Sirindhorn International Institute of Technology

Thammasat University at Rangsit

School of Information, Computer and Communication Technology

COURSE **:** ECS 210 Basic Electrical Engineering Lab

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EXPERIMENT : 08 Filters and Circuit Designs

I. OBJECTIVE

1. To develop the transfer function of low-pass and high-pass filters.
2. To determine the cutoff frequencies of low-pass and high-pass filters.
3. To design an active low-pass filter.

II. BASIC INFORMATION

II.1 Filter Descriptions

Filters are electronic circuit that selectively pass signals of certain frequency ranges and reject signals in other frequency ranges. Filters are described mathematically in terms of a transfer function [$H(j\omega)$] defined as a ratio of an output voltage signal [$V_{out}(j\omega)$] to an input voltage signal [$V_{in}(j\omega)$] as shown in Fig. 1.

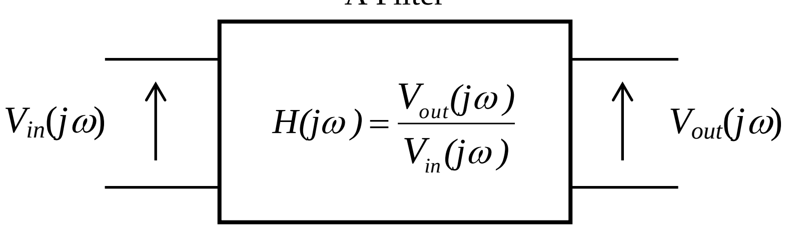


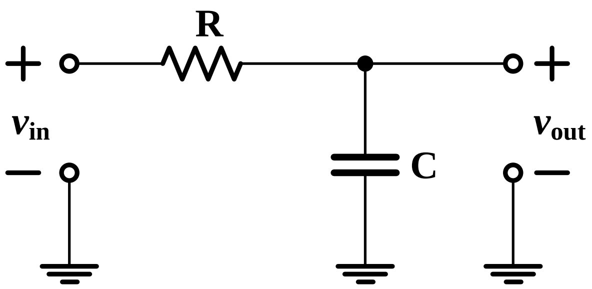
Fig. 1. The transfer function block diagram of a filter.

The ***transfer function*** $H(j\omega)$ captures magnitude and phase responses of filters at each frequency. Plot of the ***magnitude response*** (also called "voltage gain" or "frequency response") is the indicates the cut-off frequencies and how well the filter can distinguish between signals at different frequencies. The ***phase response*** (also called "phase shift") provides the amount of phase shift introduced in sinusoidal signals as a function of frequency. Both magnitude and phase responses are commonly shown on semi-logarithmic graphs where the horizontal axis is the frequency on a logarithmic scale and the vertical axis show the voltage gain in decibels or the phase shift of the output voltage with respect to the applied input voltage.

Filters are used in circuits to remove unwanted frequency components from the signal, to enhance wanted ones, or both. They can be categorized into three major types. A **low-pass filter** (LPF) allows only low frequency signals to pass through. A **high-pass filter** (HPF) allows only high frequency signals to pass through. A **bandpass filter** (BPF) allows signals within a certain frequency range to pass through. Each type of filters can also be classified as passive and active filters based on the use of electronic components. **Active filters** contain amplifying devices such as transistors and amplifiers in order to increase signal strength while **passive filters** do not contain any amplifying devices to strengthen the signal. As there are only passive components within a passive filter design the output signal has smaller amplitude than its corresponding input signal, therefore passive filters attenuate the signal and have a gain of less than unity.

II.2 Low-Pass (LP) Filter

Fig. 2 (a) and (b) show the circuit configurations, transfer functions and cutoff frequencies of both active and passive low-pass filters. It is seen in Fig. 2 (a) that the passive low-pass filter contains only RC components, and consequently the gain is fixed at unity. The active low-pass filter in Fig. 2 (b), however, alternatively comprises of an amplifier with two resistors that set the gain of values R_2/R_1.



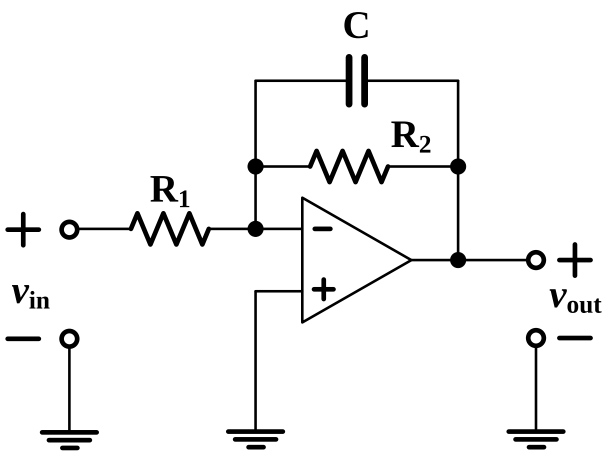
Transfer Function

$$H_{LP,passive}(j\omega) = \frac{1}{1 + j\omega RC}$$

Cut-off frequency

$$\omega_c = \frac{1}{\tau} = \frac{1}{RC} = 2\pi f_c$$

(a) A passive low-pass filter.



Transfer Function

$$H_{LP,active}(j\omega) = -\frac{R2}{R1}\left(\frac{1}{1 + j\omega R_2 C}\right)$$

Cut-off frequency

$$\omega_c = \frac{1}{\tau} = \frac{1}{R_2C} = 2\pi f_c$$

(b) An active low-pass filter

Fig. 2. Circuit configurations, transfer functions and cutoff frequencies of passive and active low-pass filters.

