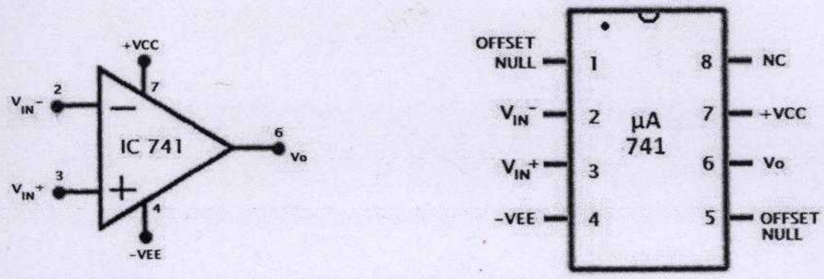
EXPERIMENT #5 LOW PASS AND HIGH PASS FILTERS

I OBJECTIVES

The broad objective of this experiment is to familiarize the student with some of the simpler single-amplifier op-amp filter topologies.

II COMPONENTS AND INSTRUMENTATION

The focus is on the 741-type op amp whose symbol and pin diagram are shown in fig. 5.1. For power, use two supplies. ±15 V for short. As well, you need a variety of resistors. For measurement, use a bench multimeter with ohms scale, a two channel oscilloscope with probes and a function generator.



(a) Symbol (b) Pin Diagram

Fig.5.1 Op-Amp μA 741

III PREPARATION

3.1 - Mid-band gain and low frequency response

Q1. For the first order low pass filter circuit shown in Fig.5.2, calculate the mid-band gain, the very-high-frequency gain, the very-low-frequency gain and the upper and lower 3-dB frequencies. Assume V_i = 0.5V (peak to peak), R_1=10kΩ, R_2=120kΩ, R_3=100kΩ, R_L=10kΩ, C=0.1μF.

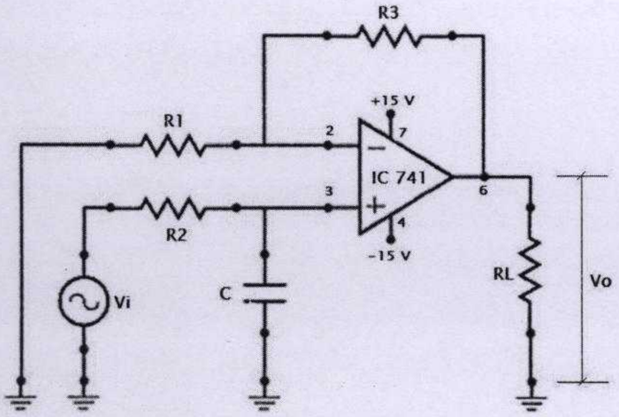
Mid-band gain (A_F) = 11 V/V (or) 20.83 dB

Very high frequency gain = 0 (at high frequencies, signal is attenuated)

Very low frequency gain = ≃ A_F ≃ 20.83dB

Upper 3dB frequency f_H = 13.263 Hz

Lower 3dB frequency f_L = 0Hz (not attenuated at low frequencies)



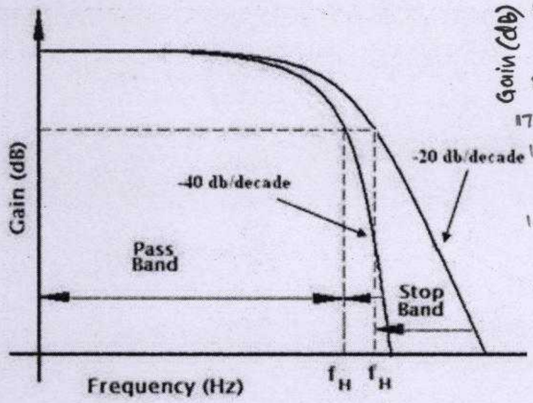
$$A_F = 1 + \left(\frac{R_3}{R_1}\right)$$

$$f_H = \frac{1}{2\pi R_2 C}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}}$$

Fig 5.2 Circuit diagram of a first order low pass filter and formulae

a) Sketch an approximate Bode magnitude plot for the data given in Q1.



