Laboratory 5

Sinusoidal Steady State Filters

S.C. Petersen

EE101L

Intro. to Electronic Circuits Laboratory

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Introduction:

The purpose of this lab was to observe the frequency domain characteristics of steady state linear wave filers. Instead of time domain, this lab will be focusing on phasor domain as well as frequency response We will investigate salient characteristics of the basic first order low-pass and high-pass filters, and second order bandpass and bandreject filters. I experimentally measured the amplitude and phase responses. With this lab, we will gain better understanding of bode plots, decibels and phasor. The first experiment was for series RC low-pass filer. The second experiment was to observe series RC high-pass filter. For the third experiment, I investigate the operational amplifier low-pass filter. For the last one, I constructed series RLC bandpass and band reject filters. One of the main factors should be noted is that the internal resistance of the signal generator is 50 ohms.

Theories:

Frequency response

Consider the filters as a transfer function H, the input is u and the output is y. The main idea of filter can be represented as: u -> H -> y. The frequency response of the system can be represented as:

$$H(j\omega)=\int_{0}^{\infty} h(t)e^{-j\omega t}dt$$

Bode plot: bode plots are logarithmic plots with the y axis being the magnitude in decibels and the x axis being the frequency.

Frequency axis is logarithmic scale for omega. Magnitude is expressed in dB. In our case magnitude

$$Magnitude = 20\log\left(\frac{|Vout|}{|Vin|}\right)[dB]$$

is

$$Phase\ (\text{degree}) = 360 \cdot f(Hz) \cdot \delta t$$ versus log frequency.

Methods:

3.1 Series RC low-pass filter

Low-pass circuit.

Low pass filters allow low frequencies to pass through but not high frequencies. With phasors and the voltage divider theorem, the low-pass response voltage across the capacitor with the input being the reference phasor is:

$$\overline{V}_{out} = \overline{V}_{in}\frac{Z_C}{R+Z_C} = V_{in}\angle 0^\circ \frac{\frac{1}{j\omega C}}{R+\frac{1}{j\omega C}} = V_{in}\angle 0^\circ \frac{1}{1+j\omega RC}$$

From the formula we can see that when frequency increase, the response will decrease. We can predict that at low frequencies, Vout will be approximately equal to Vin, and I have experimentally proved this statement.

We define cutoff frequency, at the half power or -3dB point, as

$$fc = \frac{1}{2\pi RC}$$

Passband: all frequencies to the left to fc.

Stopband: all frequencies to the right to fc

From the following experiment, we would see that how the output voltage lags the input voltage by 45 degrees at the cutoff frequency.

I constructed an RC low-pass filter using a 100nF capacitor and two resistances, 50 ohms and 9.8k+50 ohms. I also constructed an oscilloscope with the open circuits in the figure 1.1.

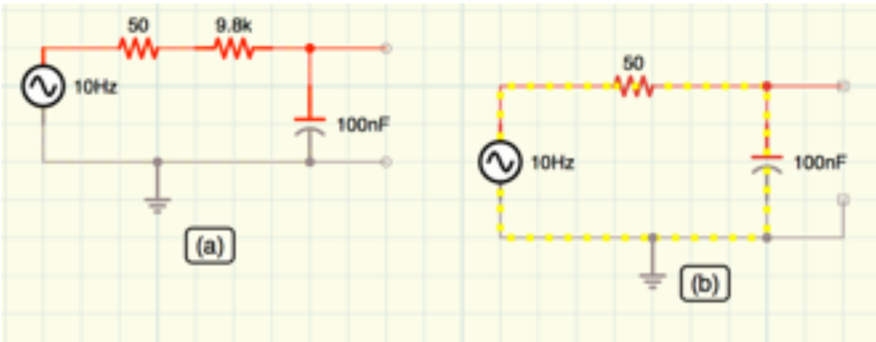
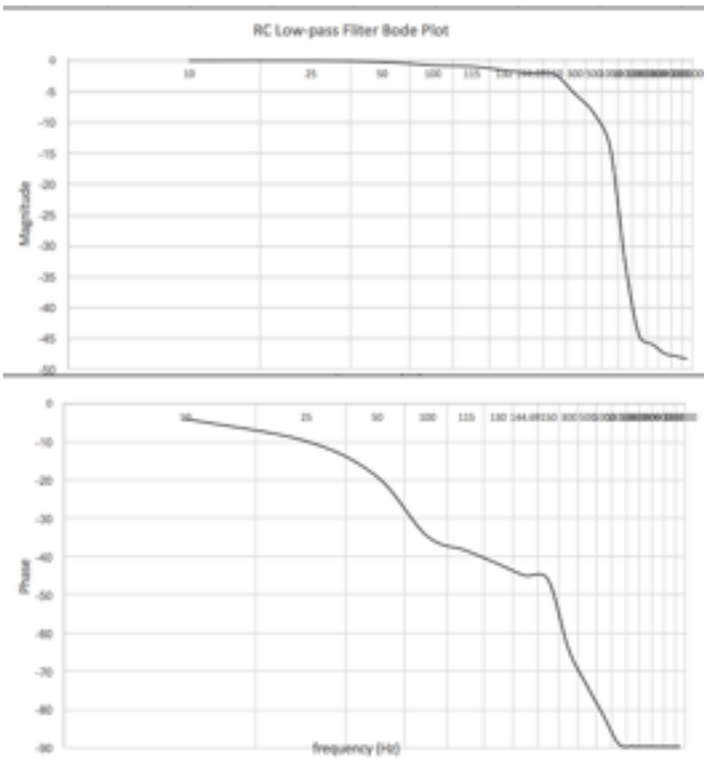


Figure 1.1 RC low-pass filter circuits

For part one, the cutoff frequency was 162Hz. I constructed a 9.8k ohms resistor in series in the circuit. With the data I generated, I constructed a bode and phase plot below in figure 1.2:



From the generated data, there are few points needed to be noticed. First of all, when the frequency was at the cutoff point, 162Hz, the dB value, -2.8671, was approximately to -3. Another point is at cutoff frequency, the phase degree was about 46.

Figure 1.2 Bode and phase Plot of RC low-pass filter with 9.8k+50 ohms resistance

For part b, the cutoff frequency was 32kHz. With the generated data, I constructed a bode plot in figure 1.3. However, since the phase shift was too small. I was not able to gather the difference of time, delta t, so that I do not have a phase plot for this experiment. When I set the frequency to 32kHz, the cutoff frequency, the dB value I had was -3.152. The value of dB was approximately -3.

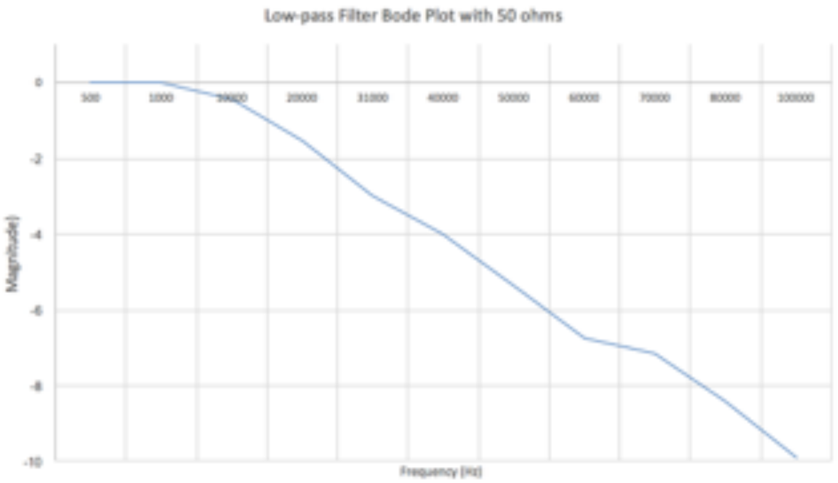


Figure 1.3 Bode Plot of RC low-pass filter with 50 ohms resistance

The two experiments of low-pass circuit both proved our theories. At low frequencies, Vout is approximately equal to Vin. At cutoff frequency, the output voltage lags the input voltage by 45 degrees. Also at cutoff frequency, the dB value is -3.

3.2 Series RC high-pass filter

For experiment 3.2, I was hoping to verify that the output voltage leads the input voltage by 45 degrees. There were three parts of this experiment. Each parts involved different resistance. I used a 11k ohms resistor in part a, 470 ohms resistor in part b, and 4.7k ohms resistor in part c. I neglected the internal resistance of a signal generator.

Part a:

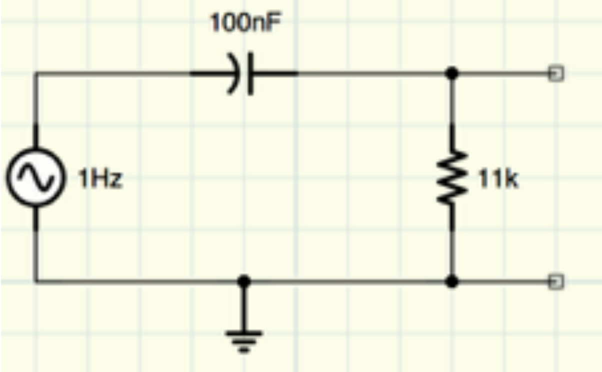


Figure 2.1 RC high-pass filter circuits with 11k resistance

I constructed the above circuit and connected a oscilloscope in the open circuit to determine the voltage across the resistor. Then I generated data from the oscilloscope while changing the input frequency. The output voltage varied with the frequency while the input voltage stayed the same. By calculation, we can get the cutoff frequency is 144Hz. With the generated data, I constructed the bode and phase plot as in figure 2.1.1.

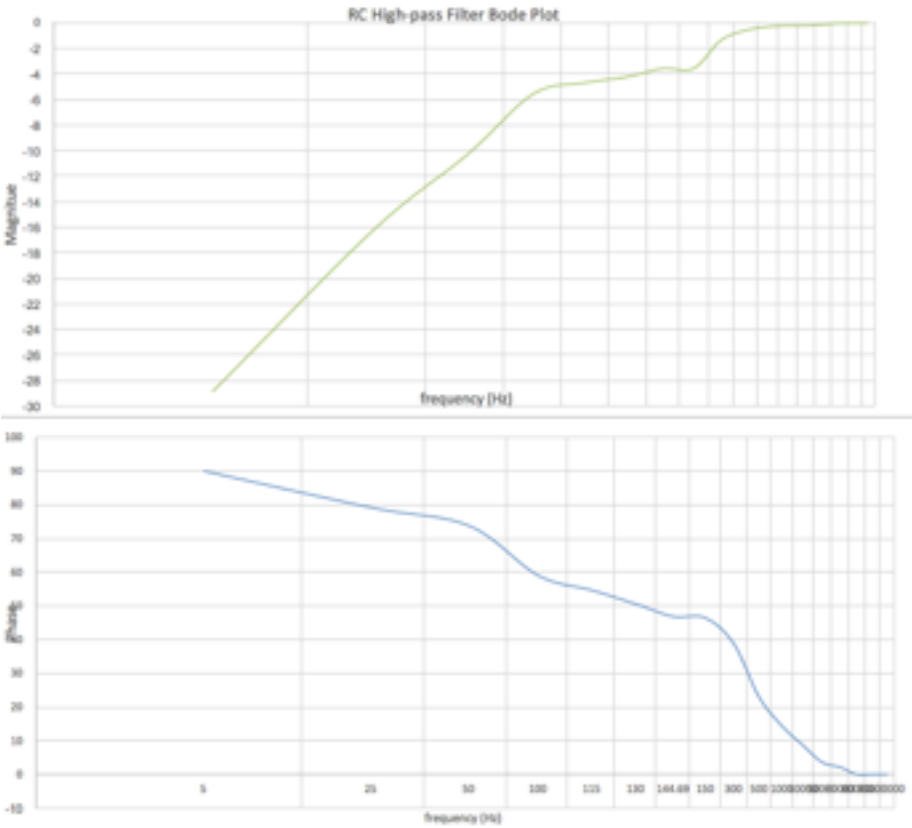


Figure 2.1.1 Bode and phase Plot of RC high-pass filter with 11k ohms resistance

We can capture some important points from the data. First, at cutoff frequency, the dB value was -3.45. This number is 15% bigger than we expected. I think one of the reasons might be I did not take the internal resistance of signal generator into consideration, though 50 ohms is fairly small comparing to 11k. Another point is that at cutoff frequency, I had the phase as 47 degree, and we expect it to be 45. 4% of derivation is acceptable.

Part b:

For part b, I simply replaced the resistor with a 470 ohms resistor and did the same process as what I did in part a. The cutoff frequency was 3387 Hz. Figure 2.2.1 is the circuit I constructed for this part. Figure 2.2.2 is the graphs I generated from my data points.

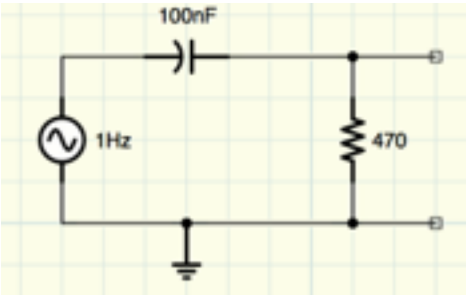


Figure 2.2.1 RC high-pass filter circuits with 470 resistance

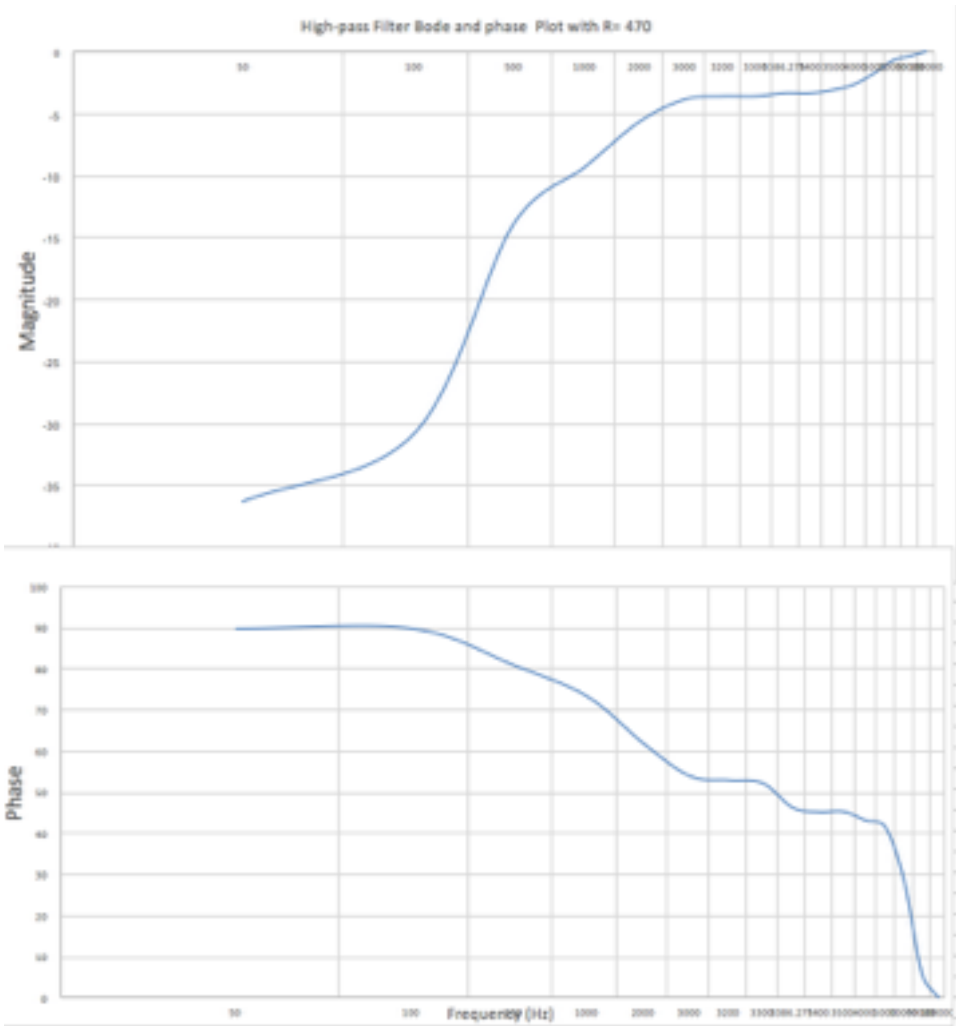


Figure 2.2.2 Bode and Phase Plot of RC high-pass filter with 470 ohms resistance

At cutoff frequency, 3387 Hz, the dB value was -3.36 which is a little bit off from -3. The phase was 46 degree, which only one degree off from expected.

Part c:

In this part, I have constructed the circuit in figure 2.3.1 below. Similarly, I constructed an oscilloscope across the resistor to monitor the voltage change and repeat whatever I did in part a and part b. The cutoff frequency was 338 Hz. I gathered data points and generated a bode and phase plot in figure 2.3.2.

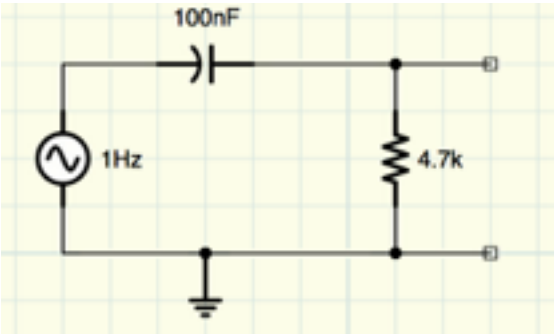


Figure 2.3.1 RC high-pass filter circuits with 4.7k resistance

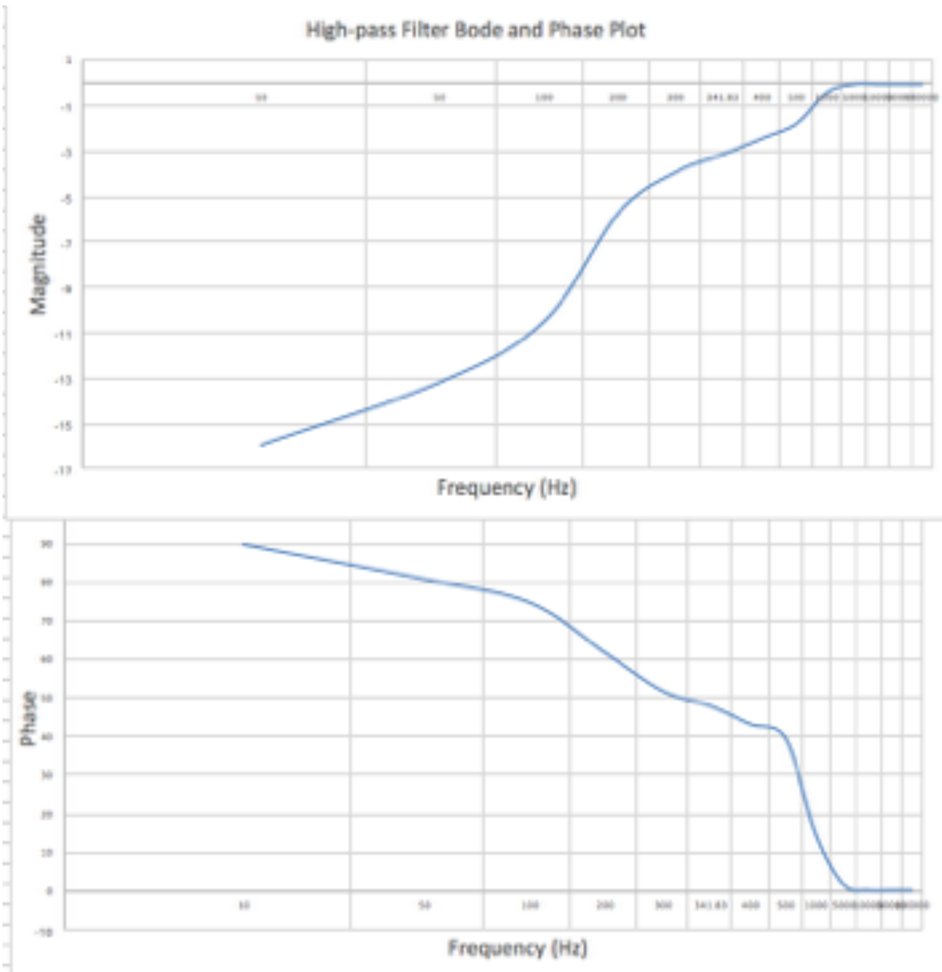


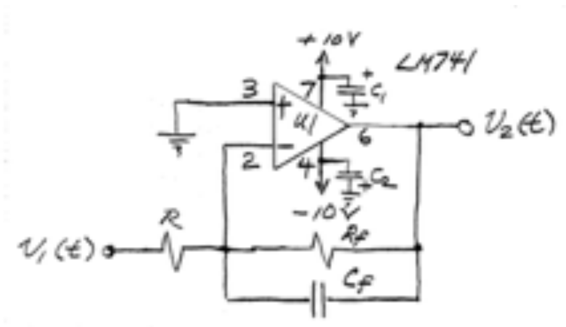
Figure 2.3.2 Bode and Phase Plot of RC high-pass filter with 4.7k ohms resistance

From the generated data points, I got the dB value of -3.08 and the phase value of 46.99 at cutoff frequency.

3.3 Operational amplifier low-pass filter

This part was to construct a low-pass filter using the LM741 op-amp, as in figure 3.1. One of the main points was to ensure the low pass response of the op-amp did not interface with the corner frequency of the low pass response of the circuit. Therefore, we had to keep the dB value below 24dB.

The graph of the circuit was copied from the lab manual. The capacitance was 100 nF. Rf was 39k. I constructed this circuit with one of the TAs. I calculated the cutoff frequency with the same formula as above sections. The theoretical cutoff frequency is 41Hz. We can calculate the response gain:



$$\frac{Vout}{Vin} = -\frac{Rf}{R(1+j\omega RfCf)}$$

Figure 3.1

Figure 3.2 represents the bode and phase plot for the operational amplifier circuit.

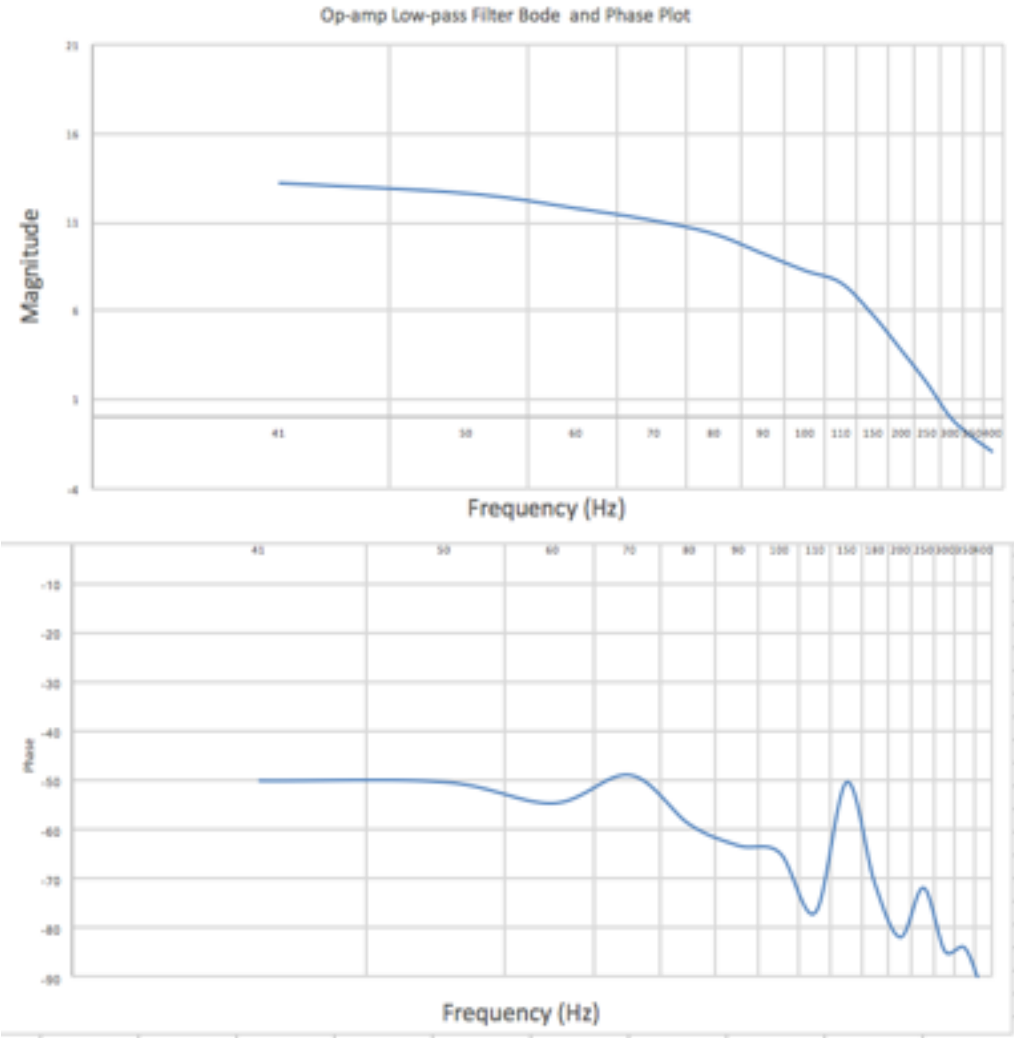


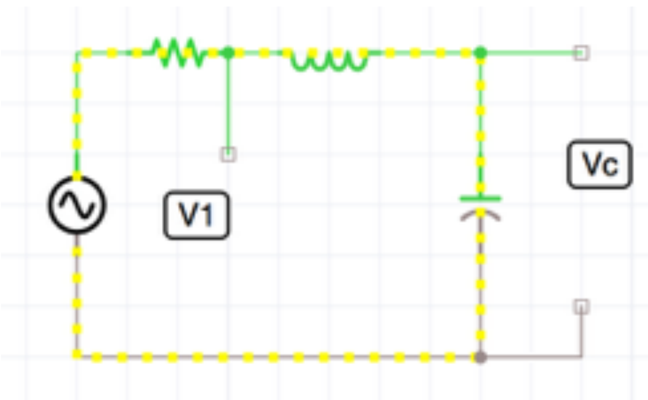
Figure 3.2 Bode and Phase Plot of operational amplifier circuit

