In this laboratory exercise you design, build and test some simple filter circuits. This is mainly for you to get comfortable with circuit design in the frequency domain, and as a brief introduction/review of filtering.

Filters are important blocks in all communication and instrumentation systems. A filter is abstractly represented in terms of the transfer function, \( H(j\omega) \), as shown in Figure 1. Filters are often categorized depending on the frequency domain behavior of the transfer function magnitude. Ideal frequency responses for lowpass, highpass, and bandpass filters are shown in Figure 2.

**Week 1: RC Circuits and Frequency Response**

Design a passive (no active components, e.g. transistors or opamps) second-order low-pass filter which meets the following specifications (specs):

- The input impedance of the filter (\( Z_{\text{in}} \) in Figure 3) should be sufficiently large compared to the signal-source output impedance which is 50 ohms.
- The output impedance of the filter (\( Z_{\text{out}} \) in Figure 3) should be sufficiently small compared to the input impedance of the load, which is 1M ohms.
- The input impedance of the filter (\( Z_{\text{in}} \) in Figure 1) should be sufficiently large compared to the signal-source output impedance.
- A magnitude response that has 3dB signal attenuation at 1kHz and at least 20dB signal attenuation at 10kHz.
- The output impedance of the filter (\( Z_{\text{out}} \) in Figure 3) with input source grounded should be sufficiently small compared to the source impedance.

The simplest possible circuit for this filter design is shown in Figure 3.

**Figure 1 — Abstract two-port representation of a filter circuit.**

\[
\frac{(\omega f)^{\text{in}} A}{(\omega f)^{\text{out}} A} = (\omega f)H
\]

The low-pass and high-pass filters are shown in Figure 2. Filters are often categorized depending on the frequency domain behavior. Ideal frequency responses for lowpass, highpass, and bandpass filters are shown in Figure 2. Filters are important blocks in all communication and instrumentation systems.
Design Procedure

Assuming that $R_S << R_1$, $C_L >> C_2$, and the magnitude of $Z_{out}$, the transfer function for this RC filter can be approximated as:

$$\frac{\frac{1}{2}R_1C_1 + \frac{1}{2}R_1C_2 + \frac{1}{2}R_1C_1}{1} + \frac{1}{2}R_1C_1 \frac{1}{2}R_1C_2 + \frac{1}{2}R_1C_1} = \frac{H(\omega)}{i}$$

Figure 2 — Ideal filter characteristics.

Figure 3 — A second-order RC low pass filter.
There are four design variables and two poles to achieve the required frequency response. The additional constraints come from the input and output impedance specifications. Explain how you selected your circuit values in your lab books and in your lab report.

Use your signal generator as the source, and your oscilloscope as the load to measure and plot the magnitude and phase responses of the output from 100 Hz to 1 MHz. Verify that your signal generator and oscilloscope are reasonably close to the actual source and load specifications. Plot your data on graphs in dB on a semi-log scale. Include on your graphs the Bode plots you obtain from the transfer function shown in equation (4).

In your report comment on your experimental results. How well does the Bode plot approximate the real response? If your design had an output impedance comparable to that of the scope, how would it affect the overall transfer function? Ideally what values of R and C would you select to meet the following specs:

- An input impedance >10 kΩ over all frequencies.
- Midband gain of 3 V/°.
- f_L = 950 Hz, f_H = 1.05 kHz.
- ±10 V is a reasonable input range with ±5 V being preferable.

Filter Design using Opamps

Our filtering capabilities with passive components is quite limited. It is extremely difficult to meet aggressive specs and produce a reasonable quality filter. With Opamps, the high-pass and low-pass regions can also be amplified if necessary. In terms of input and output impedances, overall quality, and reproducible results, Opamps can be used with R's and C's and L's to create superior filters. Our filtering, amplification, or passive components are quite limited. It is extremely difficult to meet aggressive specs and produce a reasonable quality filter.

Week 2: Filter Design using Opamps

In your report comment on your experimental results. How well does the Bode plot approximate the real response? If your design had an output impedance >10 kΩ over all frequencies.

Include on your graphs the Bode plots you obtain from the transfer function shown in equation (4).

In your lab report, explain why it is not possible to approach these ideal values for this design. Ideally what values of R and C would you select to meet the overall transfer function specs? Verify that your signal generator and oscilloscope are reasonably close to your design input and output impedances. Include on your graphs the Bode plots you obtain from the transfer function shown in equation (4).