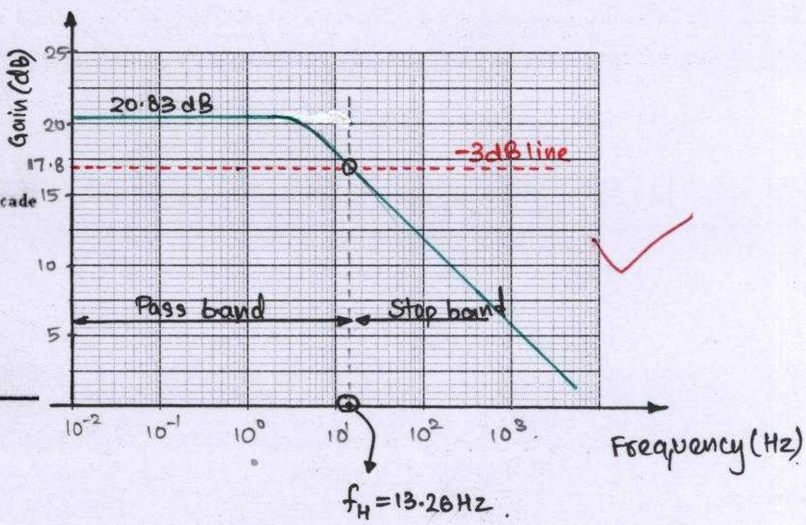


Fig 5.3 Typical response of LP filters

3.2. High-Frequency Response

Q2. For the first order high pass filter circuit of Fig.5.4, assume V_i = 0.2V (peak to peak), R_1=10kΩ, R_2=120kΩ, R_3=100kΩ, R_L=10kΩ, C=0.1µF. Compute the various parameters for the sketch. What is the effect on mid-band gain, lower and upper cut off frequencies of reducing R_1 and R_3 by a factor of 10? (Formulae given along with circuit diagram).

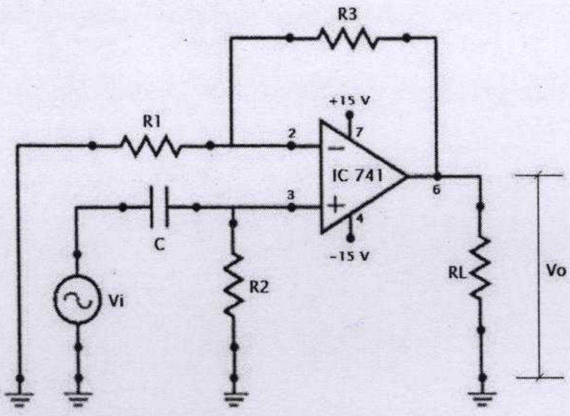
Mid-band gain (A_F) = 11 V/V (or) 20.83 dB

Very high frequency gain = $\approx A_F \approx$ 20.83 dB

Very low frequency gain = 0 (at low frequencies, signal is attenuated)

Upper 3dB frequency f_H = ∞ (not attenuated at high frequencies)

Lower 3dB frequency f_L = 13.263 Hz



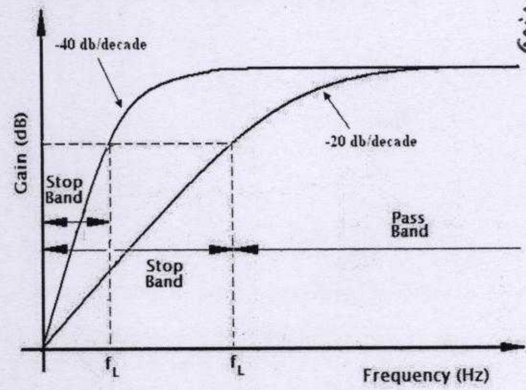
$$A_F = 1 + \left(\frac{R_3}{R_1}\right)$$

$$f_L = \frac{1}{2\pi R_2 C}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}}$$

Fig 5.4 Basic circuit of a first order high pass filter and formulae

a) Sketch an approximate Bode magnitude plot for the data in Q2.



