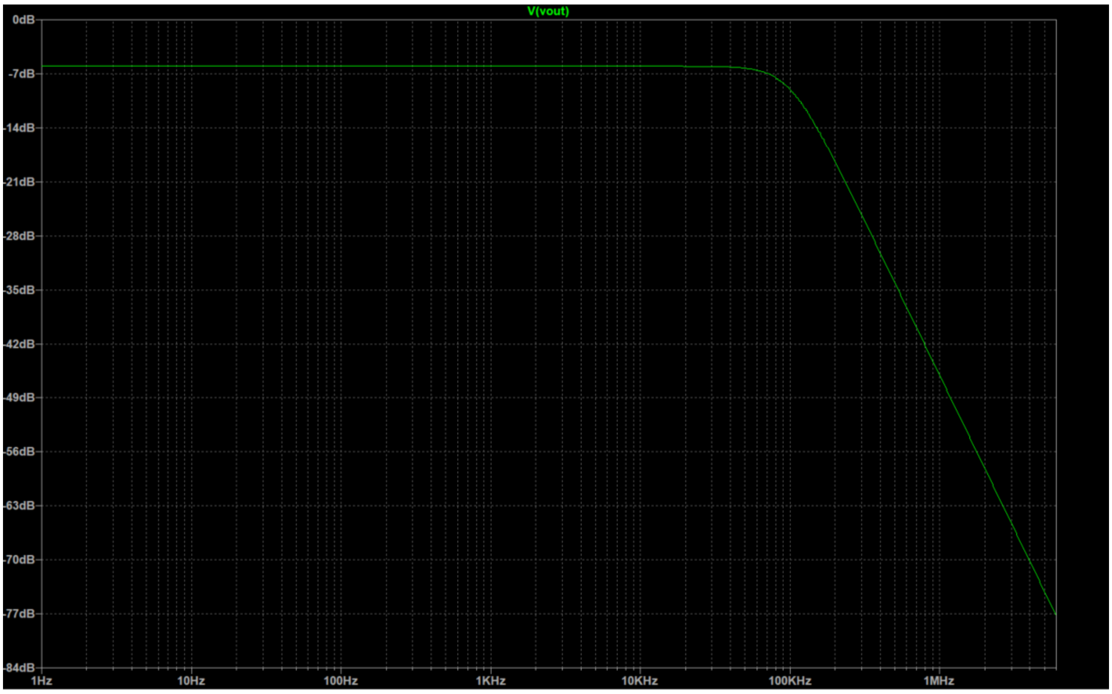

Figure 3 – LPF AC Analysis

As we want to see the exact 3dB cutoff frequency, we use cursers to give it a closer look which can be found down below.

