Laboratory 1: Review of Passive Networks

Preliminary Exercises

In this lab, you will investigate the operation of passive oscilloscope probes. As this lab aims to help you to review previously learned material, it will ask you to recall both frequency domain and transient RC network concepts, and to recall or relearn the operation of the various instruments in the laboratory.

1. Simple Low Pass Networks

Consider the low pass filter depicted in Fig. PL1.1

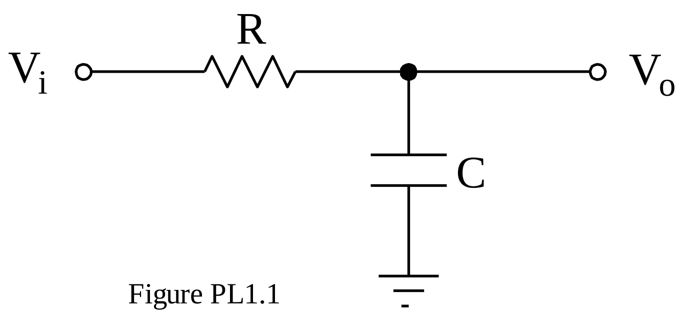

Figure PL1.1

(a) Derive an expression for the step response; i.e., an expression for $V_o(t)$ for $V_i(t)=u(t)$.

(b) Define the time for the output voltage to change from 10% to 90% of its final value as the rise time t_r. Derive an expression for the time constant $\tau=RC$ in terms of t_r. [Note: You will need to make rise time calculations later in this laboratory; make sure you feel comfortable with these computations.]

(c) Now, derive an expression for the frequency response of the network, assuming steady-state conditions. Express your answer as magnitude and phase using phasor notation. Justify its description as a lowpass filter.

(d) For a single-pole network, the cut-off frequency or *bandwidth* f_h is the frequency at which

$$V_o = V_i\left(\frac{1}{\sqrt{2}}\right)e^{-j45^\circ},$$

where V_o and V_i are phasor quantities. Derive an expression for f_h (in Hertz) in terms of τ. Notice that for a single-pole network, either the magnitude or the phase of the frequency response is sufficient to define the cut-off frequency.

2. Practical Issues in Electronic Measurement

Whenever one measures a physical system, the act of measurement alters the system of interest, thus, altering the value of the desired parameter. For the case of the laboratory measurements in EE 105, the measurement tools exhibit finite input/output impedances, which can load the circuits under test, changing their properties and altering the actual measured values. The lecture discussed resistive loading of amplifiers. As will be seen in this lab, capacitors can also significantly load circuits (as can inductors).

As an example of loading by measurement, consider the use of an oscilloscope to measure the output of a lowpass filter. Fig. PL1.2(a) below depicts the required experimental setup for this.