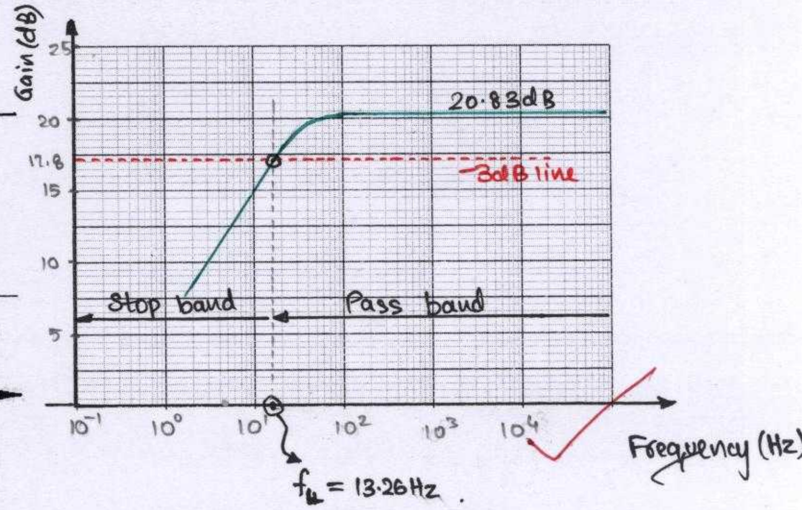


Fig 5.5 Typical response of HP filters

Q3. The input voltage to the amplifier in Fig. 5.6 (a) is as shown in Figure 5.6(b). Find and sketch the output voltage assuming that the initial condition is zero.

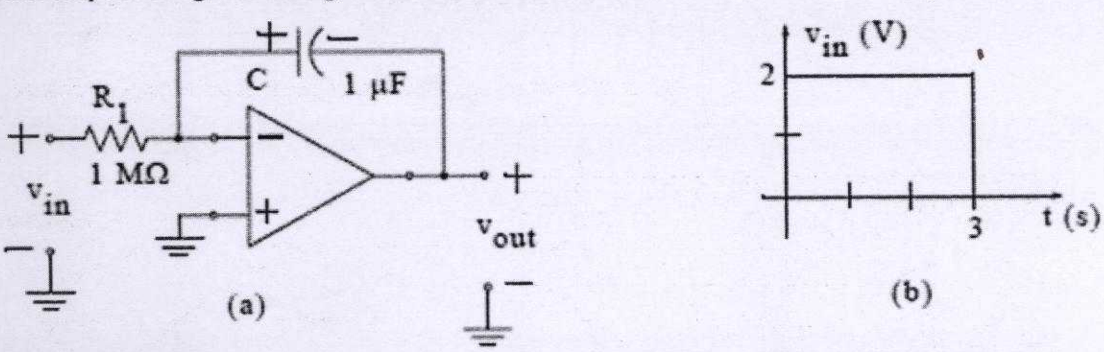


Fig 5.6. Circuit and input waveform

IV EXPERIMENTATION

4.1 – First order low pass filters

If you drive the input with a sine wave signal and measure the output, the filter will amplify low frequencies and attenuate high frequencies and so, is a "low-pass" filter.

Design and draw the diagram of the first order low pass filter circuit using μA741 with

f_H = 2KHz **A_F** = 3

$\boxed{R_3 = 10K\Omega}$

$A_F = 1 + \frac{R_3}{R_1}$

$3 = 1 + \frac{R_3}{R_1}$

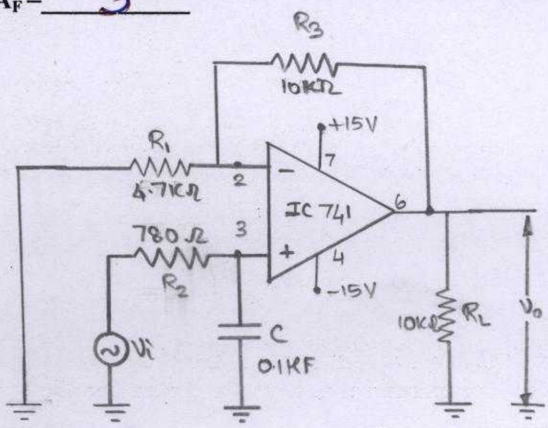
$R_3 = 2R_1$

$\boxed{R_1 = 5K\Omega}$ (used $4.7K\Omega$)

$f_H = \frac{1}{2\pi R_2 C}$

$R_2 = \frac{1}{2\pi \times 0.1 \times 10^{-6} \times 2 \times 10^3} = 795.7\Omega$ (used 780Ω)

$\boxed{R_2 = 795.7\Omega}$



1st order low pass filter

Set the input (sine wave) to 1 V (peak to peak). Record the gain (V_o/V_{in}) in units and in dB both measured and computed at the frequencies shown in the Table 5.1(a). The columns 6 to 9 are for later use.