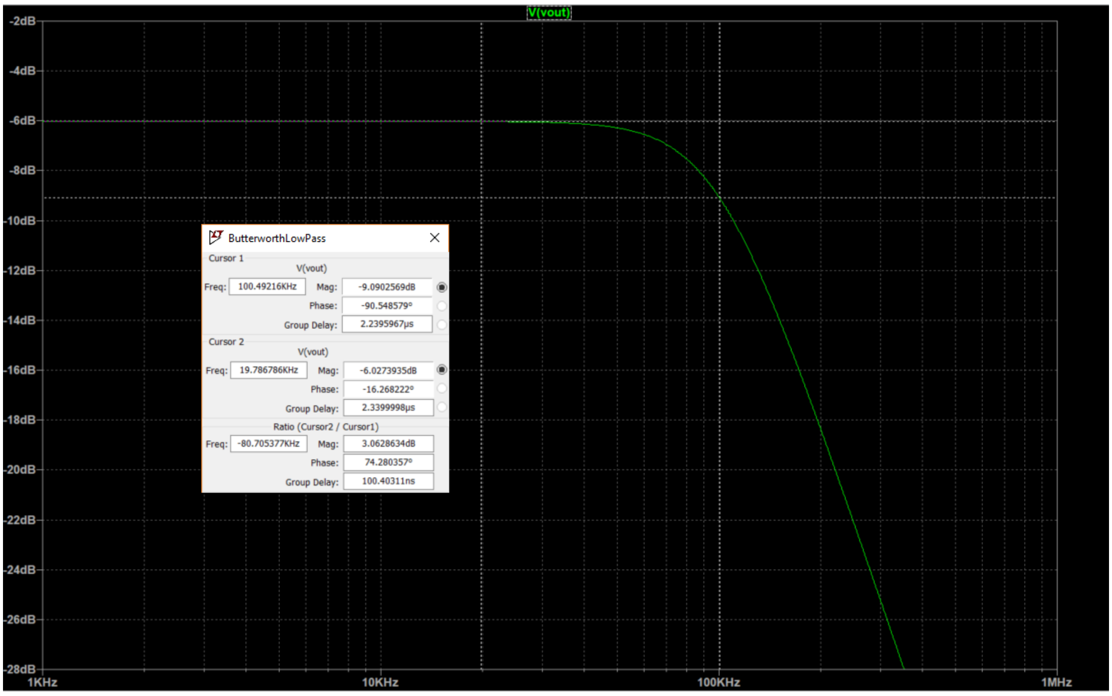

Figure 4 – LPF 3dB Cutoff Frequency

As it is seen from Figure 4, the 3dB cutoff frequency is 100.49216kHz, which is nearly 100kHz, as it is the expected value. Since the design of the LPF is finished, we move onto the second step and add the inductors and capacitors to resonate the circuit on 2Mhz center frequency. However, we first need to obtain the inductance and capacitance values that can be found down below.

$$C_1 = \frac{1}{(2\pi f_0)^2 . L_1} = \frac{1}{(2\pi . 2.10^6)^2 . (113.10^{-6})} \approx 56pF$$

$$L_2 = \frac{1}{(2\pi f_0)^2 . C_2} = \frac{1}{(2\pi . 2.10^6)^2 . (45.10^{-9})} \approx 141nH$$

With the use of these values, we have completed the data collection. The next stage is to put the BPF on test by simulating it on LTSpice. The drawing is given below.

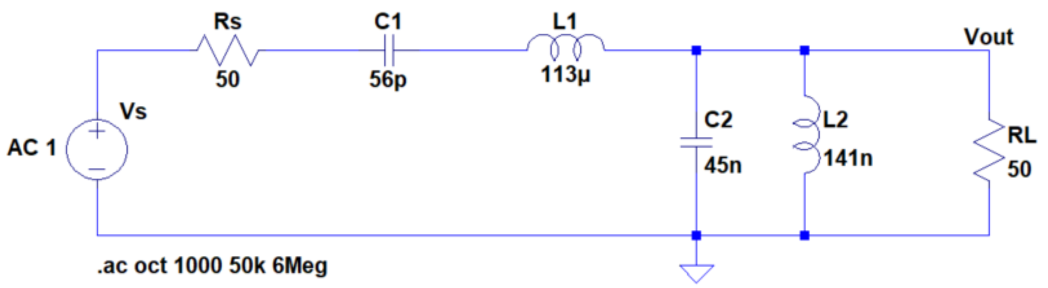

Figure 5 – The BPF Circuit Schematic

As it can be seen, we simulated the circuit from 50kHz to 6MHz to see the range in full resolution. To do, we have used an AC source with 1V amplitude. The AC analysis simulation of the BPF is given below.