In your lab report, explain how you selected your circuit values in your lab books and specifications. Explain how you selected your circuit values in your lab books and specifications. The additional constraints come from the input and output impedances. Explain how you selected your circuit values in your lab books and specifications. Include on your graphs the Bode plots you obtain from the transfer function shown in equation (4).
Measure the magnitude of the filter at the lower and upper 3dB frequencies. Comment on any discrepancies you observe between the 3dB frequencies you designed for and your measurements? Comment on the difference between your bandpass filter and the ideal transfer function model in Fig. 4. What suggestions, if any, do you recommend for an improved frequency response? If time permits, modify your design as required.

D. Notch Filter Design

Like the bandpass filter, the notch filter is simply the combination of a low pass and a high pass filter. In the case of the bandpass filter, the middle, or zero, band pass was in between the lower and upper 3dB frequencies. In the case of the notch filter, the middle, or zero, band pass is at either the lower or upper 3dB frequencies.

Appendix A: Good Analog Design Techniques

In order to have an analog circuit that functions predictably and reliably:

- Use good quality components whose value is known.
- Use dual power supplies with good bypassing.
- Use a power supply that is stable and has good bypassing.
- Use good grounding techniques, such as using a ground plane or shielded enclosure.
- Use good circuit design techniques, such as using feedback and negative impedance converters.
- Use good layout techniques, such as using a power distribution network and a ground plane.

Appendix B: Troubleshooting Analog Circuits

If you experience less than satisfactory performance, troubleshoot the circuit as follows:

1. Check the power supply voltage and current.
2. Check the input and output signals for level and distortion.
3. Check the components for good soldering and placement.
4. Check the layout for cross-talk and interference.
5. Check the circuit for drift and instability.

If any of the above steps do not resolve the problem, consider using a different power supply or layout. If the problem persists, contact the manufacturer or a professional for assistance.
Try to keep all signal lines away from power lines, and in general keep all lines as short as possible. Noise can and will find its way into your circuit wherever possible. Long signal paths and power supply lines kept near signal paths are susceptible to noise pickup and coupling.

Try to keep all your component leads as short as possible. Having wires and components going an inch up into the air and then back into your protoboard will result in noisy and unpredictable performance, especially as you get up into higher frequencies. Try to keep your components flush with the surface of your protoboard. You don’t see components with bent leads an inch up in the air.

Make sure you have a solid ground reference. Without one, your circuit will be floating and will perform miserably or not at all.

Appendix B: About Your Lab Report

Your lab report should contain all of the lab results (data, graphs, drawings, etc.). Your lab report should be a self-contained self-explanatory document. It should be more than a list of answers to the questions in the lab notes. Your comments on the results should reflect your understanding of the experiment. Your well-thought-out reasoning and answers to the questions in the lab notes. Your comments on the results should be clear and precise. Your lab report should be well-organized, self-contained, and self-explanatory. It should be more than a list of answers to the questions in the lab notes. Your report should contain all of the lab results (data, graphs, drawings, etc.).
C.1 Resistor Color Codes

<table>
<thead>
<tr>
<th>Color</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>9</td>
</tr>
<tr>
<td>Grey</td>
<td>8</td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
</tr>
<tr>
<td>Black</td>
<td>0</td>
</tr>
</tbody>
</table>

Thus, a resistor of colors Brown, Black, Red would have a value of:

\[
\text{Value} = 1 \times 10^0 + (0 + (1 \times 1))
\]

\[
= 1.0 + 0 + 1 = 2.0 \Omega
\]

Table 4. Resistor color bands.

Figure 4. Resistor color bands.
C.2 Measuring RMS values and Amplitudes

The RMS value of a periodic current/voltage signal is defined as a constant that is equal to the dc current/voltage that would deliver the same average power to a resistance, $R$. Thus, the RMS value of a periodic current/voltage signal is defined as a constant that is equal to the dc current/voltage that would deliver the same average power to a resistance, $R$.

Thus, $I_{\text{rms}} = \frac{V_{\text{rms}}}{\sqrt{2}}$

The digital multimeter on your lab bench is reading in RMS units. You might want to compare this with the ac signals displayed on your oscilloscope for some sample signals from your signal generator. For the sinusoidal signals that you will be measuring most often, the peak value is related to the RMS value by:

(1) $I_{\text{rms}} = \frac{V_{\text{rms}}}{\sqrt{2}} = \frac{V_{\text{peak}}}{\sqrt{2}}$

(2) $I_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$

(3) $I_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$

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(3) $I_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$

C.2 Measuring RMS values and Amplitudes

Parts List

- LM741 Operational Amplifiers
- Resistors
- Capacitors