Table 5.1(a) Data for 4.1 and 4.2 (low pass filters)

Frequency (Hz)	**Low-Pass Gain (measured)**		**Low-Pass Gain (computed)**		**Second order Low-Pass Gain (measured)**		**Second order Low-Pass Gain (computed)**	
		dB		**dB**		**dB**		**dB**
0	3	9.54	3	9.54	3	9.54	3	9.54
20	3	9.54	2.999	9.539	3	9.54	2.999	9.539
50	3	9.54	2.999	9.539	3	9.54	2.999	9.539
100	3	9.54	2.996	9.531	3	9.54	2.999	9.539
200	3	9.54	2.985	9.498	2.9	9.24	2.999	9.539
500	2.9	9.24	2.910	9.278	2.6	8.299	2.994	9.525
1k	2.7	9.24	2.680	8.562	2.4	7.60	2.910	9.278
2k	2.2	6.85	2.120	6.526	1.08	0.668	2.120	6.526
5k	1.22	1.727	1.110	0.906	0.38	-8.40	0.474	-6.48
20K	0.34	-9.37	0.298	-10.515	0.037	-28.63	0.03	-30.46
200K	0.035	-29.12	0.029	-30.75	0.002	-5398	3×10^{-4}	-70.46
500K	0.012	-38.42	0.012	-38.42	0	-∞	4.8×10^{-5}	-86.37

From the plot of gain vs. frequency (lo-log scale) find the frequency at which the signal drops by 3 dB from the gain in the pass band (this is the cut-off frequency, f_H). It is the frequency at which the gain amplitude is down by 3dB from the pass band amplitude, i.e. at 0.707 x (max. gain).

Look at your data and check to see that the filter has a flat gain at low frequencies and attenuates high frequencies by a factor of 1/f. That is, for each decade increase in frequency, the gain drops by 1/10. Record the frequencies and gains that you used to make this estimate.

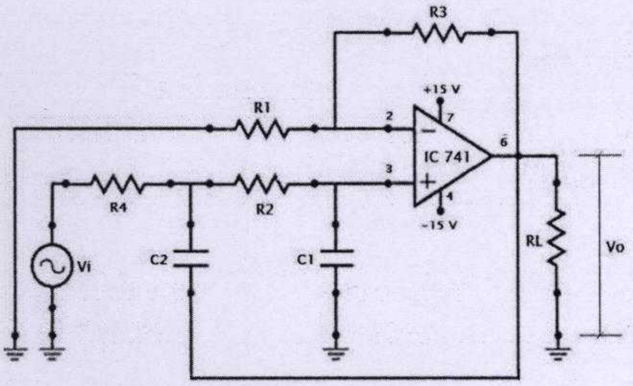
Calculate the expected cut off frequency from the component values. To do this accurately, be sure to measure the component values with a LCR meter. Using the data in the table 5.1(a), plot your measured gain vs. frequency for the low-pass filter on log-log graph sheet. Calculate the theoretical gain and plot it on the same graph. Label the important frequencies, mid-band gain and gain roll off on your plot.

Table 5.1(b)

First order LPF				Second order LPF			
Measured		Computed		Measured		Computed	
f_H (Hz)	A_F	f_H (Hz)	A_F	f_H (Hz)	A_F	f_H (Hz)	A_F
2000	3	2000	3	1950	3	2000	3
Gain roll off Measured		Gain roll off Computed		Gain roll off Measured		Gain roll off Computed	
-19 dB/dec		-20dB/dec		-33dB/dec		-40 dB/dec	

4.2 – Second order low pass filter

The low-pass filter of the previous section attenuates the signal by 1/f at high frequencies. In some cases it may be required to attenuate the signal more quickly than this. To do this, we go for higher order filters.



$$A_F = 1 + \left(\frac{R_3}{R_1}\right)$$

$$f_H = \frac{1}{2\pi\sqrt{R_2 R_4 C_1 C_2}}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1 + \left(\frac{f}{f_H}\right)^4}}$$

Fig 5.7 Second order low pass filter and formulae

Design a second order low pass filter circuit shown in Fig 5. 7 with the same corner frequency and gain as before. Compute the component values with minimal change.

If the corner frequency & gain are to be maintained as before, take $R_2 = R_4$ and $C_1 = C_2$.

Thus $f_H = \frac{1}{2\pi\sqrt{R_2 R_4 C_1 C_2}} = \frac{1}{2\pi\sqrt{R_2^2 C_1^2}} = \frac{1}{2\pi R_2 C_1}$

Build the circuit and measure the gain at the same frequencies as before. Add these measurements to the table 5.1(a). in the columns provided. Check your data to see that it behaves as you expect it to.

Find the corner frequency at which the gain is down by -6dB from the pass band gain. Add these measurements to the plot you did in 4.1. Verify that the filter attenuates high frequencies by $1/f^2$. Compare the corner frequency and roll off for the two circuits. Record these in Table 5.1(b). Are they same? The roll off frequency is much higher than the corner frequency, since it attenuates high frequency signals.

4.3 – High pass filters

If you drive the input with a sine wave signal and measure the output, the filter will amplify high frequencies and attenuate low frequencies so, "High-Pass" filter.

Design and draw the diagram of the first order high pass filter circuit using μA 741 with

f_H= 1.5KHz , A_F= 3

$\boxed{R_3 = 10K\Omega}$

$A_F = 1 + \frac{R_3}{R_1}$

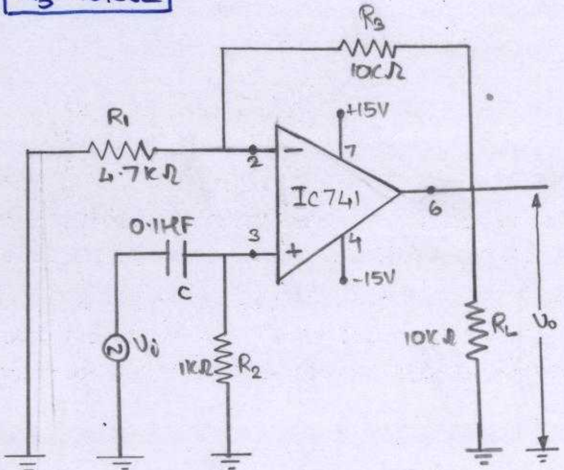
$R_3 = 2R_1$

$\boxed{R_1 = 5K\Omega}$ (used 4.7KΩ)

$f_L = \frac{1}{2\pi R_2 C}$

$R_2 = \frac{1}{2\pi \times 0.1\times10^{-6} \times 1.5\times10^3}$

$\boxed{R_2 = 1.06\,K\Omega}$ (used 1KΩ)



1st order high pass filter

Build the first order high pass filter circuit. Set the input (sine wave) to 1 V (peak to peak). Record the gain (V_o/V_{in}) in units and in dB both measured and computed at the frequencies shown in the Table 5.2(a). The columns 6 to 9 are for later use.

Also find the frequency at which the signal drops by 3 dB from the gain in the pass band (this is the corner frequency, f_L). It is the frequency at which the gain amplitude is down by 3dB from the pass band amplitude, i.e. at 0.707 x (max. gain).

Look at your data and check to see that the filter has a flat gain at high frequencies and attenuates low frequencies by a factor of 1/f. That is, for each decade increase in frequency, the gain drops by 1/10. Record the frequencies and amplitudes that you used to make this estimate

Calculate the expected cut off frequency from the component values. To do this accurately, be sure to measure the component values with a LCR meter.

Plot the Gain vs. Frequency on log-log scale for the high pass circuit. Include the important frequencies, mid-band gain and gain roll off on your plot.

Table 5.2(a) Data for 4.3 and 4.4 (High Pass Filters)

Frequency (Hz)	High-Pass Gain (measured)		High-Pass Gain (computed)		Second order High-Pass Gain (measured)		Second order High-Pass Gain (computed)	
		dB		dB		dB		dB
50	0.08	-21.94	0.099	-20.08	0	$-\infty$	3.3×10^{-3}	-49.63
100	0.154	-16.25	0.199	-14.02	0	$-\infty$	0.013	-37.72
200	0.30	-10.46	0.396	-8.04	0.044	-27.13	0.053	-25.51
500	0.73	-2.73	0.948	-0.46	0.19	-14.42	0.33	-9.63
1K	1.3	2.28	1.664	4.42	0.48	-6.37	1.218	1.713
2K	2	6.02	2.400	7.60	1.0	0	2.615	8.349
5K	2.5	7.96	2.873	9.167	2.05	6.23	2.988	9.507
10K	2.7	8.63	2.967	9.446	2.45	7.78	2.999	9.54
20K	2.8	8.94	2.990	9.513	2.8	8.94	2.999	9.54
30K	2.8	8.94	2.996	9.53	2.8	8.94	2.999	9.54
40K	2.8	8.94	2.997	9.533	2.8	8.94	2.999	9.54
50K	2.8	8.94	2.998	9.536	2.8	8.94	2.999	9.54
70K	2.8	8.94	2.999	9.539	2.8	8.94	2.999	9.54
80K	2.8	8.94	2.999	9.539	2.8	8.94	2.999	9.54

Table 5.2(b) Corner frequency and gain roll off

First Order HPF				Second Order HPF			
Measured		Computed		Measured		Computed	
f_L (Hz)	A_F	f_L(Hz)	A_F	f_L(Hz)	A_F	f_L(Hz)	A_F
2×10^3	2.8	1.5×10^3	3	2.5×10^3	2.8	1.5×10^3	3
Gain roll off Measured		Gain roll off Computed		Gain roll off Measured		Gain roll off Computed	
+20 dB/dec		+20dB/dec		+32dB/dec		+40dB/dec	

4.4 – Second order high pass filter

In order to attenuate the signals in the stop band more quickly we go for higher order filters as we did for low pass filters.

Design a second order high pass filter circuit (Fig.5.7) with the same cut-off frequency and gain as before. Compute the component values with minimal change.

For the same cut-off frequency and gain as the first order HPF circuit,

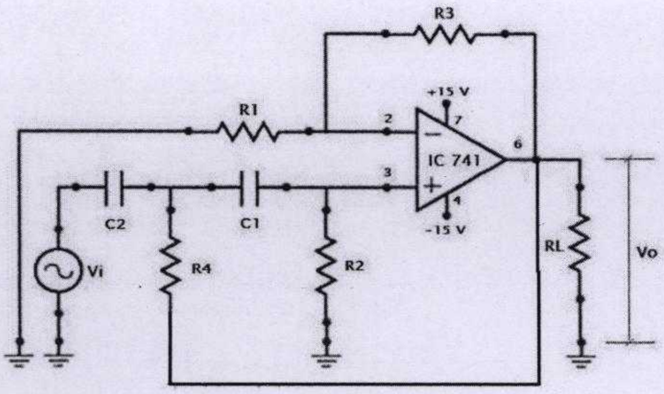
i) $f_L = \frac{1}{2\pi\sqrt{R_2R_4C_1C_2}}$ (2nd order)

ii) $f_L = \frac{1}{2\pi R_2 C}$ (1st order)

If $R_2=R_4$ and $C_1=C_2$, then

$$f_L = \frac{1}{2\pi\sqrt{R_2^2C_1^2}} = \frac{1}{2\pi R_2C_1}$$

Thus to the existing circuit, only one resistor & capacitor of values equal to their former companions is to be added. This employs minimal change.



$$A_F = 1 + \left(\frac{R_3}{R_1}\right)$$

$$f_L = \frac{1}{2\pi\sqrt{R_2 R_4 C_1 C_2}}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1+\left(\frac{f_L}{f}\right)^4}}$$

Fig 5.7 Second order high pass filter and formulae

Build the **second order high pass filter** circuit and measure the gain at the same frequencies as before. Add these measurements to the Table 5.2(a). in the columns provided. Check your data to see that it behaves as you expect it to.

Find the corner frequency at which the gain is down by -6dB from the pass band gain. Add these measurements to the plot you did in.4.3. Verify that the filter attenuates low frequencies by $1/f^2$. Compare the corner frequency and roll off for two circuits.

The roll off takes place at a higher frequency in a second order HPF, than in a first order HPF. This indicates deep attenuation with a rapidly falling gain at low frequencies in a second order HPF.