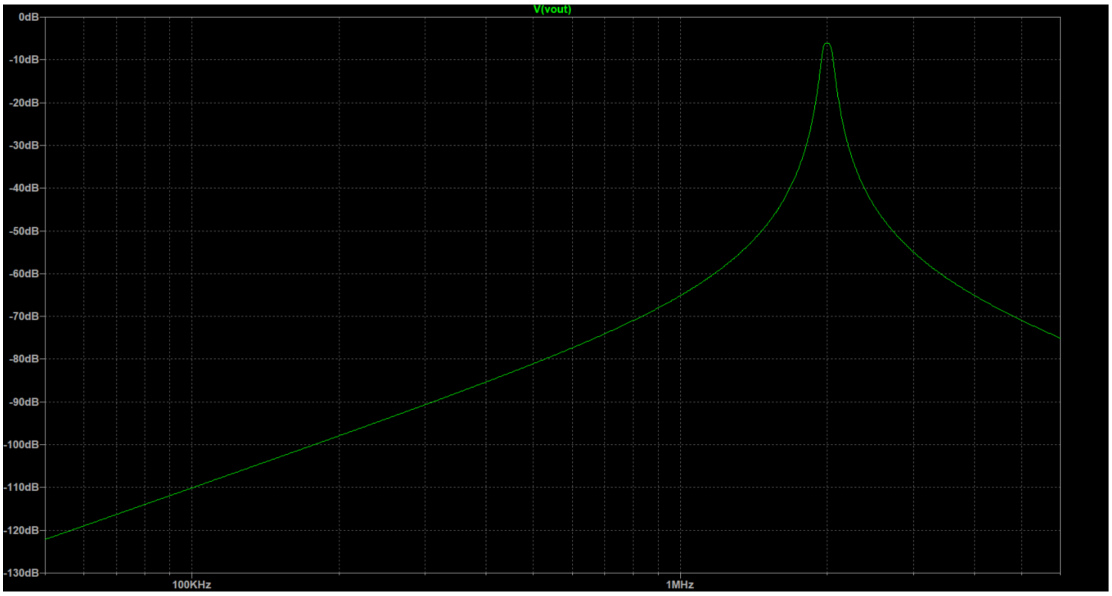

Figure 6 – The BPF AC Analysis

In general, the circuit looks like the expected graph, as this is the graph of the output voltage. However, in order to find if the experiment was a success or not, we should check whether the given criteria in the assignment is matched. First criteria states that the 3-dB filter bandwidth should be equal to $0.05f_0$, 100kHz while the second criteria states that the pass-band loss of the filter should be less than 6 dB. Finally, the third criteria states that the rejection of the filter should be at least 30 dB for 0 < f < $0.5f_0$ and $2f_0$< f < $5f_0$. In order to observe these, we use the cursors and zoom in the function

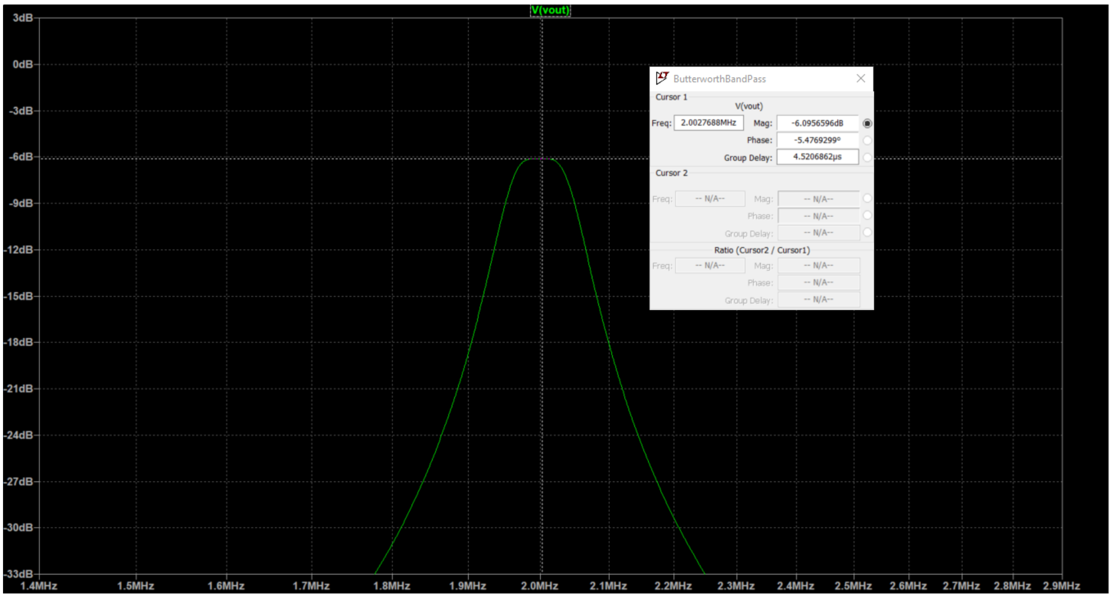

Figure 7 – Peak Zoom of Figure 6

As we can read from the screen, the pass band loss of the filter, which is 6.095dB, is nearly equal to 6dB. The following picture uses the cursors to find the 3dB bandwidth.

