Chapter 1

Lab 1 - High Frequency Characteristics of Components

The purpose of this lab is to learn how to simulate simple passive circuits using Agilent's Advanced Design System (ADS) computer aided design software, measure impedance using a Vector (or Parametric, as in our lab) Network Analyzer (VNA or PNA, but we'll stick to VNA) and to become familiar with the high frequency behavior of resistors, inductors and capacitors. You should read Chapter 3 of the course notes before coming to lab.

1.1 Background Information

1.1.1 VNA Calibration for Impedance Measurement

The VNA will be used to take impedance measurements. Note: the instrument in our lab is formally called a PNA - Parametric Network Analyzer, but we'll stick to the more generic name (V)NA - (Vector) Network Analyzer. It is necessary to calibrate the VNA every time the instrument is turned on, and also whenever the test setup is changed. It is also a good idea to recalibrate whenever the start or stop frequencies are changed. It is not necessary to recalibrate when testing multiple items using the same test configuration. Calibrating the VNA establishes a measurement reference plane. The reference plane is located where the calibration standards (open, short, load) are placed. After calibration, the measured reflection coefficient or impedance, will be the impedance at the reference location. To measure the impedance of lumped components we will employ an impedance test jig and the reference point will be located at the point where the component is inserted into the jig.

The procedure for calibration is given in the last section of the Lab 1 notes.

Your TA should give the background on the use of the test jig.

1.1.2 Capacitors

Capacitors have series lead inductance and internal inductance as well as losses caused by the finite conductivity of the dielectric material. Since losses are usually quite small in capacitors, they can often be modeled as a series LC circuit. A capacitor will therefore have a series resonant frequency above which the impedance will be inductive.

1.1.3 Resistors

Resistors of low value and appreciable lead length appear as series RL circuits. Higher value resistors in the range of 10,000 Ω are modeled as parallel RC circuits. You should go through the quick mathematical analysis to justify the above simplifications of the Chapter 3 model.

1.1.4 Lead Inductance

Lead inductance is often a dominant parasitic when the component impedance magnitude is not particularly large. A good rule-of-thumb to remember is that 1 mm of lead length has about 1 nH of inductance.

1.1.5 Inductors

Inductors often come in one of two configurations: solenoid and toroid. The solenoid can have an air core, while the toroid is usually wound around a donut-shaped core, which allows for increased inductance. Read Appendix A for more information. A significant parasitic effect in inductors is capacitance between its coils. It leads to a parallel resonant frequency as discussed in Chapter 3 of the course notes. The parallel resonance depends on the construction of the inductor. In addition, inductors wound on a core material will be subject to dielectric loss in the core material. The loss is very important in determining the "Q" of the inductor.

1.2 Lab 1 Step-by-Step Guide

This is *only* a *recommended* sequence of steps. The students have some freedom to rearrange the procedure at their convenience or as suggested by their TA in order to accomplish lab goals and satisfy the report requirements in a time-efficient manner.

1.2.1 ADS Tutorial and Component Model Files

1. Complete the ADS Tutorial (Appendix B - MP0). This introduction to the ADS circuit simulation package will prepare you for the modeling required in this lab.
2. Create and save an ADS simulation file for each of the following: 5.6 Ω resistor, 56 kΩ resistor, 22 pF capacitor, 0.047 μF capacitor, 56 nH inductor, 2 μH inductor. The models are described in Chapter 3 of the course notes and will be reviewed by your TA. Initially, set the values of parasitics to minimize their effect. For each file, plot resistance and reactance (magnitude, phase, and Smith chart are not necessary). Spend a minute to make sure you understand the graphs.

1.2.2 Calibration of the VNA

3. Calibrate the VNA with the attached test jig. Follow the procedure included in these lab instructions. In this step you will set the scan parameters (i.e. 300 kHz - 500 MHz, 1601 points) for the subsequent measurements.

4. Verify the calibration with the Smith Chart display. Make sure the jig thumb-screw is tightened for each standard as it was during the calibration. You should see dots at appropriate points on the Smith chart.

5. Include a print-out or a good sketch of each calibration standard impedance displayed on the Smith chart. Label the standards and specify impedance (Z) and the corresponding reflection coefficient (Γ) for each standard.

1.2.3 Capacitor and Resistor Measurements

When you conduct measurements, be sure to keep your components organized.

6. Measure the impedance versus frequency of two (small and large value) axial and two chip capacitors given by your TA. Save the four *.cti files in your directory (or use *s2p Touchstone files which we'll use later). Follow the procedure included in these lab instructions. It is recommended that you create a folder for Lab 1, and that you give consistent and descriptive names to data files.

7. Measure the impedance versus frequency of two (small and large value) axial and two chip resistors given by your TA. Save the four *.cti files in your directory.

