ECE 404L: RF ELECTRONICS LABORATORY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

MICHIGAN STATE UNIVERSITY

I. **TITLE:** Lab VI - Measurement of Passive Elements Using a Network Analyzer

II. PURPOSE:

Spectrum analyzers allow visualization of only the magnitude of RF signals. The network analyzer gives both magnitude and phase information. With the network analyzer, RF components can be measured at very high frequencies.

Resistors, capacitors and inductors have limitations at high frequencies. Models of these elements, in reality, are made up of all three elements which will resonate. With the network analyzer, this resonant frequency can be found and the upper useable frequency of any component can be identified.

The concepts covered are:

1. Phase plane adjustments;
2. Equivalent circuit of a resistor;
3. Equivalent circuit of a capacitor;
4. Equivalent circuit of an inductor;
5. Formula for winding an inductor.

The laboratory techniques covered are:

1. Calibrating the network analyzer;
2. De-embedding the test fixture;
3. Measuring the reflection coefficient;
4. