ECE 4670 Spring 2014 Lab 1
Linear System Characteristics

1 Linear System Characteristics

The first part of this experiment will serve as an introduction to the use of the spectrum analyzer in making absolute amplitude measurements. The signals considered will be common periodic signals which are produced by a function generator (i.e. sine, square, and triangle waveforms). Next swept frequency measurements using a spectrum analyzer with a tracking generator will be investigated. The amplitude response of an active notch will be characterized. In the third portion of this experiment both the amplitude and phase response of linear systems will be considered. The use of a gain-phase meter will be introduced.

1.1 Basic Spectrum Analyzer Measurements

The spectrum analyzer is a device which displays an amplitude versus frequency plot of the frequency components or spectrum of any input signal. Located on roll-about carts, the lab has three Agilent 4395A spectrum/network analyzers. The analyzers cover the frequency range from 10Hz to 500MHz. The 1 MΩ high impedance adapter, used frequently throughout the course, additionally limits the bandwidth to 5 Hz to 100 MHz.

The operation of the 4395A is not as difficult as it might appear from just looking at the front panel controls. You will need to spend some time becoming familiar with both the *Network Analyzer* (quick start guide pp. 3-1 to 3-14) and *Spectrum Analyzer* (quick start guide pp. 3-15 to 3-30) operating modes. Read through the *Quick Start* instructions carefully before proceeding any further with this experiment. For the first part of this experiment you will be using the analyzer in the *Spectrum* mode. When making measurements with this instrument the first step is to configure the operating state to the proper measurement mode, activate appropriate source and receiver ports, select frequency sweep parameters, and display formats. If you encounter difficulty or become frustrated trying to figure out the front panel controls, please ask the lab instructor for assistance.

The detailed front panel operation of both of these analyzers is described in the respective operators manual. A PDF version of the 4395A operators manual can be found on the course Web site (`http://www.eas.uccs.edu/wickert/ece4670`). Printed copies of the manuals can also be found on the respective carts. Ask your lab instructor to explain anything you don't understand. The spectrum/network analyzer is a sophisticated instrument and can be easily damaged. **DO NOT EXCEED THE MAXIMUM ALLOWABLE INPUT SIGNAL LEVELS** (orange lettering below the input terminals). This instrument is very expensive, costing in excess of **$28,000** when new. Additionally, Agilent no longer makes an instrument with the combined spectrum vector network analysis capability of this instrument, with these same features. Getting a return on our investment is important.

An overview of the spectrum analyzer measurement capabilities and input signal level maximums can be found in Table 1. An overview of the network analyzer measurement capabilities and input signal level maximums can be found in Table 2.

The spectrum/network analyzer will first be used in the spectrum analyzer mode. Use of the

Table 1: Agilent 4395A spectrum analyzer mode general specifications and corresponding input maximums.

Spectrum Analyzer Specifications		Attenuator Setting (dB)	Full Scale (max) Input (dBm)
Frequency Range	10 Hz to 500 MHz		
Noise Sidebands	< -104 dBc/Hz typical at 10 kHz offset	0	-20
Resolution Bandwidth	1 Hz to 1 MHz in 1-3-10 steps	10	-10
		20	0
Dynamic Range	> 100 dB third-order free dynamic range	30	+10
Level Accuracy	±0.8 dB @ 50 MHz -145 dBm/Hz	40	+20
		50	+30
Sensitivity	-145 dBm/Hz @ freq. = 10 MHz		

Table 2: Agilent 4395A network analyzer mode general specifications and corresponding input maximums.

Network Analyzer Specifications		Attenuator Setting (dB)	Full Scale (max) Input (dBm)
Frequency Range	10 Hz to 500 MHz		
Frequency Resolution	1 mHz	0	-10
Output Power Range	-50 to +15 dBm	10	0
Dynamic Range	115 dB @ 10 Hz IFBW	20	+10
Dynamic Accuracy	±0.05 dB/0.3 deg.	30	+20
Calibration	Full two-port	40	+30
		50	+30

network analyzer mode will be explored in the following section of the lab. In general spectrum and network analysis will be carried out as needed, throughout the entire series of lab experiments.

1.1.1   Laboratory Exercises

1. Using an Agilent 33120A (up to 15 MHz operation) or Agilent 33250A (up to 80 MHz operation with a more capable user interface) function generator connect a 1v p-p sine wave at 100KHz to the spectrum analyzer input as shown in Figure 1. The 1v p-p amplitude can be set using an oscilloscope provided the scope is set for 50Ω *input impedance*. The generator frequency can be set using an HP 5384A frequency counter.

   The measurements you will be taking are with respect to a 50 ohm impedance system. In a linear systems theory course a 1 ohm impedance environment is often assumed. This is convenient for mathematical modeling purposes, but in practice 50 ohms (75 ohms for cable TV) is the way radio frequency (RF) measurements are actually taken. The most common
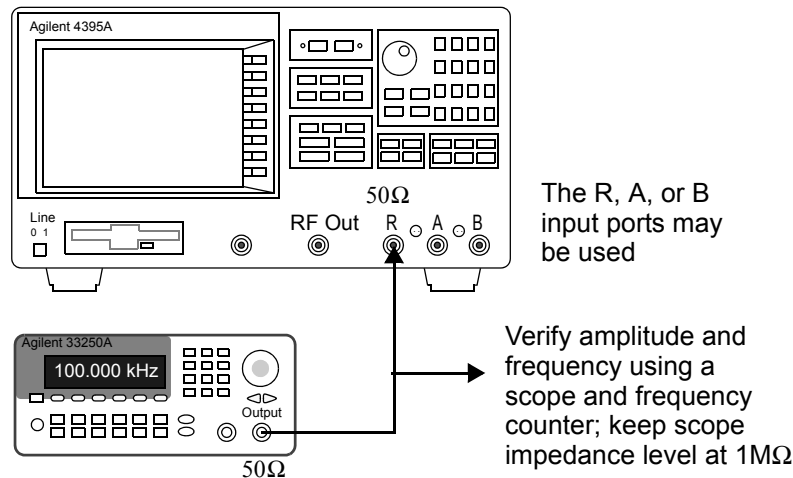
Figure 1: Agilent 4395A Spectrum measurement test setup

display mode for a spectrum analyzer is power in dB relative to one milliwatt (dBm). The units are denoted dBm. To find the power in dBm delivered to a 50 ohm load ,from a single sinusoid waveform, we might start with a scope waveform reading of volts peak-to-peak or peak. From basic circuit theory, the power delivered to a load R is

$$P_l = \frac{1}{2} \cdot \frac{v_{\mathrm{peak}}^2}{R} = \frac{1}{2} \cdot \frac{(v_{\mathrm{pp}}/2)^2}{R} = \frac{v_{\mathrm{rms}}^2}{R} \text{ watts.} \tag{1}$$

Recall that for a sinusoid, the rms value is $v_{\mathrm{peak}}/\sqrt{2}$, and clearly the peak value is one half the peak-to-peak value. In dBm the power is

$$\left(P_l\right)_{\mathrm{dBm}} = 10 \log_{10} \left[\frac{P_l \text{ (watts)} \cdot 1000 \text{ mW/W}}{1 \text{ mW}} \right] = 10 \log_{10} \left[P_R \text{ (watts)} \right] + 30 \tag{2}$$

Suppose we have a 1v rms sinusoid in a 50 ohm measurement environment. The power level is

$$\left(P_l\right)_{\mathrm{dBm}} = 10 \log_{10} \left(1^2/50\right) + 30 = 13.01 \text{ dBm} \tag{3}$$

Measure the input signal amplitude directly from the spectrum analyzer cursor numeric display using the following 4395A display modes:

(a) dBm (default)

(b) dBV

(c) VOLT

2. By observing an oscilloscope display in 50 Ω input mode (no other instruments connected), adjust the output of a function generator to obtain a 1v p-p square wave at 100KHz. Connect this signal to the spectrum analyzer. Note that you can "sharpen up" the frequency spike for each of the harmonics if you reduce the resolution bandwidth (RES BW) setting. On

the Agilent 4395A analyzer this requires using appropriate front-panel key strokes (under BW/Avg key). The quick start explains how to alter the resolution bandwidth (p. 3-23). Ask your lab instructor for assistance if you are having problems.

 (a) Identify and read the amplitudes of the various harmonics contained in the input signal in dBm and V_{rms}. Compare your measured values with theoretical calculations obtained from Fourier analysis. Compare the roll-off of the harmonics versus harmonic number, i.e., for a square wave the Fourier coefficient formula contains $1/n$, where n is the harmonic number.

 (b) Investigate the harmonic content of a triangle waveform, again compare the experimental results with theoretical calculations. Note for the triangle wave the coefficient formula contains a $1/n^2$.