From the data, we can see the cutoff frequency was about 410 Hz, which is ten times larger than our theoretical cutoff frequency. Also, if we check for phase, when frequency was at 500Hz, the phase was 90 exactly. 500 Hz is close to 410 Hz. My guess is probably something was wrong with my calculation even though I could not find what went wrong. Otherwise, I don't know why the experimental data would be 10 times larger than excepted.

Frequency	Vout	Vin	dB	Δt	Phase	Expected Phas
41	18.4	4	13.2551566	8.8	-50.112	-40.3683607
50	17.2	4	12.6693691	7.2	-50.4	-46.033027
60	15.6	4	11.8212921	5.8	-54.72	-51.207232
70	14.4	4	11.12605	5.2	-48.96	-55.4338406
80	13.2	4	10.3702788	4.2	-59.04	-58.9159213
90	11.6	4	9.24795996	3.6	-63.36	-61.8142453
100	10.4	4	8.29946696	3.2	-64.8	-64.2525581
110	9.6	4	7.60422483	2.6	-77.04	-66.3252705
150	7.8	4	5.80069223	2.4	-50.4	-72.1760965
180	6.4	4	4.08239965	1.68	-71.136	-75.0006189
200	6.2	4	3.80663396	1.36	-82.08	-76.4423143
250	5	4	1.93820026	1.2	-72	-79.0809169
300	4	4	0	0.88	-84.96	-80.8671268
350	3.52	4	-1.11034656	0.76	-84.24	-82.1542519
400	3.2	4	-1.93820026	0.6	-93.6	-83.124925
500	2.48	4	-4.15216621	0.5	-90	-84.4904349
600	2.12	4	-5.51448261	0.46	-80.64	-85.4043723
700	1.84	4	-6.74484337	0.42	-74.16	-86.05865

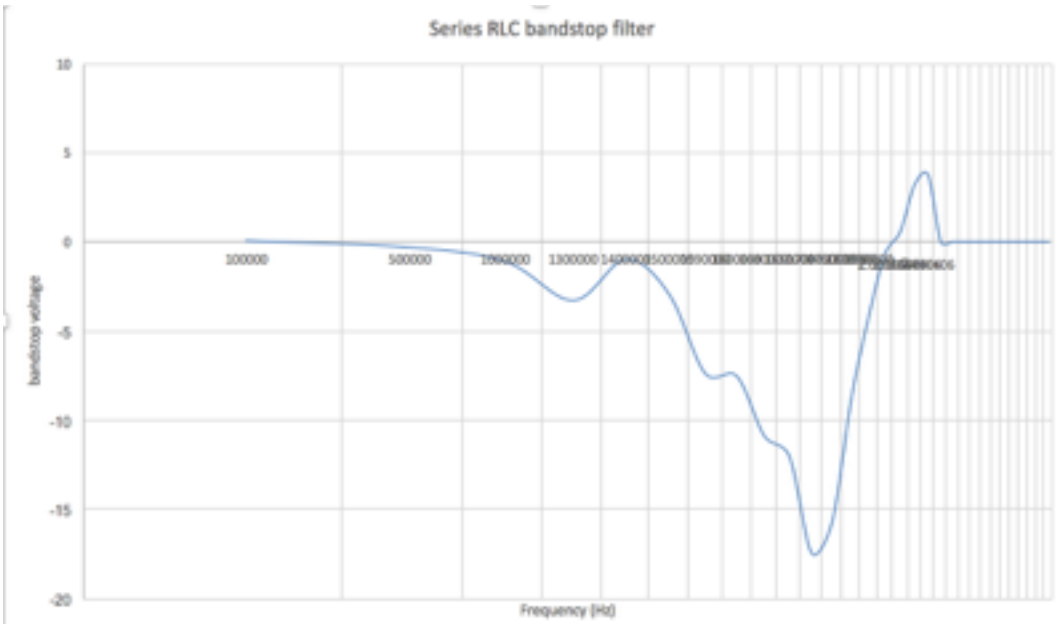
3.4 Series RLC bandpass and band reject filters

The experiment was to construct the series RLC circuit, and connect the oscilloscope with the input voltage and the voltage across the capacitor. Band-pass and band-reject filters utilize phase difference between capacitor and inductor with the input excitation. Band-pass takes measurements across the capacitor and inductor. Band-reject singles out the response from the capacitor only. Bandwidth for a series RLC circuits is approximately the ratio of the circuit resistance to the circuit inductance. I constructed the circuit in figure 4.1. The open circuit was connect to an oscilloscope. No resistance but the internal resistance of signal generator needed because I wanted to ensure the underdamped case. The capacitor was 100nF.



The oscilloscope was connected to v1 and vc.

Figure 4.1 Series RLC bandpass and band reject filters circuit



Data was collected from the circuit and plotted in Figure 4.2.