1.2.4 Capacitor and Resistor Modeling

8. Open an ADS file for a large capacitor. Load the data from the corresponding axial capacitor. Save the file under a descriptive name corresponding to the axial cap value and type (e.g. 56pFaxial...) Plot the data on the same plot as the model. Remember, the graphs which you put in your lab notebook should be well-labeled either electronically or by hand.

9. Using markers on the graphs, record low ($<$ 2 MHz), high frequency (as high as possible and at least four times the series resonance) reactance values. Determine the series resonant frequency (zero reactance point) from the graph. From the low frequency value, calculate the model capacitance. From the series resonant frequency, calculate the lead inductance for the axial capacitor. Put the values into the model. Fine tune the model to get a good match with the *axial* capacitor. Note: a good match would be within 10 percent of measured value throughout all frequencies, and you may have to observe several vertical scales (can be changed on the graph y-axis) to verify.

10. Repeat the above two steps (data plotting, parasitic calculation) for the large chip, small axial, and small chip capacitors. Note: if the resonant frequency is not available, use high frequency reactance value and capacitance calculated at low frequency to calculate the lead inductance. (Any two points, if not too close, can be used to solve for parasitics as long as you can solve the two equations.) The chip capacitor may have a somewhat different capacitance value. Comment on the comparison between the effect of parasitics on the axial and chip capacitors.

11. Repeat data plotting, parasitic calculation for the small resistor. Resistance value is read from the low frequency resistance measurement. (Notice, the measured resistance drifts up for increasing frequency. This is likely due the fact that the chip resistor load is not a perfect calibration standard.) Explain why series inductance is sufficient for modeling parasitic effects for small resistors. Identify the series inductance from the high-frequency reactance values. Put the values into the model. Fine tune the model to get a good match with the *axial* resistor. Comment on the comparison with the small chip resistor.

12. Repeat data plotting, parasitic calculation for the large resistor. Resistance value is read from the low frequency resistance measurement. (Notice again, the measured resistance drifts up for increasing frequency. Again, calibration is at least partially responsible.) Explain why parallel capacitance is sufficient for modeling parasitic effects for large resistors. Identify the parallel capacitance from the high-frequency reactance values. Put the values into the model. Fine tune the model to get a good match with the *axial* resistor. Comment on the comparison with the large chip resistor.

1.2.5 Inductor Construction, Measurements, and Analysis

13. Each member of the group should construct a 2 μH inductor around an iron powder core specified by the TA. Refer to the Appendix A, equation A.7 and Table A.5.
14. If needed, calibrate the VNA with the jig. Measure and save the data (.cti in your directory on the network drive) for each of your group's toroid inductors. Repeat for the small 56 nH Coilcraft air-core inductor. Store the inductors carefully. You will need them later.
15. Open the ADS model for the Coilcraft inductor. Load the data for the 56 nH inductor and plot on the same plot as the model. Estimate inductance and capacitance using two points on the data curve. Identify which points you chose and explain why. Include the calculation in your notebook. Fine-tune the model to match the data. Does the measured inductance correspond to the nominal? Compare also the value to the value calculated by equation A.1 in Appendix A.
16. Open the ADS model for one of the toroid inductors. Load the data for one of your inductor and plot the on the same plot as the model. Record the parallel frequency. Estimate inductance and capacitance by calculating at two points on the data curve. Identify which points you chose and explain why. Include the calculation in your notebook. Fine-tune the model to match the data.
17. Repeat for the second torroidal inductor. Compare the inductance and capacitance values for your inductors. Comment on significance of the loss as measured by resistance values used to match the width of the resonance peak.

1.3 Procedures Required for Lab 1

1.3.1 One Port VNA Calibration for Impedance Measurement

The following procedure will be used to calibrate the E8357A VNA for one port impedance measurements using the 16092A Spring Clip Fixture:

1. Carefully connect the 16092A spring clip fixture to port 2.
2. Set the instrument to a known state using the green preset button on the instrument front panel.
3. Set the start and stop frequencies. Use the mouse to navigate through the following menus:
   [Channel][Start/Stop]
   Set the start frequency to 300 kHz and the stop frequency to 500 MHz.

4. Set the number of sample points. This will be the number of equally-spaced measurements recorded within the frequency range that was set in step 3.
   [Sweep][Number of Points]
   Select the desired number of sample points. We suggest a number between 201 points per sweep and 3201 points per sweep. Too many points will cause the sweep to take a long time to complete. (Make sure the trigger is set to continuous sweep.)

5. Select the measurement data that is displayed. In this case, since the impedance test fixture is connected to port 2 we will want to display "S22" (the scattering parameter that measures the response at port 2 due to an excitation at port 2):
   [Trace][Measure]
   Select "S22".