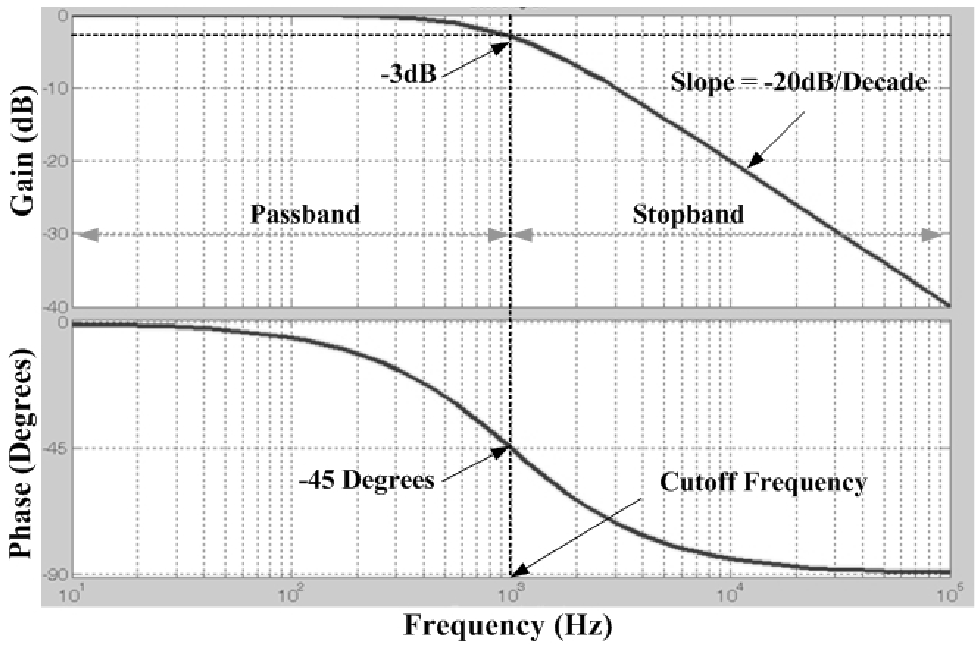


Fig. 3. Magnitude and phase responses of passive low-pass filter.

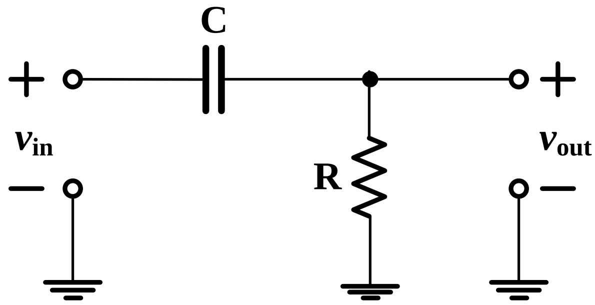
Fig. 3 shows the magnitude and phase responses of the passive low-pass filter. The frequency at which the filter begins to attenuate signals is called the "cutoff frequency". At this cutoff frequency, the output voltage is attenuated to 70.7% of the input voltage (or -3dB of the input in Decibels). Note that the cutoff frequency can be expressed as ω_c in radians per second or as f_c in Hertz. (Watch out for a factor of 2π!) All the frequencies below the cutoff frequency, which is unaltered with little or no attenuation, are considered to be in a **passband zone**. Other signal frequencies above the cutoff frequency are generally considered to be in the filters **stopband zone**. As the filter contains a capacitor, the phase angle of the output signal lags behind that of the input and at the -3dB cut-off frequency and is -45^o out of phase.

II.3 High-Pass (HP) Filter

As the name implies, the high-pass filter permits high frequencies to pass from the input through to the output of the filter. Due to the abundance of electric motors and fluorescent lights, 60-Hz noise is the most prevalent unwanted signal. Although many applications exist, one of the most common uses for the high-pass filter is to prevent 60-Hz noise from entering a sensitive electrical or electronic system.

Fig. 4 (a) and (b) show the circuit configurations, transfer functions and cutoff frequencies of both passive and active high-pass filters, respectively. It is seen in Fig. 4 (a) that the passive high-pass filter also contains only RC components, but exact opposite to the low- pass filter, as the two components have been interchanged, with the output signal being taken from across the resistor.

Fig. 5 shows the magnitude and phase responses of a passive high-pass filter. The high pass filter only passes signals above the cutoff frequency, eliminating any low frequency signals. The magnitude response of the high-pass filter is the exact opposite to the low-pass filter, i.e. the signal is attenuated or damped at low frequencies with the output increasing at +20dB/Decade until the frequency reaches the cutoff frequency. The phase of the output signal leads the input signal and is equal to $+45^o$ at the cutoff frequency. The frequency response curve for a high pass filter implies that the filter can pass all signals out to infinity. However in practice, the high-pass filter response does not extend to infinity but is limited by the characteristics of the components used.



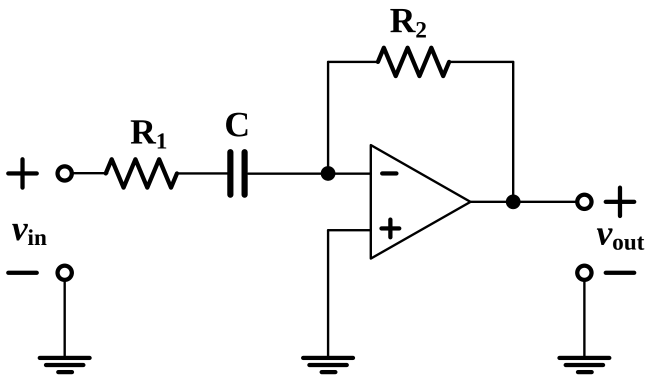
Transfer Function

$$H_{HP,passive}(j\omega) = \frac{j\omega RC}{1 + j\omega RC}$$

Cut-off frequency

$$\omega_c = \frac{1}{\tau} = \frac{1}{RC} = 2\pi f_c$$

(a) A passive high-pass filter.



Transfer Function

$$H_{HP,active}(j\omega) = \frac{j\omega R_2 C}{1 + j\omega R_1 C}$$

Cut-off frequency

$$\omega_1 = \frac{1}{\tau_1} = \frac{1}{R_1 C} = 2\pi f_1$$

~~$$\omega_2 = \frac{1}{\tau_2} = \frac{1}{R_2 C} = 2\pi f_2$$~~

(b) An active high-pass filter

Fig. 4. The circuit configurations, transfer function and cutoff frequencies of passive and active high-pass filters.