1.2   Vector Network Analyzer Measurements

In this portion of the experiment the 4395A will be used to characterize several linear systems. In particular linear two-port circuits will be analyzed in terms of the transmission parameters amplitude ratio (gain magnitude), phase, and group delay.

When making network analyzer measurements with this instrument the first step is to configure the operating state to the proper measurement mode, activate appropriate source and receiver ports, select frequency sweep parameters, and display formats. See the quick start guide pp. 3-1 to 3-14. If you encounter difficulty or become frustrated trying to figure out the front panel controls, please ask the lab instructor for assistance.

The front panel signal ports of the 4395A are designed for 50 ohm impedance level measurements (source and load resistances). Typical radio-frequency (RF) transmission measurement test setup are shown in Figure 2. For this course you will use the (b) configuration, since the circuit you test are below 100 MHz and the impedance levels are most often well above 50Ω.

Although not pafrt of this course, note that the 50 ohm power splitter of Figure 2a provides equal amplitude and phase output signals with a 50 ohm source resistance to each of the splitter ports. This is not equivalent to a BNC tee! Receiver port R is used to measure the signal at the input of the circuit under test while Receiver port B measures the circuit output. With the measurement format set to Network: B/R (B the output and R the input) the complex ratio of these signal quantities as a function of sweep frequency is then formed by the analyzer. The analyzer screen can be configured to display two traces versus frequency, on a single plot or on a split plot (see the 4395A operators manual p. 6-3). For transmission measurements the typical display format would be the magnitude of the ratio in dB and the phase or group delay, which on the 4395A are display formats LOG MAG, PHASE, DELAY and T/R(dB)-τ).

For audio frequency circuits, which is the subject of this portion of the lab, we need a higher impedance level for making measurements. The setup shown in Figure 2.1b, which uses impedance transforming adapters or active probes on the receiver inputs, is more appropriate for audio measurements. The Agilent 41802A input adapter allows an ordinary 1MΩ scope probe to be used as an input device via an active network impedance transformation. The active probes HP 1124A transform the 50 ohm input impedance level to 1 MΩ shunted by 10 picofarads. The analyzer usable measurement bandwidth is reduced to about 100 MHz with both the 41802A and 1124A.

(a) Formal RF Measurements
(not used in this course)

(b) Audio Measurements and
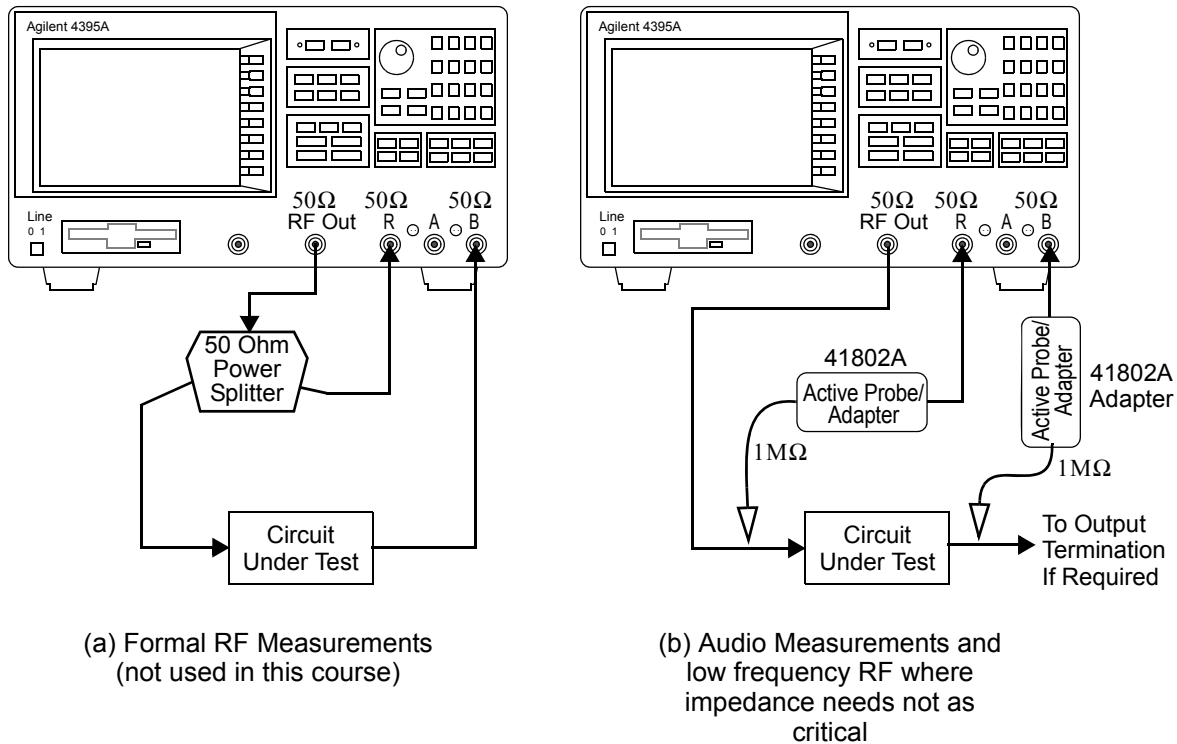low frequency RF where
impedance needs not as
critical