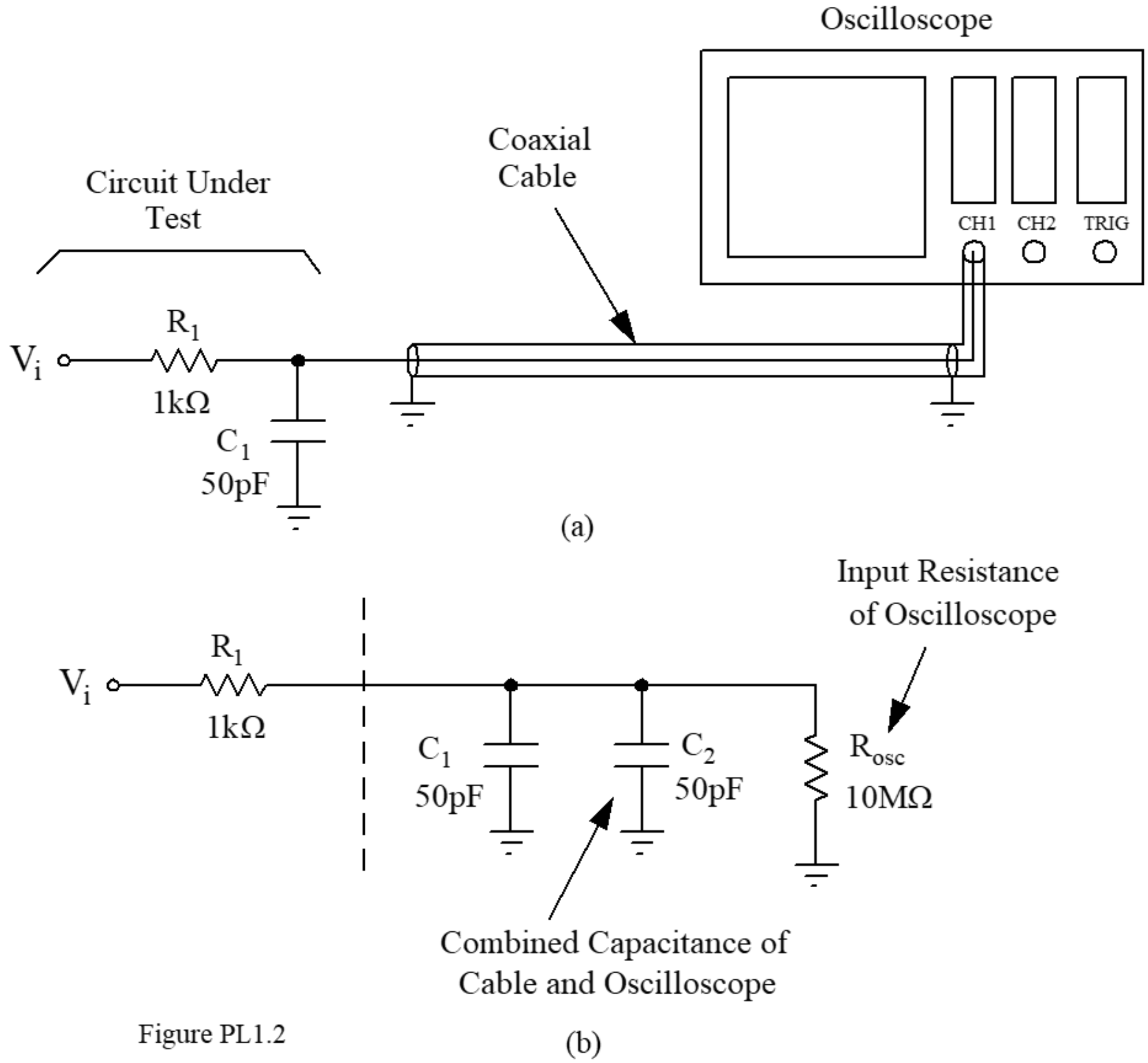

Figure PL1.2

Fig. PL1.2(b) presents an equivalent circuit schematic for the experimental set-up of Fig. PL1.2(a). Here, the combined capacitance of the oscilloscope and the coaxial cable is C_2=50 pF, and a resistance R_{osc}=10 MΩ models the input resistance of the oscilloscope.

(a) Compute the rise time t_r of the test circuit, both with and without the loading induced by the oscilloscope (i.e., with and without C_2 and R_{osc}). [Note: Reasonable engineering approximations are permissible here. For example, you should be able to neglect the resistive loading for *this* computation.]

(b) What is the percent error in rise time measurement induced by loading? Use the following expression for percent error:

$$\% \ error = \left| \frac{t_r(theoretical) - t_r(measured)}{t_r(theoretical)} \right| \times 100 \quad [\%],$$

where t_r*(theoretical)* is the rise time without oscilloscope loading, and t_r*(measured)* is with oscilloscope loading.

(c) One way to reduce the effective capacitance loading the original "circuit under test" is buffer the circuit from the oscilloscope input by adding a series resistor R_{buff} between the test circuit and the input of the oscilloscope, as shown in Fig. PL1.2(c).