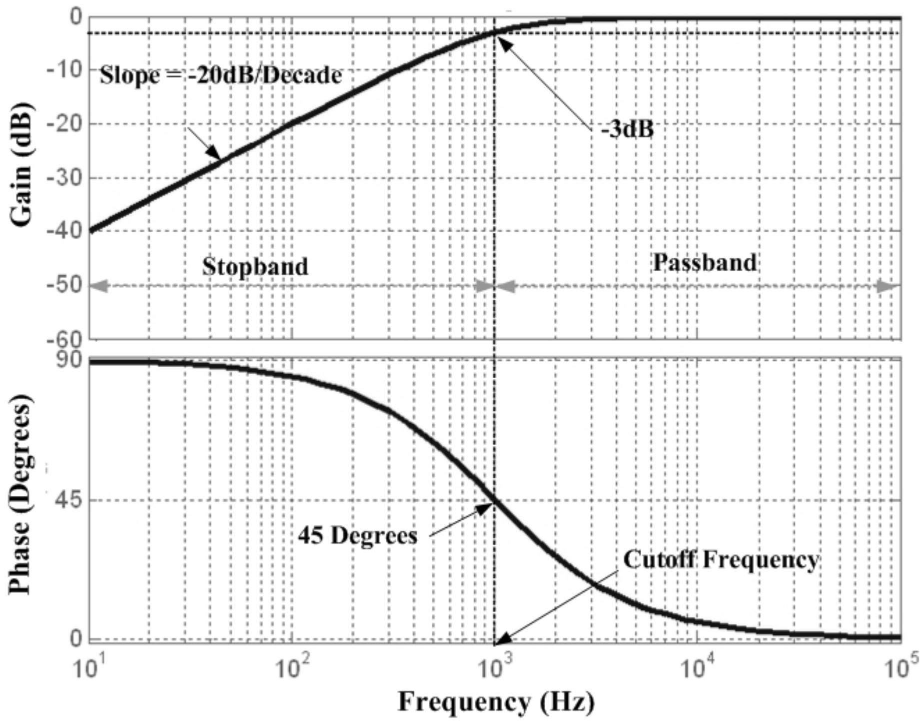
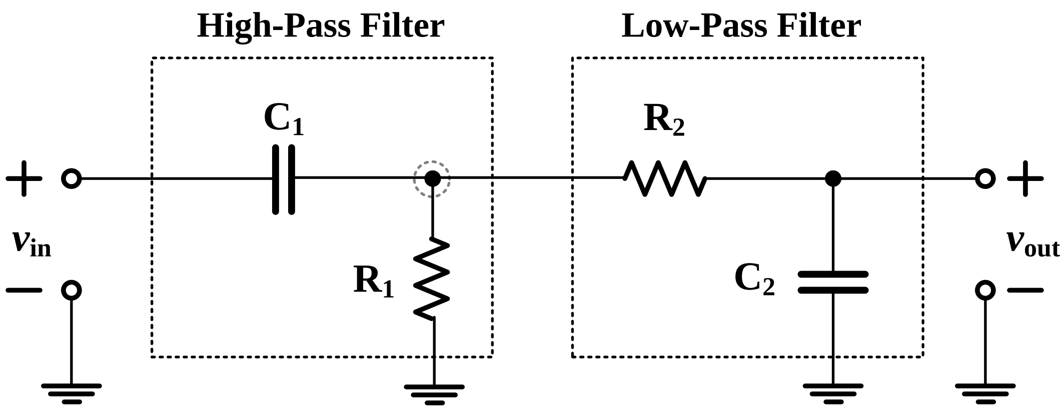


Fig. 5. Magnitude and phase responses of the passive high-pass filter.

II.4 Bandpass (BP) Filter

The bandpass filter permits a range of frequencies to pass from one stage to another. Many different types of bandpass filters are used throughout electronics. For instance, the typical television receiver uses several stages of filtering to achieve a bandwidth of 6 MHz, while an AM receiver has circuitry which restricts the bandwidth to only 10 kHz. The bandpass filters can be very elaborate depending on the application, Fig. 6 shows the simple passive bandpass filter constructed by combining a low-pass filter and a high-pass filter.



Lower cutoff frequency (Determined by HP filter)

$$\omega_1 = \frac{1}{\tau_1} = \frac{1}{R_1 C_1} = 2\pi f_1$$

Upper cutoff frequency (Determined by LP filter)

$$\omega_2 = \frac{1}{\tau_2} = \frac{1}{R_2 C_2} = 2\pi f_2$$

Fig. 6. The circuit configurations, transfer functions and cutoff frequencies of the passive bandpass filters.

The bandpass filter has two cutoff frequencies as determined by the cutoff frequencies of the individual low-pass and hig-pass stages. The frequency below which the high-pass filter attenuates the signal is called the lower cutoff frequency f_1. The frequency at which the low-pass filter begins to attenuate is called the upper cutoff frequency f_2. The difference between the two frequencies f_2 - f_1 is the bandwidth BW.

III. MATERIALS

1. Signal generator (sinusoida1 function generator)
2. Digital Multimeter
3. Dual trace oscilloscope
4. Resistors (1/4-W carbon, 5% tolerance): 330-Ω, and others
5. Capacitors (10% tolerance): 0.047-μF, 0.47-μF, and others
6. Op-Amp: LM741

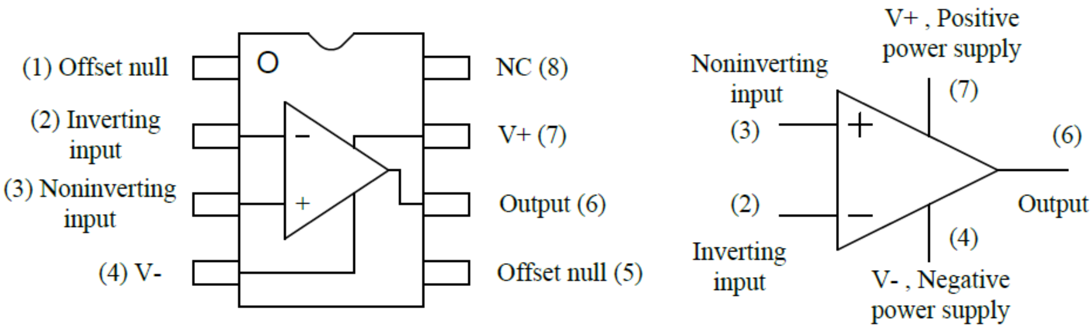


Fig. 7. Pin details and configuration of IC 741.