Figure 2: Agilent 4395A transmission measurement test setups

The 1124A active probes are being replaced by the 41802A adapters. The specifications for the 41802A adapters is given in Table 3.

1.2.1   Linear Circuits

You will investigate two linear circuits using the vector network analyzer configured as in Figure2b. The first is the familiar RC lowpass filter as shown in Figure 3. This circuit has no doubt received considerable attention in past lecture courses as well as electronic circuit laboratories. It is hoped that testing this circuit while you are becoming familiar with the network analyzer, will make the interpretation of the experimental measurements easier. The value for R is undetermined since you will have fewer choices for C, you often back into the value for R by choosing C first then find R to obtain the desired 3 dB cutoff frequency.

For the second circuit you have your choice of analyzing an active bandpass filter (BPF) or an active bandstop filter (BSF). Both bandpass and bandstop filters are important in communication systems. The exact implementation technique of course depends on the particular application. Here we are assuming an audio frequency type application.

The design formulas for second order Sallen-Key BPF and BSF filters are provided below[1]. The circuit diagram of an equal component BPF is shown in Figure 4. The filter transfer function

---

[1]F. W. Stephenson, *RC Active Filter Design Handbook*, Wiley, New York, 1985.
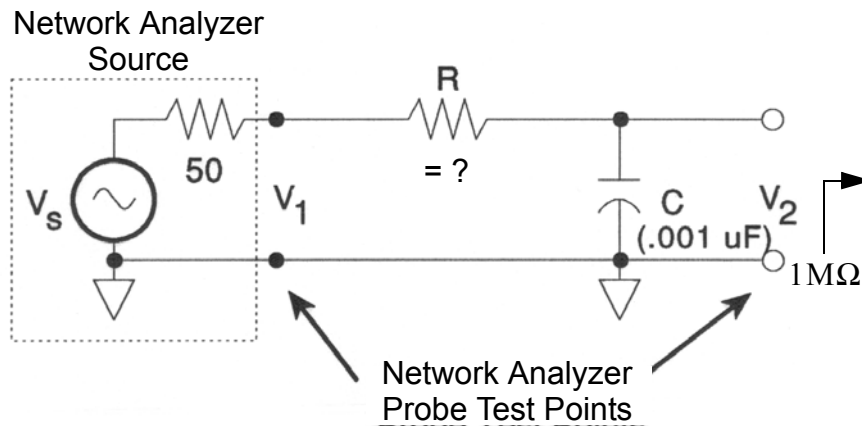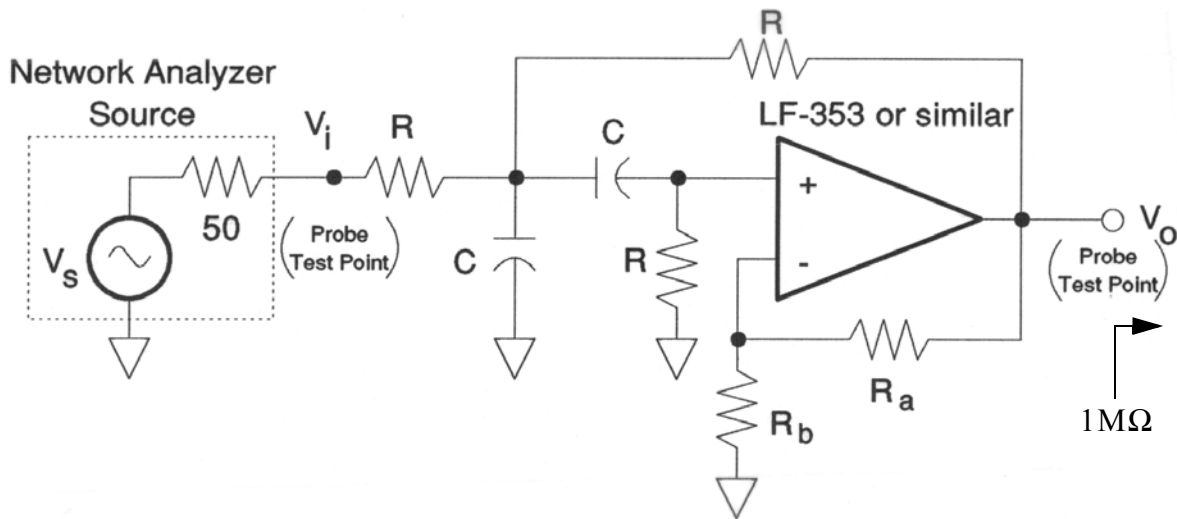
Figure 3: RC Lowpass Filter