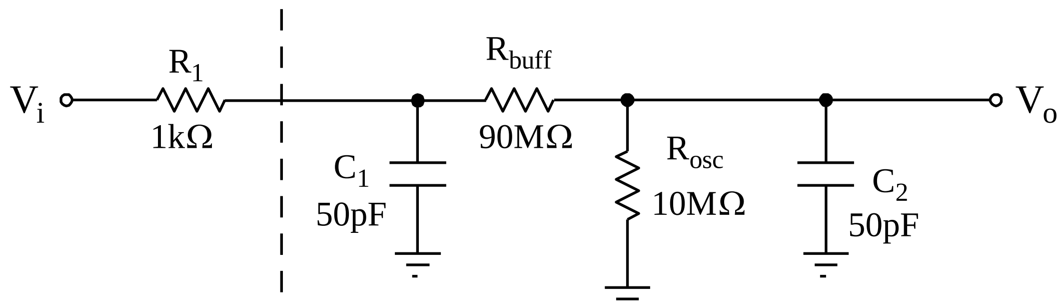

Figure PL1.2(c)

Note that now V_o is attenuated by the resistive voltage divider formed by 90 MΩ and 10 MΩ resistors.

Determine the effective value of C_2 (call it C_{2eff}) that now loads the test circuit. Do this via the following procedure:

(i) Determine the input impedance of the circuit to the right of the dashed line in Fig. PL1.2(b) in terms of C_1, C_2, and R_{osc}. Call it Z_{in1}.

(ii) Determine the input impedance of the circuit to the right of the dashed line in Fig. PL1.2(c) in terms of C_1, C_2, R_{buff}, and R_{osc}. Call it Z_{in2}.

(iii) The zero in the expression for Z_{in2} determines the infinite-time response of the circuit, not the step response. Since we are concerned primarily with the step response, here, we can neglect the zero, i.e., ignore the s term in the numerator. Also, the s^2 term in the denominator of Z_{in2} can be neglected if we assume that the poles of this circuit are far apart— i.e., if we assume that this circuit has a dominant pole. Eliminate the zero and the s^2 term from the Z_{in2} expression. Call the new expression Z_{in2}'.

(iv) Compare Z_{in1} and Z_{in2}'. The real part of Z_{in2}' (call it R_{eff}) is the effective resistance in parallel with C_1+C_{2eff}; it is analogous to R_{osc} in Z_{in1}. Thus, C_{2eff} is the capacitance required to make the imaginary term in Z_{in2}' equivalent *in form* to that in Z_{in1}. With this information, find C_{2eff}. [Alternatively, you could just get Z_{in2}' into exactly the same form as Z_{in1} except for the C_2 term, and then compare the "C_2 terms".]

Although the loading is now smaller, we have effectively added an additional low-pass filter in series with the input of the oscilloscope. Thus, when measuring the step response of the test circuit, we will actually be measuring the combined step response of both the circuit *and* the oscilloscope.

(d) Compute the rise time *for the oscilloscope* used in this manner. (It derives from the lowpass filter formed by R_{buff}, R_{osc}, and C_2.)

(e) Based on your result in (d), do you expect the measurement of the test circuit using the scheme of Fig. PL1.2(c) to be accurate? Why or why not?

3. Practical Oscilloscope Probes

To minimize the effects of loading, oscilloscope probes often come as *compensated attenuators*. Fig. PL1.3 shows the equivalent circuit schematic for a typical compensated attenuator.