IV. PROCEDURES

<u>Conceptual Diagram of Experiment Procedures</u>

Since there are many types of filters, this lab focuses only on the study and design of some simple and useful filters in parts *A*, *B* and *C* as shown in Fig. 8, involving passive and active low-pass filters and the passive high-pass filter. **<u>The passive bandpass filter in part *D* is optional</u>**, but students are highly excouraged to study if time is available.

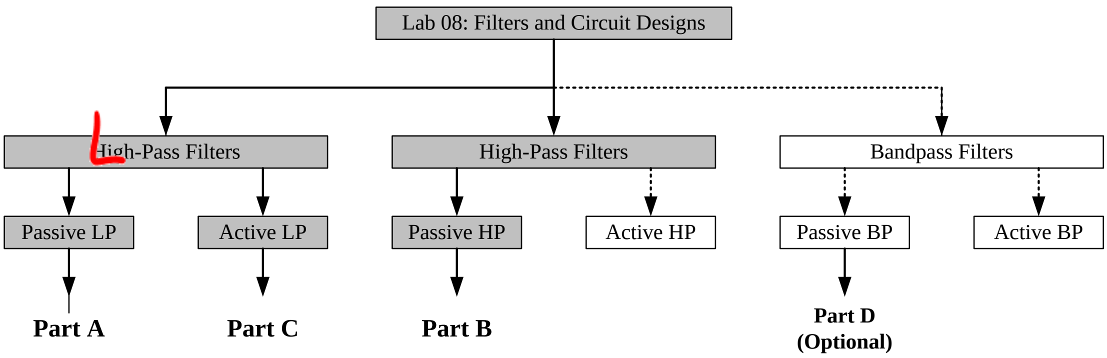


Fig. 8. A conceptual diagram of filter types and experiment parts.

Part A: Passive RC Low-pass Filter

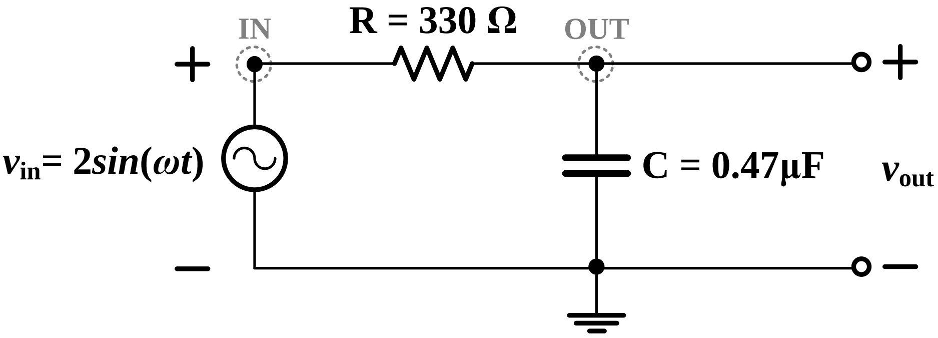


Fig. 9. The passive low-pass filter.

1. Measure the actual values of R and C in Fig. 9, and record in Table A.1.
2. Connect the passive low-pass filter (LPF) circuit as shown in Fig. 9.
3. Set the input v_{in} from the function generator to be a sinusoidal signal with amplitude of $2V_{0\text{-}P}$ (4.0 Vp-p) and the frequency of 100 Hz. Connect this input v_{in} to the input node IN of the LPF.
4. Connect Channel 1 of the oscilloscope to the input node IN and connect Channel 2 to the output node OUT.
5. Increase the frequency of the signal generator to the frequencies indicated in Table A.1. Use the oscilloscope to measure the amplitude and phase shift of v_{out} (with respect to v_{in}) for each frequency. Record the values in Table A.1.
6. Use your measurements recorded in Table A.1 to calculate the magnitude of the gain as a ratio of the amplitudes v_{out}/v_{in}. Calculate the voltage gain in Decibels as

$$[A_v]_{dB} = 20 \log \frac{V_{out}}{V_{in}} \quad \frac{V_{out}}{V_{in}}$$

   Record the calculated voltage gain and measured phase shift for each frequency in Table A.1.
7. Plot the data of Table A.1 on the semi-logaritmic scales of Fig. A.1. Connect the points with the best smooth continuous curve.
8. Find the DC gain and cutoff frequencies in radians and record the calculated cutoff frequency in Table A.2.

Part B: Passive RC High-pass Filter

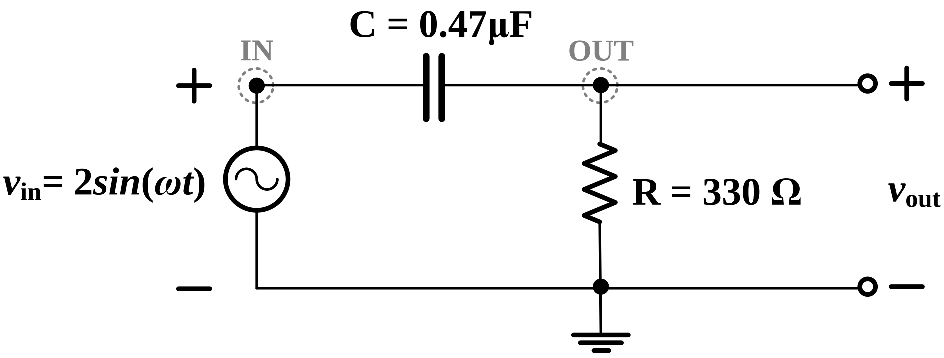


Fig. 10. The passive high-pass filter.