Figure 4.2 Series RLC bandpass and bandstop filters

The bandpass and band reject responses approximately match the expectation. However, more data points might help to see it clearer. We can see from the band reject graph, when frequencies approach the resonant frequency, the load response decreases. The voltage response increases when the frequency got larger than the resonant frequency. For the band pass situation, the voltage was low when far away from the resonant frequency and high at the resonant frequency. We can calculate the resonance frequency bandwidth and quality by the following formulas:

$$f0=\frac{1}{2\pi\sqrt{LC}} \qquad B=\frac{R}{L} \qquad Q=\frac{2\pi f0}{B}=\frac{2\pi f0L}{R}$$

	Quality Factor	Bandwidth	Resistance
Experimental	1.34	954,253	59
Theoretical	1.64	795,775	50

3.5 Parallel RLC bandpass filters

In this part, I constructed a parallel RLC bandpass filter as in figure 5.1. Bandwidth for a parallel RLC circuits is approximately the ratio of the circuit inductance to the circuit resistance. I did two experiments for this part. I picked 465 ohms as my resistor and also the internal resistance.

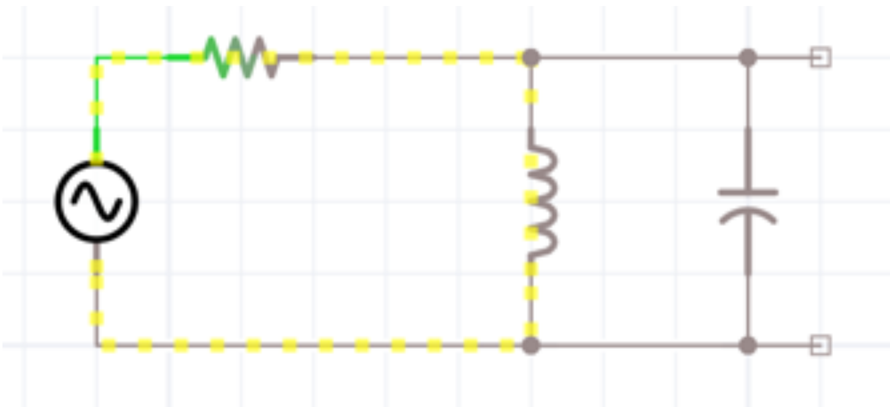
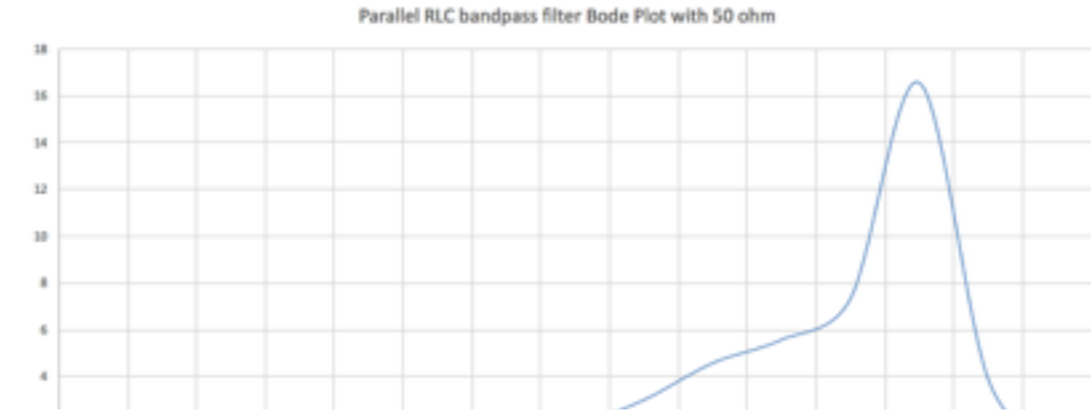
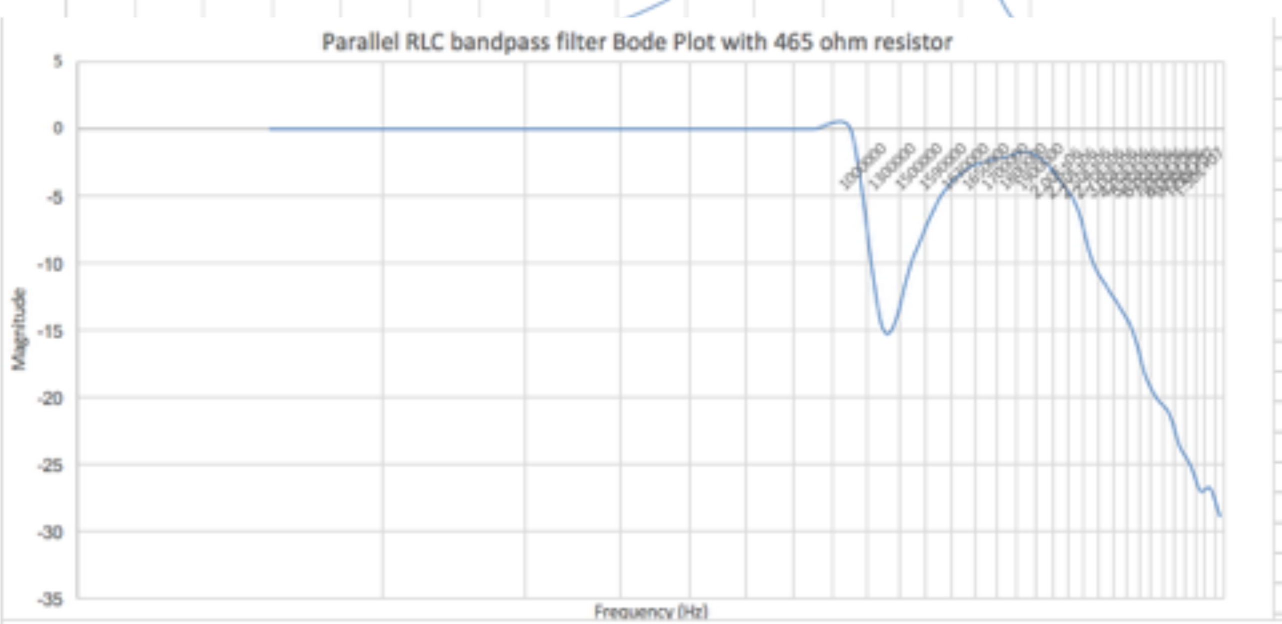