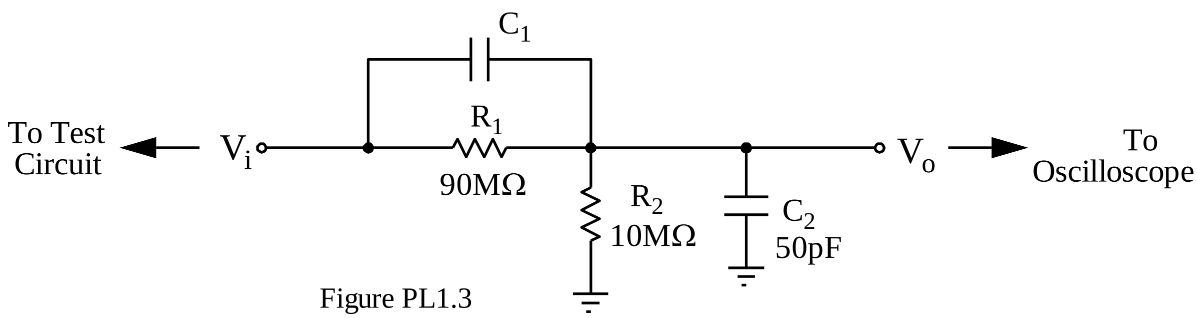

Figure PL1.3

(a) Derive an expression for the V_i to V_o transfer function in terms of the Fig. PL1.3 variables.

(b) Derive an expression for C_1 based on the values of R_1, R_2, and C_2 to yield the following transfer function:

$$\frac{V_o(s)}{V_i(s)} = \frac{R_2}{R_1 + R_2},$$

(c) What is the rise time of the circuit for the case where C_1 takes the value you derived in 3(b)?

(d) Is your result in (c) reasonable? Comment on any limitations that manifest in a real circuit.

Laboratory 1: Review of Passive Networks

Results Sheet for Preliminary Exercises

NAME: ________________________________ **LAB SECTION:** _____

1. Simple Lowpass Networks

(a) ______________________________

(b) ______________________________

(c) ______________________________

(d) ______________________________

2. Practical Issues in Electronic Measurement

(a) ___________________________ , with ___________________________ , without

(b) ________________________________

(c) ________________________________

(i) ____________________

(ii) ____________________

(iii) ____________________

(iv) ____________________

(d) ________________________________

(e)

3. Practical Oscilloscope Probes

(a) ________________________________

(b) ________________________________

(c) ________________________________

(d)

Laboratory 1: Review of Passive Networks

Laboratory Exercises

INTRODUCTION

Objectives

This lab is intended to help you review basic circuit construction and measurement techniques, and to review basic passive circuit concepts by demonstrating the "anti-loading" function of oscilloscope probes.

Summary of Procedures

(i) Determine the properties of a simple lowpass network by measuring its step response and frequency response.

(ii) Construct a simple oscilloscope probe to study its operation and demonstrate the need for compensation.

Materials Required

- Oscilloscope
- Proto-board
- Function Generator
- Capacitance Meter
- Assorted Resistors and Capacitors

PROCEDURE

As you do this lab, be sure to look at the *Results Sheet for Laboratory Exercises* to make sure you are obtaining enough data to answer all of its questions.

1. Compensating the Oscilloscope Probe

The first step in any lab is to organize the required equipment and to COMPENSATE THE OSCILLOSCOPE PROBE. You can easily compensate the probe as follows:

(a) Connect the probe to the test point located below the Agilent oscilloscope display labeled **PROBE COMP**. The test point provides a square wave of known properties. The scope must be DC coupled for this operation.

(b) Set the triggering to normal and adjust the trigger level for a stable display.

(c) Adjust the sweep time and vertical sensitivity to display about two cycles of the square wave.

(d) With a nonconductive adjustment tool, gently adjust the compensation control on the probe tip while observing the image displayed on the screen. Continue to adjust the probe until the square wave has as "flat a top" as possible, as in the far right of Fig. L1.1.