Figure 4: Second Order Sallen-Key BPF

Table 3: Agilent 41802A input adapter specifications.

41802A 1MOhm Input Specifications	
Frequency Range	5 Hz to 100 MHz
Input Resistance	1 MOhm
Input Capacitance	12 pf
Accuracy	0 dB $\pm$ 0.5 dB
Gain Flatness	1 MHz $\pm$ 1 dB @ 50 Hz to 100 MHz and $\pm$ 0.5 dB @ 5 to 50 Hz
1 dB Gain Compression	0.32 Vrms @ at 1 MHz
Maximum Level	2 Vrms, 50 Vdc

is given by

$$H(s) = \frac{K\omega_o s/\sqrt{2}}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2} \tag{4}$$

where ω_o is the filter center frequency, Q, is the resonator quality factor related to the 3 dB bandwidth, and K is the amplifier voltage gain. In particular from (6) notice how Q and K are related. The design equations are

$$\omega_o = \frac{\sqrt{2}}{RC} \tag{5}$$

$$Q = \frac{\sqrt{2}}{4 - K} = \frac{f_o}{\text{BW}} \tag{6}$$

$$K = 1 + \frac{R_a}{R_b} \tag{7}$$

Note that the filter gain at center frequency is given by

$$H(j\omega_o) = \frac{K}{4 - K} \tag{8}$$

A general BPF frequency response showing the relation between Q and BW is shown in Figure 5a. The schematic of the Sallen-Key BSF is shown in Figure 6. The filter transfer function is given by

$$H(s) = \frac{K(s^2 + \omega_o^2)}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2} \tag{9}$$

The parameters ω_o, Q, and K have the same meaning as in the BPF case except the design equations for $= \omega_o$ and Q are now

$$\omega_o = \frac{1}{RC} \tag{10}$$

$$Q = \frac{1}{4 - 2K} \tag{11}$$

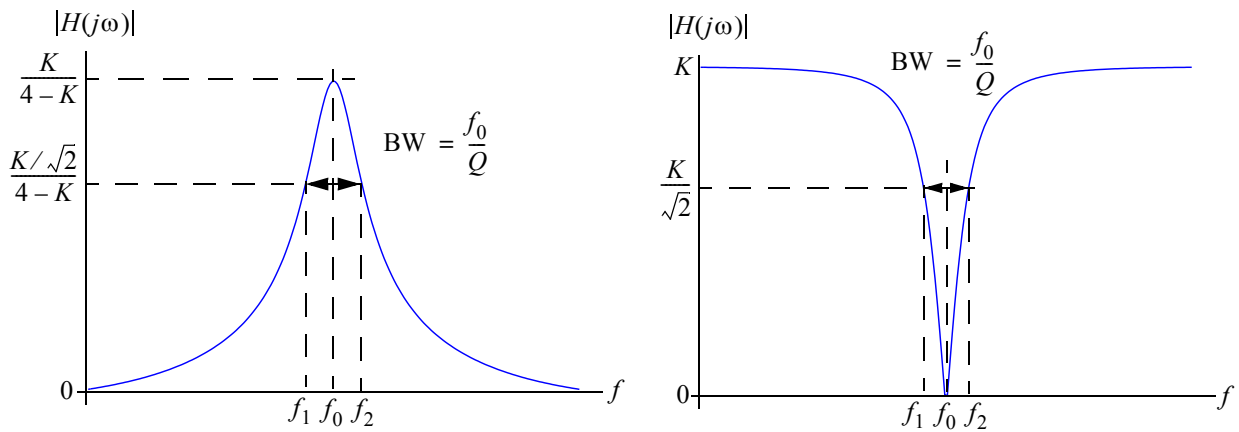The general BSF frequency response and bandwidth definitions are shown in Figure 5b.