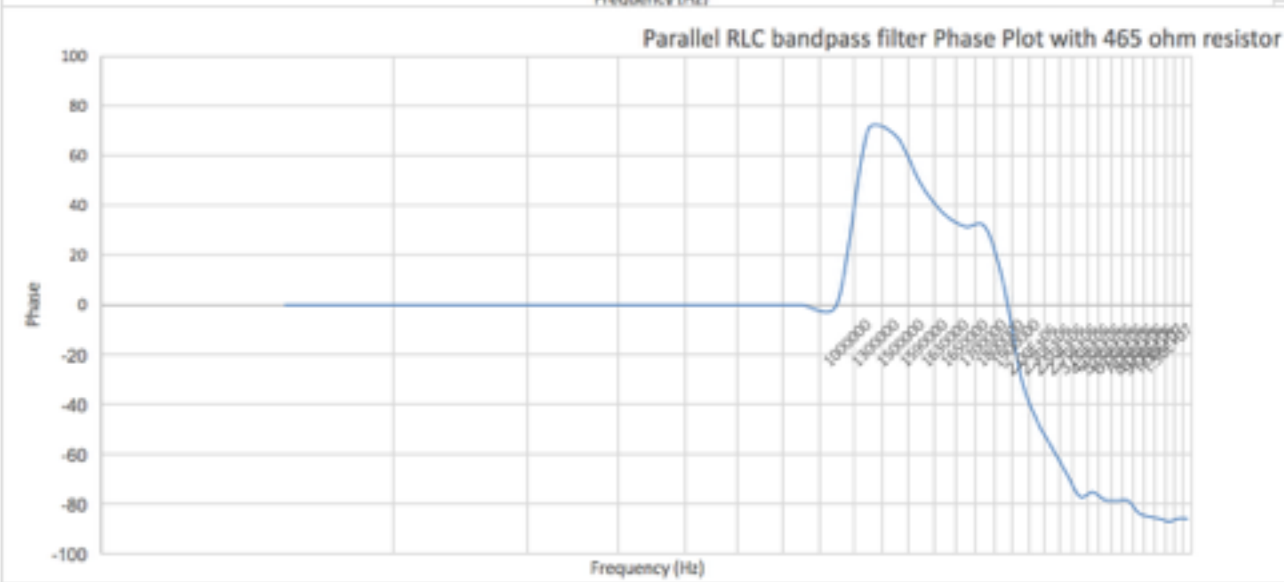
Figure 5.1 Parallel RLC bandpass filters

The oscilloscope was connected with the input and the capacitor. The following figures are the graphs generated from data points. We can calculate the resonance frequency bandwidth and quality by the following formulas:

$$(Bandwidth) B = \frac{1}{RC} \qquad (Quality\ Factor)\ Q = \frac{2\pi f_0}{B} = 2\pi f_0 RC$$


Parallel RLC bandpass filter Bode Plot with 50 ohm
18
16
14
12
10
8
6
4


Parallel RLC bandpass filter Bode Plot with 465 ohm resistor
Magnitude
5
0
-5
-10
-15
-20
-25
-30
-35
Frequency (Hz)


Parallel RLC bandpass filter Phase Plot with 465 ohm resistor
Phase
100
80
60
40
20
0
-20
-40
-60
-80
-100
Frequency (Hz)

Conclusion:

The lab introduced the fundamental filter circuits, high pass, low pass, band reject and band pass, as well as bode and phase plot. From this lab, I have learned many important concepts such as cutoff frequency, bandwidth, feedback, and resonance. Some experiments were off from expectation may because of the non-ideal nature of real circuits and non-ideal components, such as feedback or impedance. Another thing is the actual values of capacitance and inductance. I don't know how to measure that. Human error or equipment readings could also be the reason why the datas were off. I just want to say I have spent a lot of time on this lab. At the beginning, I have done many experiments but they turned out to be useless. Also, picking a right resistor is extremely important in this lab. The data I collected mostly matches our expectation. There were too many new material to me in this lab. It costed me some time to figure out how to draw bode and phase plot, but I am still sure if I did that right. I know I could have done more explanation for this lab but I don't have enough time. I am glad that I have this quarter behind me. I want to thank my TAs for helping me out all the time.