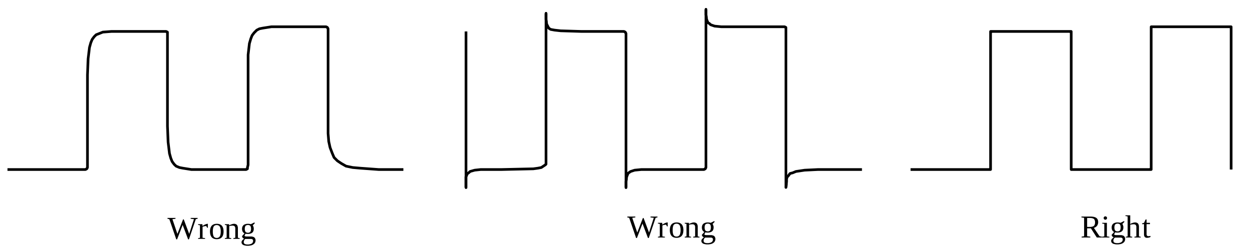

Figure L1.1

2. Finite Instrumentation Impedance

Measure the low frequency output impedance of the function generator. Do this by hooking the output of the generator to a test resistor R_{test} of value from 50 Ω to 100 Ω to ground, as shown in Fig. L1.2.

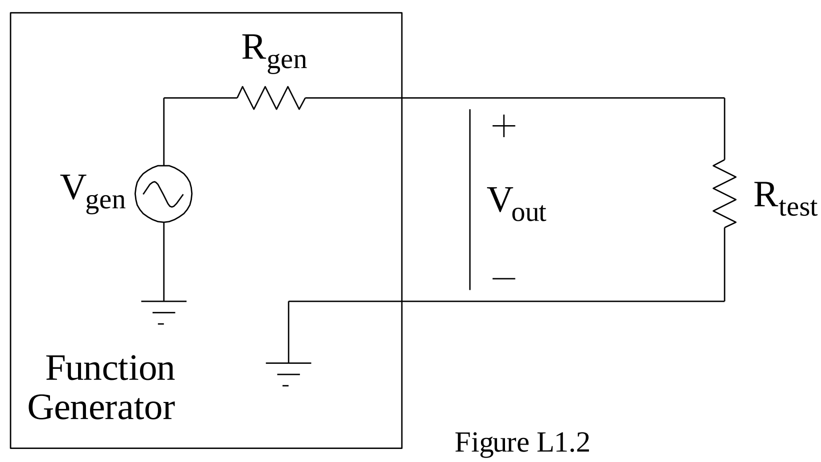

Figure L1.2

In this configuration, the voltage V_{out} indicated in Fig. L1.2 takes the form

$$V_{out} = \frac{R_{test}}{R_{test}+R_{gen}} \times V_{gen}.$$

Thus, with knowledge of V_{gen} and with measurements of the resistor R_{test} and the voltage V_{out}, one can compute R_{gen}.

(a) Choose a test resistor R_{test} with value between 50 Ω and 100 Ω and hook up the circuit shown in Fig. L1.2. Set the function generator to output a sinusoidal waveform with a reasonable choice of amplitude (e.g., 1V) and a frequency of 10 kHz or lower. Measure the value of V_{out} using your oscilloscope (with a properly compensated probe).

(b) Compute the value of R_{gen}.

3. A Simple Lowpass Network

Build the simple lowpass filter shown in Fig. L1.3 below. Be sure to follow the construction suggestions described in Section 2.1 of the Laboratory Manual.

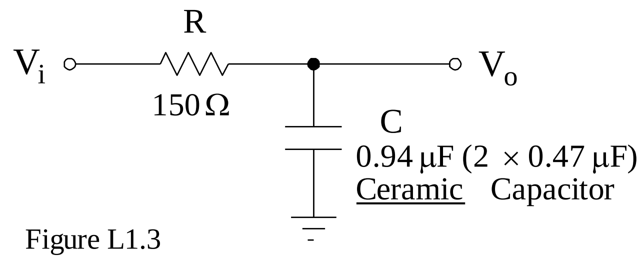

Figure L1.3

Also, make sure you measure the component values.