1. Measure the actual values of R and C of Fig. 10 and record in Table B.1.
2. Connect the passive low-pass filter circuit as shown in Fig. 10.
3. Redo as in steps 3 – 7 of Part A, but record all the values in Table B.1, plot the data of Table B.1 in Fig. B.1, and find the DC gain and cutoff frequencies in Table B.2.

Part C: Design of An Active Low-pass Filter

1. Design the "**Active Low-Pass Filter**", which has the cut-off frequency = 1 kHz, and the DC gain = ~~5~~ 3.3.
2. Indicates the chosen values of input signal amplitude, power supply voltages, resistors and capacitors in Fig. C.1. Note that the operating power supply range of the OP-AMP no. LM 741 is 5V-15V, i.e. the positive and negative power supplies must not exceed +15V and -15V, respectively.
3. Test for the DC gain by applying the appropriate value of the DC input signal and notice that the DC output signal is ~~5~~ 3.3 times larger than the DC input signal. Draw the DC input and output signals in Fig. C.2
4. Test for the cut-off frequency by applying the sinusoidal input signals at different frequencies. Sketch sinusoidal input and output signals and record the corresponding values in Fig. C.3 – C.5.

Part D: Passive RC Bandpass Filter (Optional)

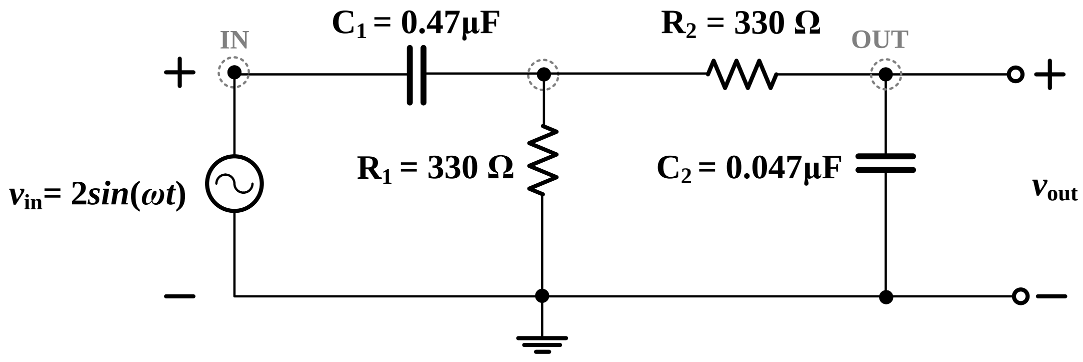


Fig. 11. The passive bandpass Filter.

1. Measure the actual values of R1, R2, C1 and C2 of Fig. 11, and record these values in Table D.1.
2. Assemble the passive bandpass filter in Figure 11.
3. Redo as in steps 3 – 7 of Part A, but record all the values in Table B.1, plot the data of Table D.1 in Fig. D.1, and find the cutoff frequency for the high-pass stage (ω_1, f_1) and the low-pass stage (ω_2, f_2) as well as the bandwidth in Table D.2.

Table A.1: Voltage gain and phase shift of the passive low-pass filter
R = ____________________, C = _________________________

Frequency f	v_{out}		Gain	Response	
	Amplitude (Vp-p)	Phase shift (degrees)	$A_v = V_{out}/V_{in}$	Amplitude $[A_v]_{dB}$	Phase θ (Degree)
100 Hz					
200 Hz					
400 Hz					
800 Hz					
1 kHz					
2 kHz					
4 kHz					
8 kHz					
10 kHz					