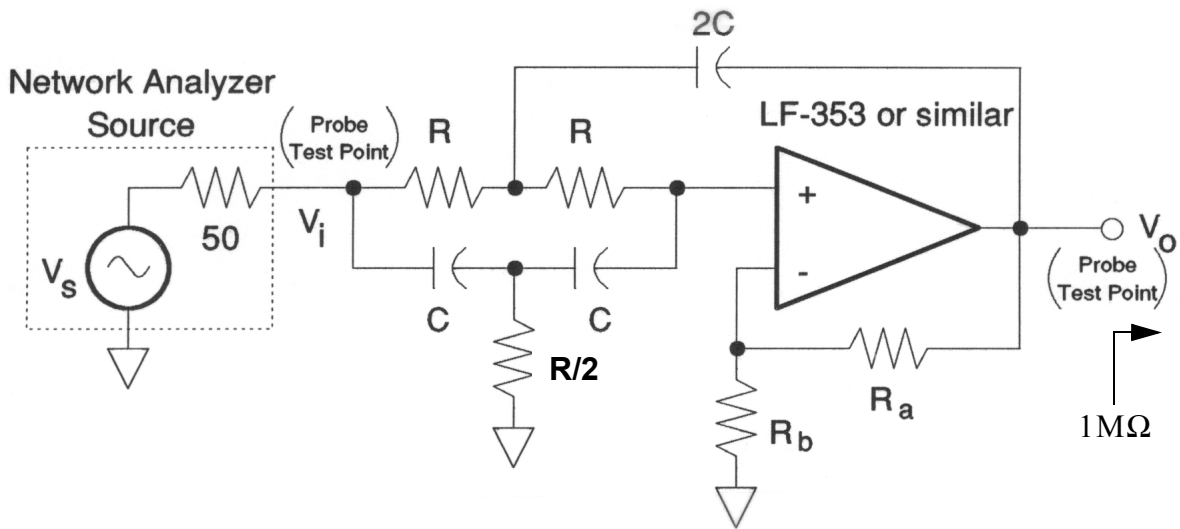Figure 5: BPF and BSF Frequency Response and Bandwidth Definitions

Figure 6: Second Order Sallen-Key BSF

1.2.2 Laboratory Exercises

1. *Lowpass Filter*

    (a) Referring to the lowpass filter of Figure 3 using $C = 1$ nF or another suitable value, determine R such that the cutoff frequency is near 10 kHz.

    (b) Using the 4395A configured for vector network transmission measurements, frequency sweep the lowpass filter from 10 Hz to 100 KHz to obtain gain in dB, phase in degrees, and group delay in microseconds versus frequency. Plot and label your experimental data using the *screen capture* capability of the 4395A in combination with a 3.5 inch floppy (what's that you say) and a portable floppy drive to USB. The instructor will help you with this. You can also save your data in an Excel data file. Furthermore, you may wish to investigate the marker/line cursor menus for analyzing you experimental results. A screen capture will also capture the marker settings.

    (c) Derive the corresponding theoretical expressions for gain, phase and group delay and then compare your experimental data with theoretical predictions. Seriously consider also an Agilent Advanced Design System (ADS) simulation using the AC analysis controller. Your lab instructor will give you an introduction to ADS. A zip package containing an ADS project is available on the course Web Site. There is also a short tutorial document that teaches you the basics of Agilent ADS. ADS will be used in future labs as well.

    A screenshot showing the contents of the Lab1 ADS *workspace* is shown in Figure 7. Drilling down into the workspace I have opened up the schematic of an RC lowpass filter in Figure 8 and the magnitude response in dB in Figure 9. Data can be exported from ADS plot windows so the experimental (measured) and theoretical (circuit simulation) results can be brought together in say MATLAB.

    (d) Attempt to justify any significant deviations from your theoretical predictions. For example the lumped element RC filter model could be enhanced by including the parasitic capacitance between terminal strips of the breadboard.