(a) Using the function generator to produce a 100 Hz square wave, measure the rise time t_r of the lowpass filter (use the *X/Y* cursors on the oscilloscope; do not use the Quick Measure function). Compute the value of τ from t_r.

(b) Measure t_r of the generator while it is not hooked up to your circuit (again, use the *X/Y* cursors on the oscilloscope; do not use the Quick Measure function). You may find it useful to adjust the frequency of the function generator to make this measurement.

(c) Take frequency response data sufficient to construct a Bode plot of both the gain and phase of the network. You should take this data using the oscilloscope with the input signal displayed on one channel and the output on the other.

4. A Prototype Oscilloscope Probe

As discussed in Part 3 of the *Preliminary Exercises*, attenuating oscilloscope probes can increase measurement accuracy by minimizing the loading effects of the oscilloscope input capacitance on the circuit under test.

Earlier, in Part 2 of the *Preliminary Exercises*, you showed that although a simple voltage divider did minimize the loading on the circuit under test, it also slowed the response of the oscilloscope probe. You then showed in Part 3 of the *Preliminary Exercises* that the addition of a compensation capacitor (C_1 in Fig. PL1.3) to the simple voltage divider can significantly "speed up" the response. Indeed, by adding the capacitor C_1, one can theoretically compensate perfectly for the "slowing" effects of C_2 and obtain an ideal step response.

To ensure we are all working with correct formulas (i.e., in case your *Preliminary Exercises* answers were not correct), let us derive the appropriate formulas here. This time, however, instead of using nodal analysis, as was done for the *Preliminary Exercises*, let use some intuition to arrive at the same result, but with a simpler approach. We start by first recognizing that for perfect compensation, the initial (t = 0+) voltage across R_2 must equal the final voltage ($t = \infty$). For this to be true, the following relation must hold: (refer to Fig. PL1.3 for variable definitions)

$$\frac{R_2}{R_1+R_2} = \frac{C_1}{C_1+C_2}.$$

Thus, for compensation, we must have

$$C_1 = \frac{R_2 C_2}{R_1} \qquad \text{or} \qquad R_1 = \frac{R_2 C_2}{C_1}.$$

In practice, the required value of C_1 is so critical that its value must be determined experimentally, as is done when compensating an oscilloscope probe.

The above derivation (as well as the one in the *Preliminary Exercises*) implicitly assumes a zero source impedance. An analysis with finite source impedance would show that perfect compensation is no longer possible. However, as you will soon demonstrate, significant improvement in rise time over the uncompensated case is still attainable.

Because of the above finite source impedance problems, a handful of real oscilloscope probes actually use a more complicated circuit than indicated in Fig. PL1.3. The majority of probe circuits, however, do use the circuit topology of Fig. PL1.3. In particular, high speed (>200 MHz) probes are often designed exactly like the one you will now evaluate.

Construct the prototype oscilloscope probe shown in Fig. L1.4 below. In a real probe, the capacitance C_2 represents the parasitic capacitance associated with the probe cable. Compensation of a real oscilloscope probe normally comes about through adjustment of the compensating capacitor C_1. The resistive voltage divider provides the required probe attenuation. In this lab, for ease of construction, we are adjusting R_1, rather than C_1.