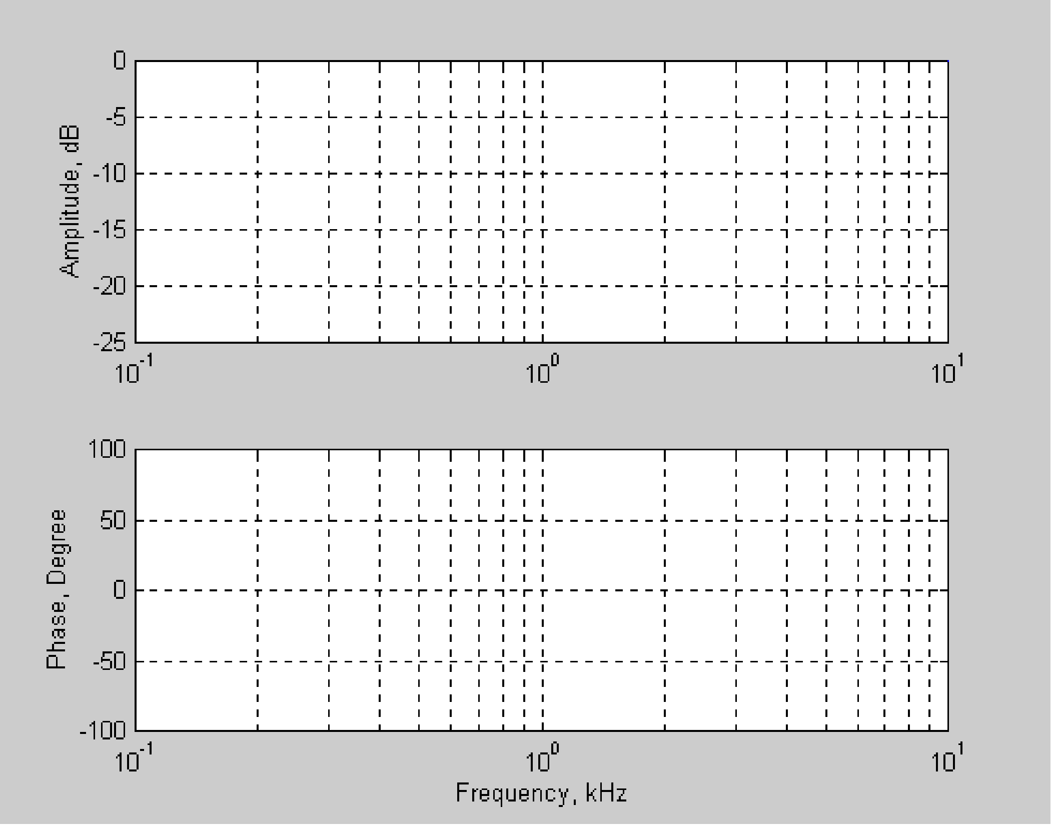


Fig. A.1: Frequency Response of the passive low-pass filter

Table A.2: DC Gain and cutoff frequency of the passive low-pass filter

Parameters	Calculation	Experiments	% error
DC Gain			
Cut-Off Frequency ω_c in rad/s			
Cut-Off Frequency f_c in Hz			

TA's Signature: _________________________

Table B.1: Voltage gain and phase shift of the passive high-pass filter

R = ____________________, C = _________________________

Frequency f	v_{out}		Gain	Response	
	Amplitude (vp-p)	Phase shift (degrees)	$A_v = v_{out}/v_{in}$	Amplitude $[A_v]_{dB}$	Phase θ (Degree)
100 Hz					
200 Hz					
400 Hz					
800 Hz					
1 kHz					
2 kHz					
4 kHz					
8 kHz					
10 kHz					

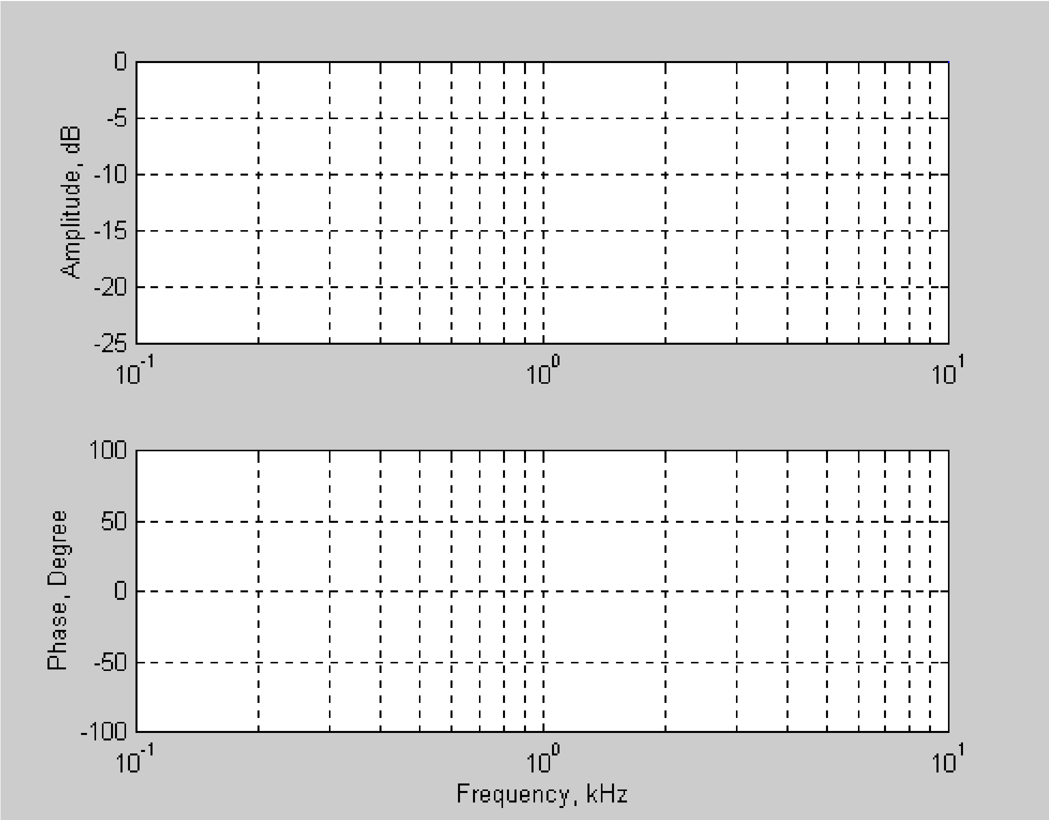


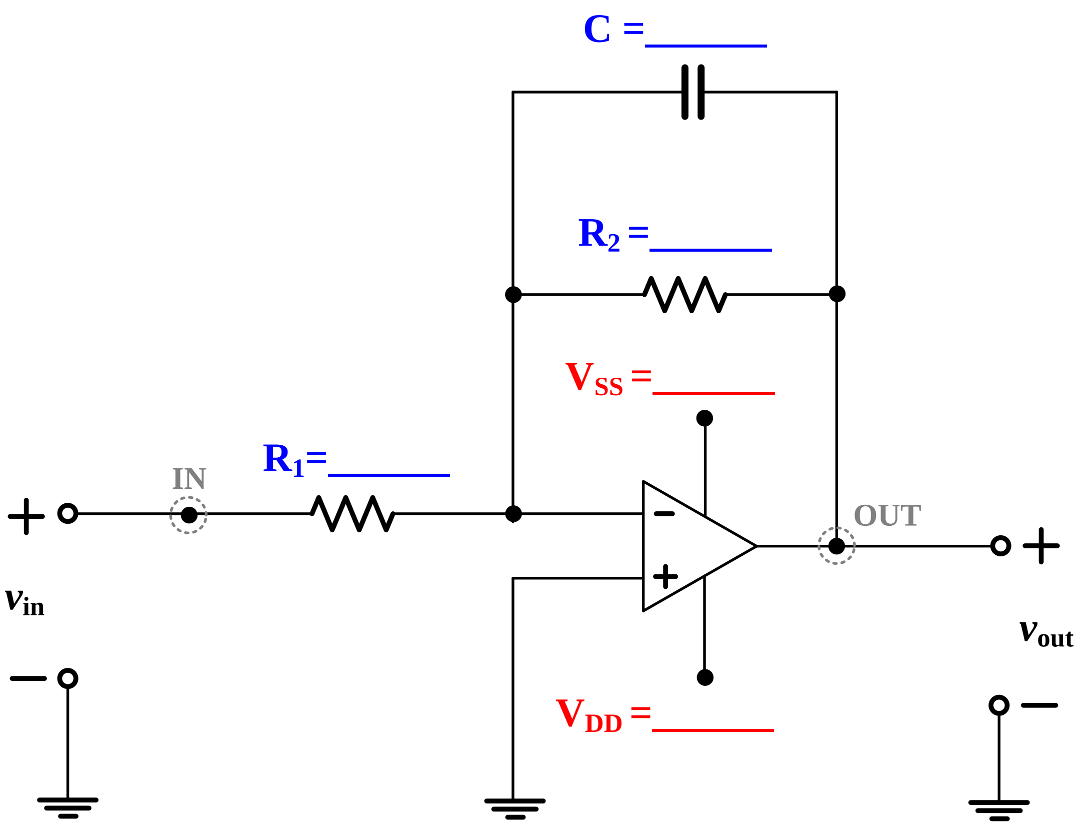
Fig. B.1: Frequency response of the passive high-pass filter

Table B.2: DC Gain and cutoff frequency of the passive high-pass filter

Parameters	Calculation	Experiments	% error
DC Gain			
Cut-Off Frequency ω_c in rad/s			
Cut-Off Frequency f_c in Hz			

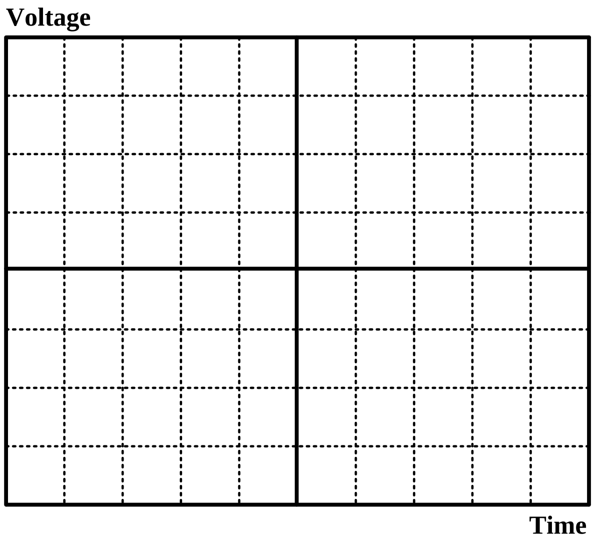
TA's Signature: _________________________

Fig. C.1: Chosen values of signals and components of the active low-pass filter to be designed for the cut-off frequency = 1 kHz, and the DC gain = 3.3



TA's Signature: ________________________

Fig. C.2: Tests for the DC gain.



Chosen V_{in} (DC) =________________

V_{out} (DC) =______________________

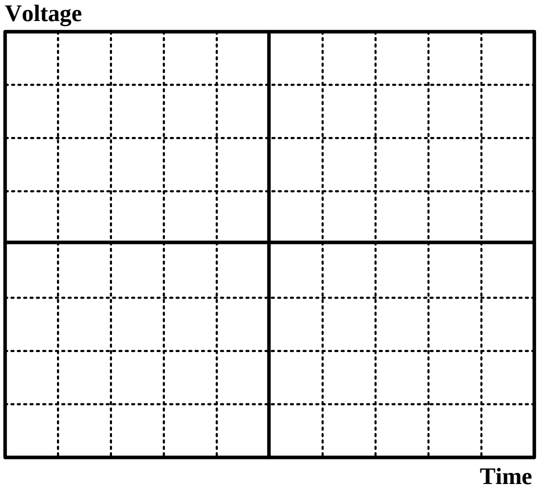
DC Gain =________________________

Channel 1: volts/div = _____________

Channel 2: volts/div = _____________

Time/div = ____________

Fig. C.3: Tests for the cutoff frequency at f << 1kHz



Chosen amplitude of v_{in} ($v_{p\text{-}p}$) =______________

Chosen frequency of v_{in} =___________________

Gain =___________________________________

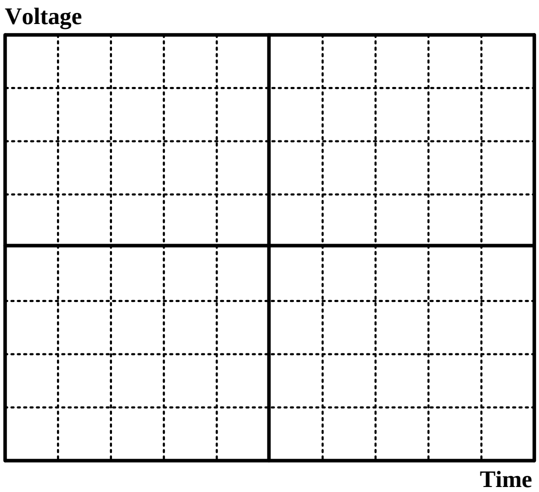
Phase shift =_____________________________

Channel 1: volts/div = _____________________

Channel 2: volts/div = _____________________

Time/div = ____________________

Fig. C.4: Tests for the cutoff frequency at $f = f_c$ = 1kHz



Chosen amplitude of v_{in} ($v_{p\text{-}p}$) =____________

Frequency of v_{in} =_______________________

Gain =_________________________________

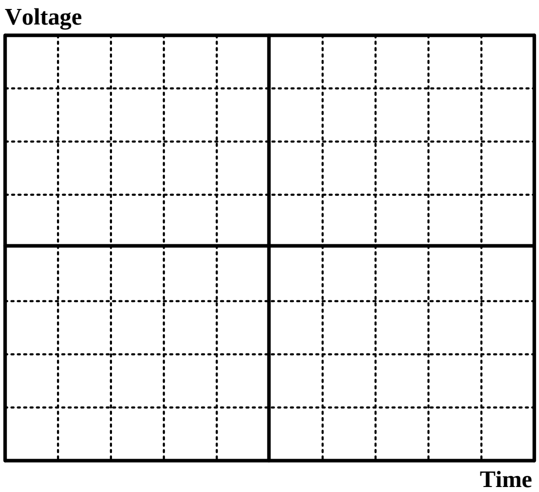
Phase shift =____________________________

Channel 1: volts/div = ___________________

Channel 2: volts/div = ___________________

Time/div = __________________

Fig. C.5: Tests for the cutoff frequency at $f >> f_c$



Chosen amplitude of v_{in} ($v_{p\text{-}p}$) =____________

Chosen frequency of v_{in} =_________________

Gain =_________________________________

Phase shift =____________________________

Channel 1: volts/div = ___________________

Channel 2: volts/div = ___________________

Time/div = __________________

TA's Signature: _________________________

Table D.1: Voltage gain and phase shift of the passive bandpass filter. (Optional)

R1 = __________, R2 = ___________,C1 = __________, C2 = ____________

Frequency f	v_{out} Amplitude (vp-p)	v_{out} Phase shift (degrees)	Gain $A_v = v_{out}/v_{in}$	Response Amplitude $[A_v]_{dB}$	Response Phase θ (Degree)
100 Hz					
200 Hz					
400 Hz					
800 Hz					
1 kHz					
2 kHz					
4 kHz					
8 kHz					
10 kHz					
20 kHz					
40 kHz					
80 kHz					
100 kHz					

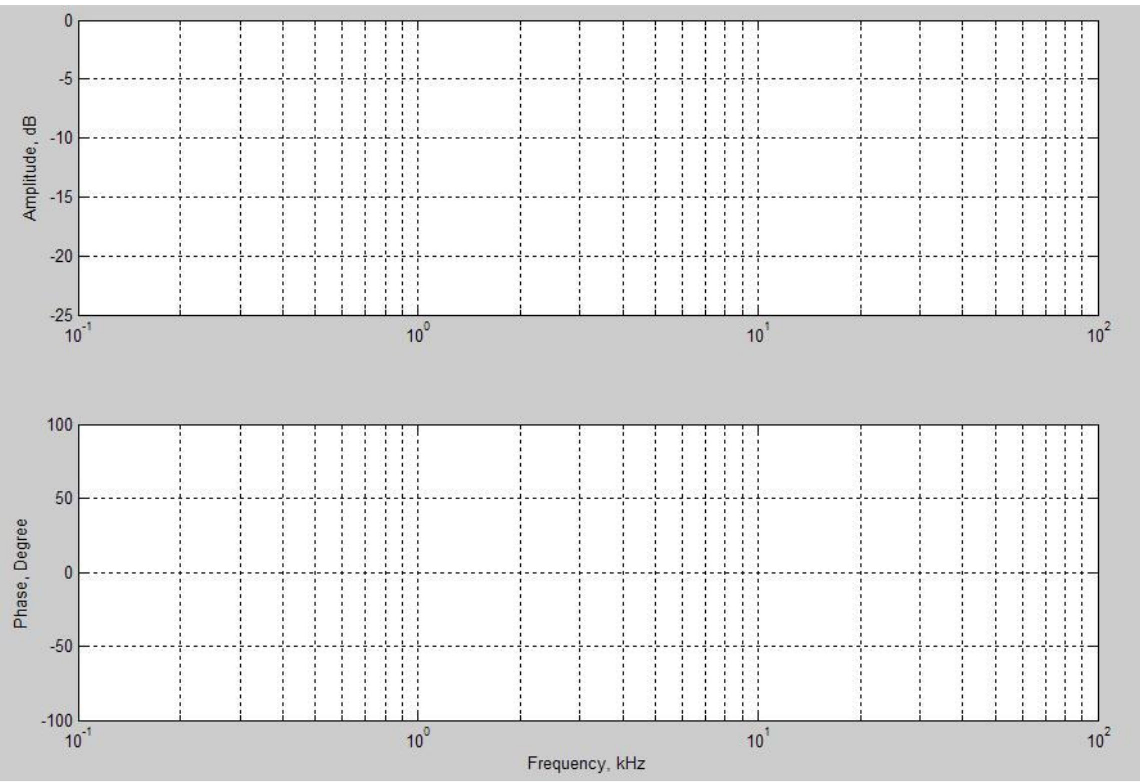


Fig. D.1: Frequency response of the passive bandpass filter.

Table D.2: DC Gain and frequencies of the passive bandpass filter (Optional)

Parameters	Calculation	Experiments	% error
DC Gain			
Frequency ω_1 in rad/s			
Frequency f_1 in Hz			
Frequency ω_2 in rad/s			
Frequency f_2 in Hz			
Bandwidth in Hz			

V. QUESTIONS

1. Figure Q-1 shows the response of ……………filter.

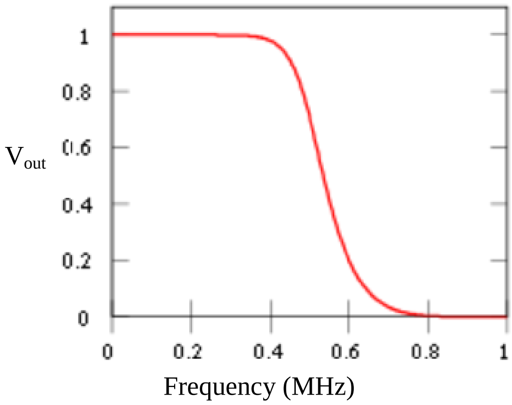


Figure Q-1

(a) a low-pass (b) a high-pass (c) a band-pass

(d) a stop-band (e) none of the above

2. Briefly explain the major characteristics of the low-pass filter and give some example of applications.
3. Briefly explain the characteristics of the high-pass filter and give some example of applications.
4. Briefly explain the characteristics the bandpass filter and give some example of applications.