V INFERENCE/CONCLUSIONS

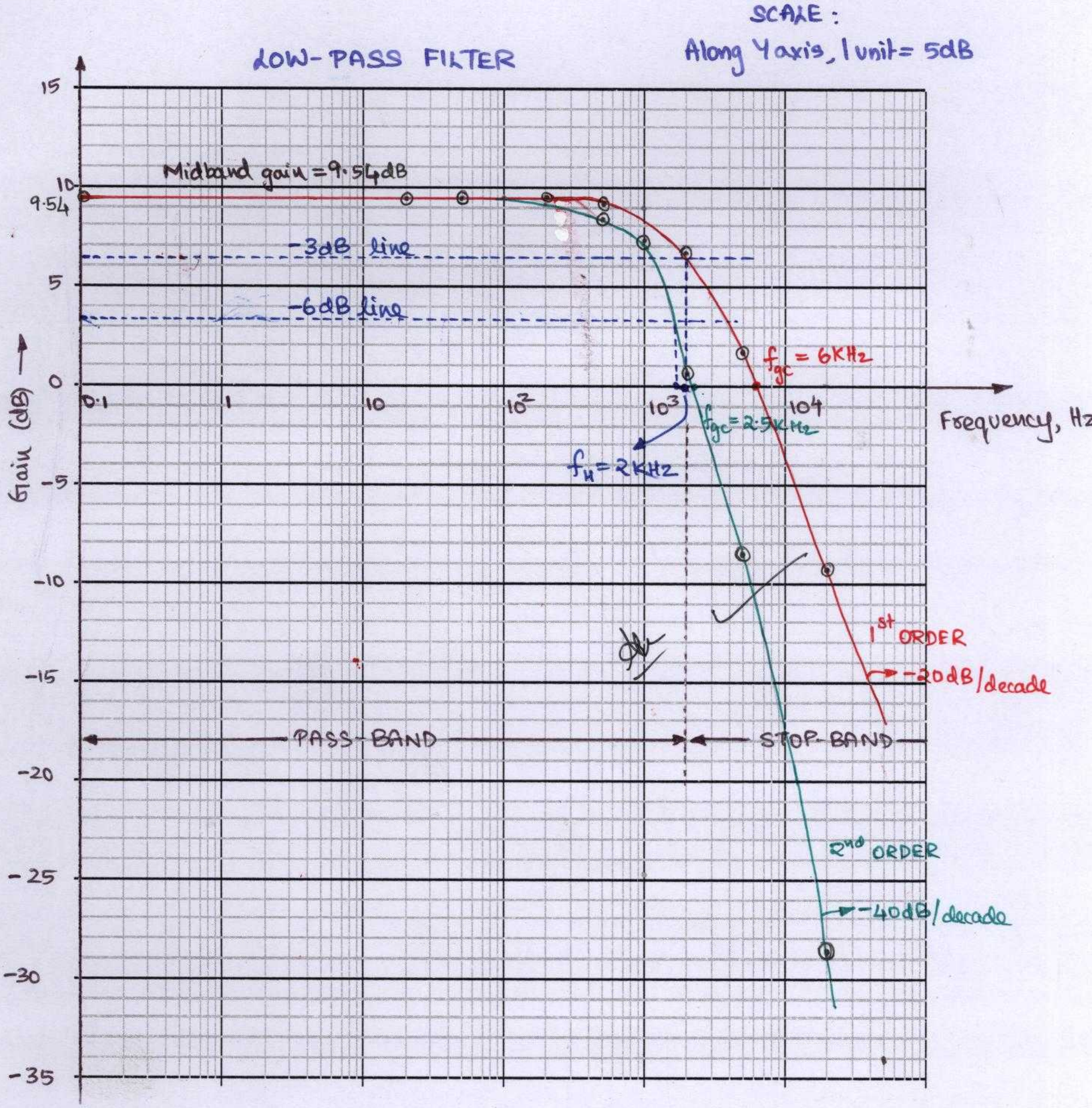
① An ideal filter has 0dB gain in the stop band region & constant mid-band gain throughout its pass band.

② However, in practical filters, the signal in the stop band is attenuated at a rate directly proportional to the order of the filter used.