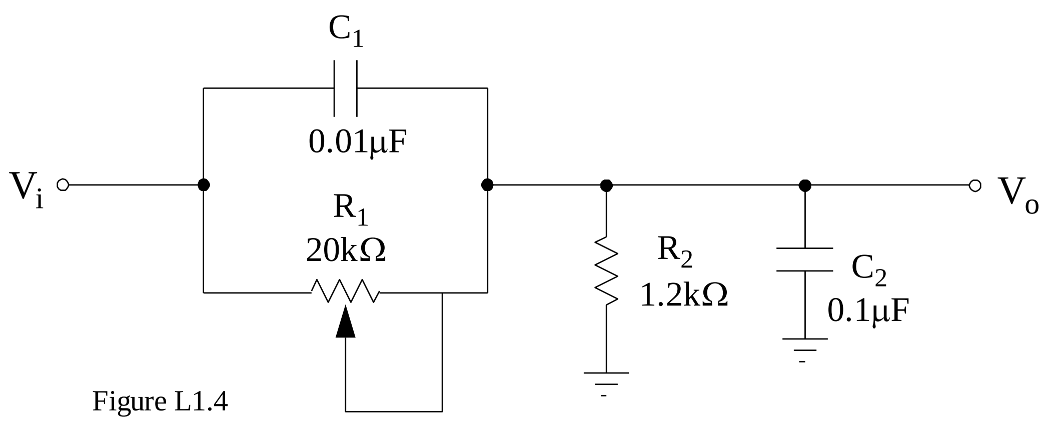

Figure L1.4

(a) Temporarily remove C_1 and set R_1 to 10 kΩ. Note that now the network condenses to the simple lowpass filter of Fig. PL1.2. Using a square wave, repetitively display the step response on the oscilloscope. Using a step response measurement, determine t_r.

(b) Using the variable resistor setup for R_1, compensate your prototype oscilloscope probe. Measure C_1, C_2, R_1, and R_2, and verify the formulas derived above. Measure the rise time of the voltage step at the input and the output of the network. Measure the time required for the output of the prototype oscilloscope probe to settle to its final value, defined as $V_o(\textit{final value}) = V_o(t = \infty) \pm 1\%$.

Laboratory 1: Review of Passive Networks

Results Sheet for Laboratory Exercises

NAME: ________________________________ **LAB SECTION:** _____

2. Finite Instrumentation Impedance

(a) R_{test} = ________________________

V_{out} = ________________________

(b) R_{gen} = ________________________

3. A Simple Lowpass Network

(a) Filter Rise Time t_r= ________________________ (attach oscilloscope plot)

Value of τ computed from measured rise time ________________________

(b) Rise Time of Generator = ________________________ (attach oscilloscope plot)

Is the rise time of the generator small enough to be ignored? Justify by computing the predicted error resulting from an assumption that the generator output is an ideal step; i.e., compute the theoretical rise time for the lowpass filter circuit using your measured values of R and C and assuming an ideal step input (but don't neglect the R_S of the generator), then calculate the percent error between the measured and theoretical rise times.

Value of τ predicted from the component values ________________________
(and assuming an ideal step input)

% error between measured and computed τ's from (a) and (b) above ______________

Explain any discrepancies between the computed and measured values of τ.

(c) Using a semi-log scale, construct and attach the Bode plot of the lowpass filter. (The gain and phase should be on separate axes.) How many points did you use? _______. Attach annotated oscilloscope plots showing measurement of both gain and phase at the 3dB point.

Assuming that you know a given circuit has a single pole, and that you can make qualitative observations over a very broad frequency range, how many quantitative data points are required to construct the asymptotic Bode plot? ______________

From the Bode plot, or otherwise, determine the cut-off frequency of the lowpass filter ______________________. Does this value agree with the value of τ measured above? Explain.

4. A Prototype Oscilloscope Probe

(a) Rise Time t_r = ______________________________ (without C_1; attach annotated oscilloscope plot)

Predicted Rise Time Using Circuit Analysis = ____________________________

(b) After compensation:

C_1 = _________________________

C_2 = _________________________

R_1 = ___________________________

R_2 = ___________________________

Rise Time at Input = __________________________ (attach annotated oscilloscope plot with scale magnified to accurately show t_r)

Rise Time at Output = _________________________ (attach annotated oscilloscope plot with scale magnified to accurately show t_r)

After compensation, is the output voltage a reasonable representation of the input voltage? Do you need to take the actual oscilloscope probe characteristics into account in your discussion? Justify.

How long did the prototype oscilloscope probe take to reach its final value? _______________

How long would the prototype probe have taken without compensation? __________________

Comment on the need for compensation and its benefits.