6. Change the format of the displayed data to a Smith Chart display:
   [Trace][Format]
   Select "Smith Chart".

7. Begin the calibration procedure:
   [Calibration][Calibration Wizard] will bring up a dialog box entitled "Calibration Wizard: Begin Calibration". Choose "UNGUIDED Calibration: Use Mechanical Standards". Be sure that the "Create New Cal Set" box is checked. Press NEXT - to bring up a dialog box entitled "Select Cal Set for Mechanical Standards". Press "Next" to move to the next dialog box entitled "Select Calibration Type for Mechanical Standards". Choose "1-PORT SOLT (or reflection on some NAs)". If the fixture is connected to port 2, make sure you are selecting port 2. Make sure that the box "View or Select Cal Kit" is selected. Press "Next" to bring up a dialog box entitled "Unguided Calibration: Select Cal Kit". Choose "16092A fixture". Press "Next" to bring up a box entitled "Measure Mechanical Standards".

8. Next, each of the three calibration standards (LOAD, OPEN, and SHORT) will be measured. It is important to use a 50 Ω chip resistor (the 49.9 Ω chip resistors available from the shop are adequate for this purpose) for the load calibration standard. If resistor with wire leads is used, the calibration will be inaccurate.

   (a) Measure the OPEN standard. Loosen the thumbscrew and slide the grounded conductor away from the center post so that there is no contact between the grounded conductor and the post. The space between the sliding grounded conductor and the post should be approximately equal to the width of your 50 Ω chip resistor. You want the capacitance between the center post and ground to be approximately what it will be when a chip component is installed in the fixture. Press [Measure].
   (b) Measure the SHORT standard. Slide the test fixture closed so that the grounded conductor touches the center post and tighten the thumbscrew. Make sure that the grounded conductor is touching the center post. Press [Measure].
   (c) Measure the LOAD (50 Ω) calibration standard: Insert the 50 Ω chip resistor between the ground conductor and the square post. Slide the grounded conductor to the right so that the resistor is pressed against the post and so that one of the contacts on the resistor makes a good connection with the square post and the other contact makes a good connection with ground. Make sure that the resistor is securely compressed between ground and the post. Tighten the thumbscrew. Press [Measure].

9. After all three calibration standards have been measured, press "Finish" to complete the calibration. You will be asked if you want to save an instrument state that points to this cal set. You can just say No.

Always verify your calibration by measuring the impedance of each standard after completing the calibration procedure. First, make sure that the calibration is being applied to the displayed data. Select the [Calibration] menu and make sure that the option “Correction ON/off” is checked. Now, measure the impedance of each calibration standard and verify that the measured data corresponds to a dot in the appropriate place on the Smith chart. If you do not know where the dots corresponding to OPEN, SHORT, and LOAD (50 Ω) should appear on a Smith Chart, then it’s time to review your ECE 450 notes. Little loops or wildly erratic traces are indicative of a bad calibration.

In the future you will be able to skip steps 1-9 if you do not require the highest possible precision from the VNA. Simply load the saved *.cst file. This will import the instrument state and calibration settings that you saved in step 9. You should always verify the calibration by measuring the LOAD, OPEN and SHORT standards. For high precision measurements, you should always calibrate before the measurement.

1.3.2 Plotting measured impedance data using ADS

Once you have good data on the VNA screen:

1. Save the data in a file:
   [File][Save As]
   Save as type “Citifile Data Data (Real.Imag) (*.cti)”.
2. Open ADS and either create a new project, or open the project that you would like to import the measured data into.
3. Open a Data Display window:
   [Window][New Data Display]
4. From the Data Display window menu bar:
5. [Tools][Data File Tool...]
   Input File Name: (your citifile name)
   File Format to read: Citifile
   Dataset name: (enter a descriptive name, e.g. inductor_dataset or somesuch...)

   Press “Read File”. Your datset name should show up under the “Datasets” list.
6. Select the Smith Chart icon and drag a new Smith Chart to the data display page. A dialog box entitled “Plot Traces & Attributes” will pop up. You will see three items in the list of data objects: freq, S, S(2,2). Select “S” and press “>>Add>>”. Press “OK”. The Smith Chart plot should now match the display that you had on the VNA when the data was saved.
7. To real/imag or mag/phase of impedance, place an equation on the page: Z=stoz(S,50). This equation transforms the scattering parameter data to impedance format.
8. Place a rectangular plot on the page (or a dual rectangular plot) and select “Equations” from the drop-down menu in the “Plot Traces & Attributes” dialog box. Select “Z” and “>>Add>>” it to the list of traces. When you press “>>Add>>” a dialog will allow you to choose Real, Imag, Mag, or Phase...