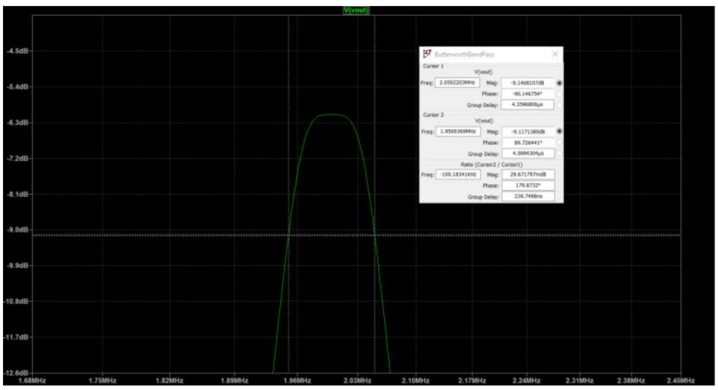

Figure 8 – The 3dB Bandwidth Analysis of Figure 6

From this picture, we can read that the 3dB Bandwidth is equal to 100.1834kHz which is nearly equal to the 100 kHz that we wanted to see. Therefore, we can say that the circuit fulfills the first two criteria. Then, we need to check the third which is the rejection of the filter. The figure shows the two cursors placed on $0.5f_0$ (1MHz) and $2f_0$ (4MHz) as these are the maximum values these voltages can get in the assigned intervals.

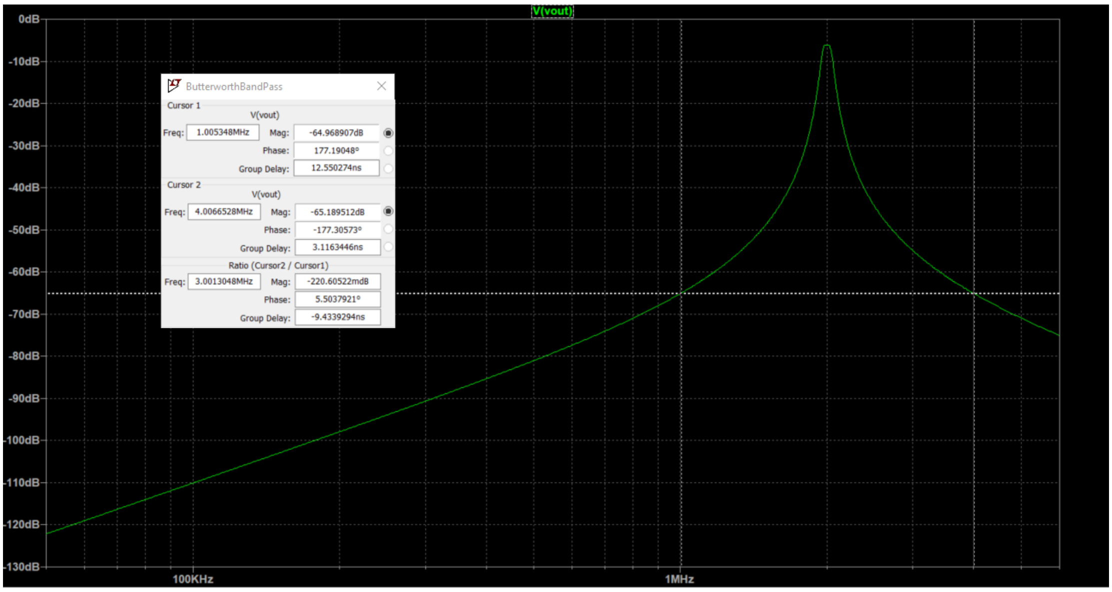

Figure 9 – Rejection of the BPF

It was stated that the rejections should be bigger in dB than 30dB. As we see in the graph, rejections of the points are -64.969dB and -65.190dB respectively. Which means their absolute values are nearly equal to the double of what is required, which is a nice accomplishment. Therefore, we can conclude that we have successfully designed a Butterworth Band-Pass Filter that fits the criteria given.