2. *Bandpass or Bandstop Filter*

    (a) Design and build either a BPF or a BSF as shown in Figure 4 and Figure 6 respectively. Use an LF-353 or similar (bi-fet) op-amp. Design the filter to have a center frequency of about 10 kHz and $2 \leq Q \leq 5$. As a starting point you may wish to choose $C = 1$ nf. To allow a variable Q you may also wish to replace the gain set resistors, R_a and R_b, with a potentiometer (10 k ohm works fine).

    (b) Using the 4395A configured for network transmission measurements, frequency sweep the active filter circuit over a range of frequencies centered on ω_o. Measure filter performance data corresponding to the design parameters. The gain in dB is of primary importance here. Again use the screen capture capabilities of the 4395A for obtaining a hard copy of your data.

    (c) Compare the measured amplitude response with the design parameters and comment on deviations from theory.
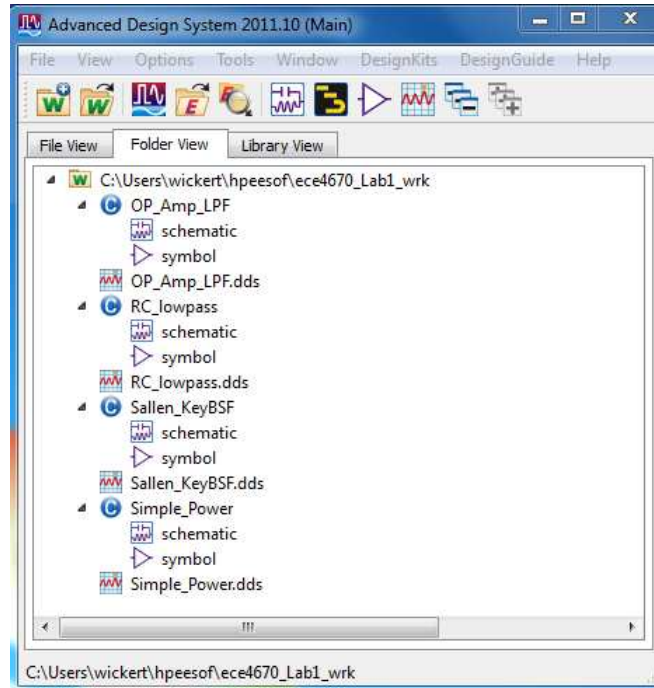
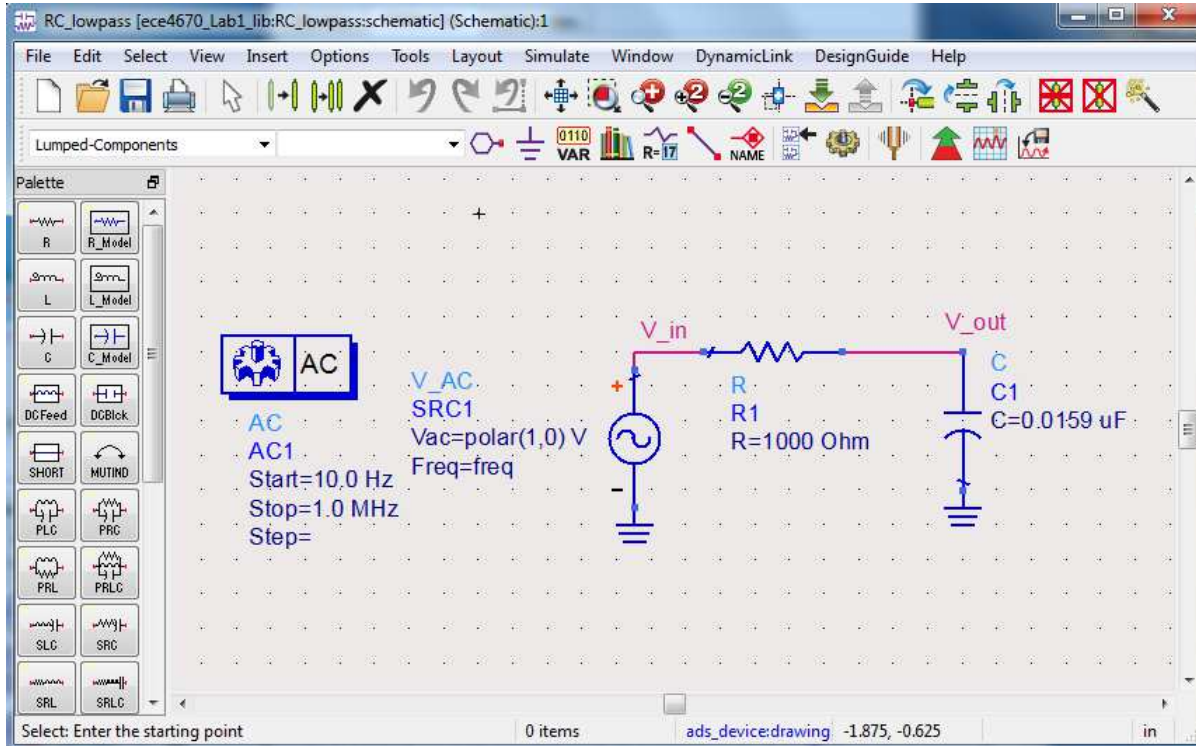Figure 7: Lab 1 ADS workspace contents.
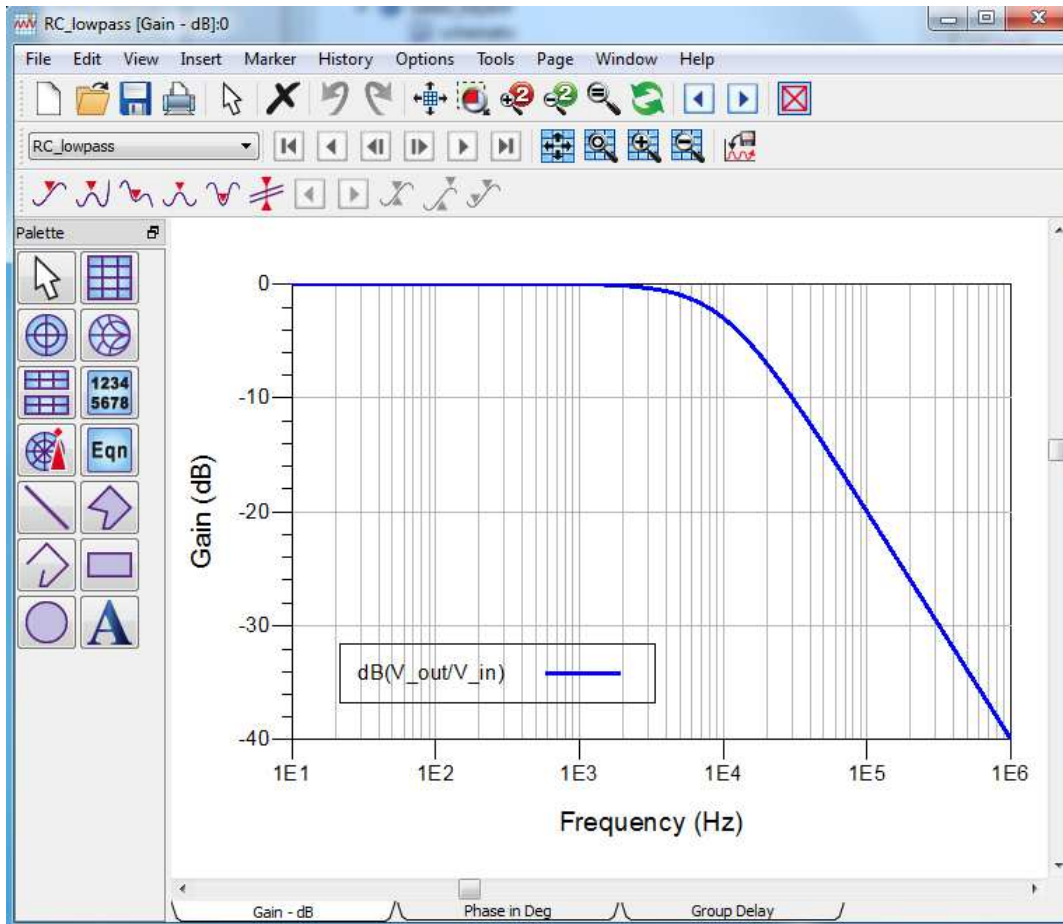

Figure 8: RC circuit schematic in ADS.

Figure 9: RC circuit frequency response magnitude in dB in ADS.

(d) To obtain a better understanding of the theoretical circuit performance simulate the circuit using ADS (see the Lab workspace for a prebuilt model you can play with). The lab PC's have ADS installed. Additional tutorial notes and screencasts on using ADS can be found on Dr. Wickert's ECE 5250/4250 Web Site.

(e) Why is it impractical to obtain high Q's from these circuits ?