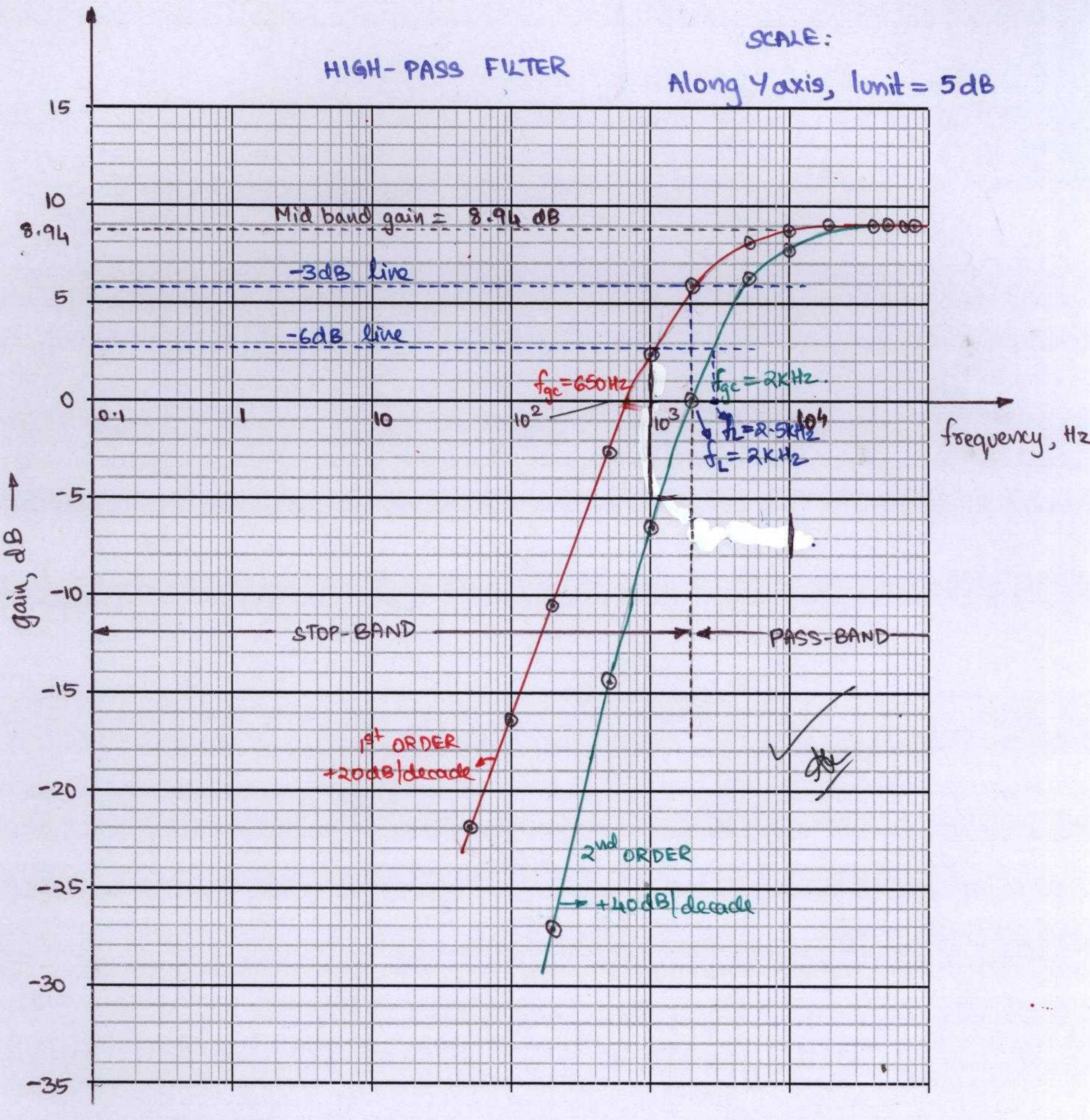
③ For a 1st order filter, the rate at which signals are attenuated is ±20dB/decade.

④ For a 2nd order filter, the rate at which signals are attenuated is ±40dB/decade.

Integrated Circuits Lab		
	Credit	Maximum Marks
Preparation	5	5
Experimentation	10	10
Reporting	4 1/2	5
Total Marks	19.5	20



The 2nd order frequency response is better as it attenuates unwanted high frequency signals faster than 1st order low pass filter.

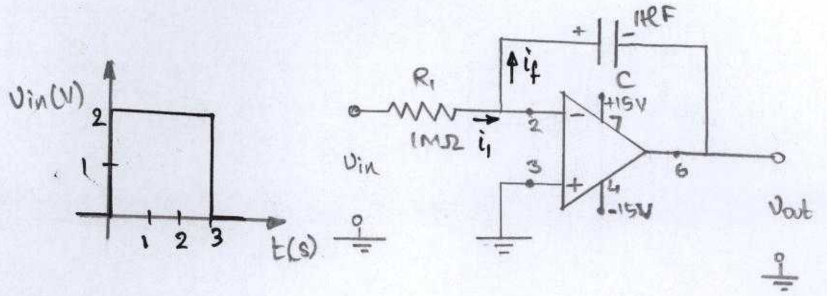


The 2nd order high pass filter attenuates low frequency signals at a faster rate than the 1st order high pass filter.

EXPERIMENT-5 PREPARATION

26/08/10

Q3) The input voltage to the amplifier shown below is as shown. Find and sketch the output voltage assuming that the initial conditions are zero.



Analysis:

$$i_1 = i_f$$

$$\frac{V_{in} - 0}{R_1} = C\frac{d(0 - V_{out})}{dt}$$

$$-\frac{V_{in}}{R_1} = C\frac{dV_{out}}{dt}$$

$$\boxed{V_{out} = \frac{-1}{R_1 C}\int_0^t V_{in}\,dt}$$

(ie) $$V_{out} = \frac{-1}{10^6(10^{-6})}\int_0^3 2\,dt$$

$$= -2\,t\Big]_0^3$$

$$= -6\,V \quad \text{(at } t = 3s\text{)}$$

∴ when $t \leq 3s$, $V_{out} = -2t$ V

$t > 3s$, $V_{out} = -6$ V