Hardware Results

As mentioned in the software analysis, we will be implementing a second order Butterworth band-pass filter. However, we have designed the circuit to be working on the 2MHz range. Then, when I have done the calculations, I saw that a 4MHz filter would work a lot better and also standard values will be a lot easier to use. Then the new values for the capacitances and inductors became as below.

$$C_1 = 28pF$$

$$C_2 = 22.5nF \cong 23nF$$

$$L_1 = 56.5\mu H \cong 57\mu H$$

$$L_2 = 70.5nH \cong 71nH$$

The implemented circuit is given below,

Figure 10 – The BPF Circuit

As you can see, we have used, 22pF and 6.8pF capacitances to obtain 28.6pF which is nearly equal to 28pF. Then for the 57µH inductance, we have connected 47µH and 10µH serially which adds up to 57µH. Then for the 22nF capacitor, we have used the standard 22nF capacitor. However, for the 71nH inductor, we have run the following calculations. We have used T50-7 toroidal core, which has 4.3 nH/n^2 nominal inductance.

$$71 = 4.3 * n^2$$

$$n^2 = 16.512$$

$$n_2 = 4.063 \approx 4\ turns$$

$$L = 4.3 * 16nH = 68.8nH \approx 71nH$$

Hence, we have winded 4 turns onto the core. Also, we have connected two 100Ω resistors in parallel to get the 50Ω of output resistance. As we have constructed the circuit, the next phase is to observe if it is working the way it is supposed to. We use 10Vp-p sine voltages to obtain our results. The output voltage can be seen below.

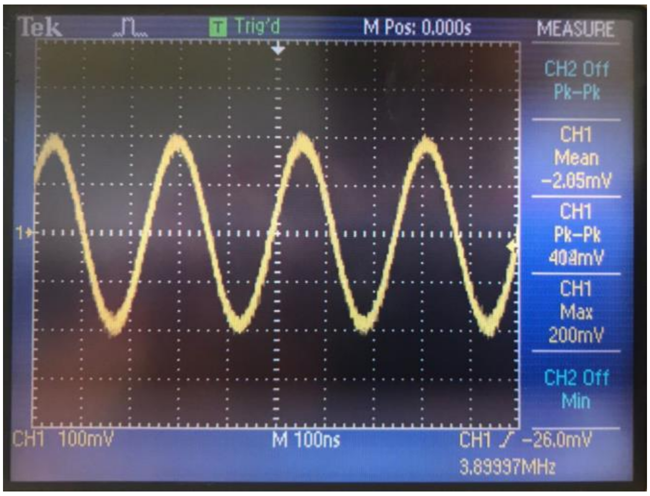

Figure 11 – The Output Waveform

We can see the sinusoid with some amount of loss, but we will not be calculating the loss this way and we will use the FFT (Fast Fourier Transform) option of the oscilloscope to find if the filter-built meets the expectations. First thing that we need to do is to find the actual f_0 of the filter, that happened due to resistances and the failure to find the exact values of the capacitances and inductors. We see that the maximum allowance happens at 3.90MHz with trial and error. Then we arrange the signal generator to 3.9MHz and use FFT to find the pass band loss. Both of the images can be found below. FFT (Fast Fourier Transform) is translating the signal to the frequency domain, enabling us to see the waveforms peak points at units of dB in the desired frequency.

Figure 12 – 3.9MHz source input.

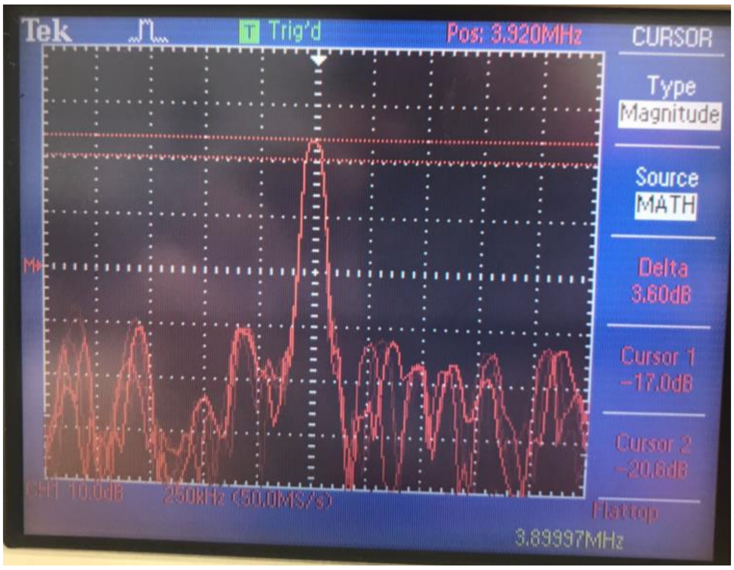

Figure 13 – FFT for the Central Frequency

As we can see there is a peak on the 3.9 MHz as we have applied 3.9MHz to the circuit. However, if we look at the maximum point, we see that is -17dB, which becomes our pass-band loss. The circuit does not do its job regarding the allowance of 6dB of loss. We will discuss the reasons for that in the conclusion. Then, we see if the ±3dB frequencies are equal to the (1±0.05) f_0 frequencies. For that, we set the signal generator to 4.095MHz and 3.705MHz in order to observe their peak points.

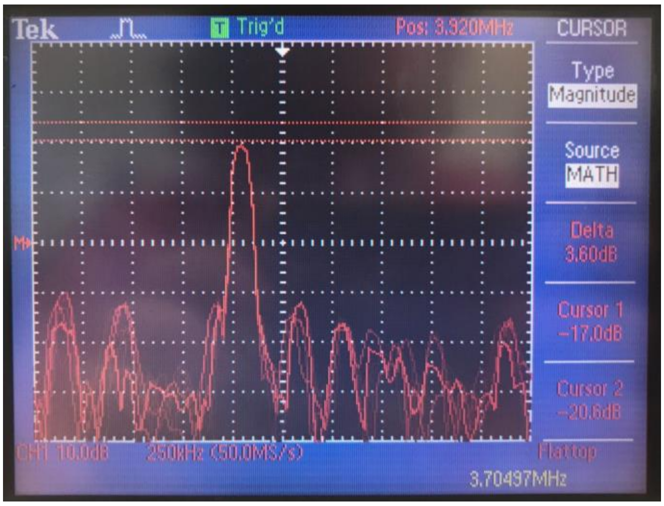

Figure 14 – FFT of (1-0.05) f_0

As you can see, the curser up top is the curser assigned to the peak point of 3.9MHz and the lower cursor is on the peak of the 3dB corner frequency. When we look at delta, we see that the difference is 3.6dB which is nearly equal to 3dB. Then we look at the 4.095MHz.

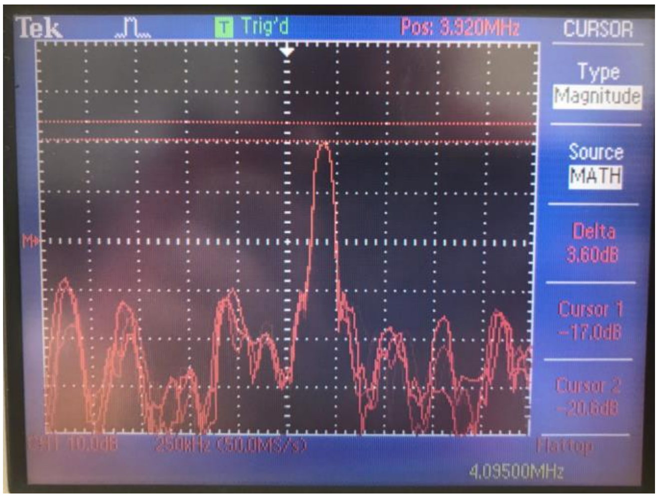

Figure 15 - FFT of (1+0.05) f_0

We can see the similarity with the previous figure and directly look at the delta which is also 3.6MHz. As we look into these, we can conclude that the 3dB cutoff frequencies are equal to $0.05f_0$. Then we need to check the third and final condition, which is the $0.5f_0$ and $2f_0$ frequencies. It is stated in the assignment that the loss on these frequencies are bound to be at most -30dB. We look for the FFTs of 7.8MHz and 1.95MHz to see if that is the case.

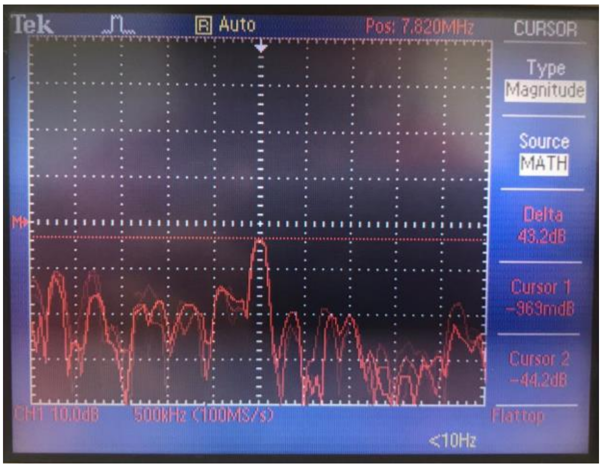

Figure 16 - FFT of $2 * f_0$

As seen from the graph the loss at this frequency is equal to -44.2dB which is smaller than -30dB. Then we look at the 1.95MHz.

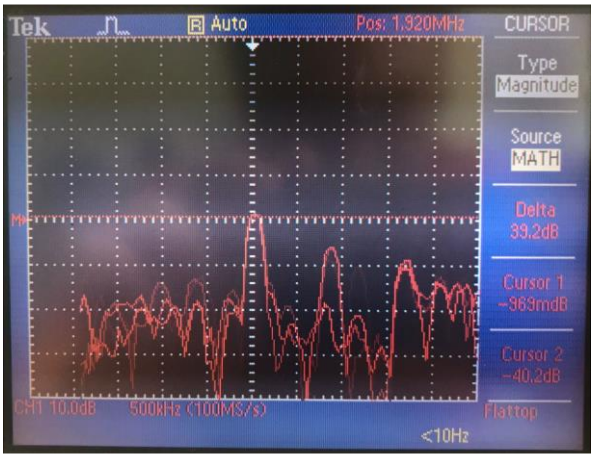

Figure 17 - FFT of $f_0/2$

Now we see that the cursor value shows -40.2dB, which is also smaller than -30dB. Hence, we can easily say that the losses at half and double center frequencies are more than 30dB. Hence, we have concluded reading the results of this lab assignment. Next and final stage is to discuss the errors that have occurred and their reasons.

Conclusion

This laboratory exercise demanded us to design a band pass filter with center frequency in the range 1MHz and 6Mhz and 3dB cutoff frequency equal to $0.05f_0$. We have chosen the frequency to be 4MHz and hence the 3dB bandwidth has become 400kHz. Then using what we have learned in EEE-211 Analog Electronics, we have designed a Butterworth band-pass filter that fit the criteria. As the steps of designing Butterworth included two steps, we designed those steps and finally simulated each on LTSpice. We see that the circuit worked nearly perfect with some minor and unimportant errors.

The next stage was to construct the circuit that we have designed. We could not exactly build the circuit as desired and the result for that is we could not reach some of the expectations that are given. The most important that that we have ignored is the band loss came up to be -17dB which was not related with the -6dB that we have achieved on the simulation. As this is a physical circuit with physical losses on every component, it is only natural to find such solutions. However, the 3dB bandwidth and other losses turned up to be the way we desired. There was one thing, that the center frequency of our circuit turned out to be 3.9MHz and not 4MHz. This is an acceptable error as again, we couldn’t use the exact values that we have seen on the LTSpice design.

Finally, we can say that this lab was very useful for our knowledge on band-pass filters and Butterworth filters. Furthermore, we have increased our knowledge on using LTSpice and resonating circuits. We have also refreshed our memories about the frequency domain and Fourier Transforms on signals.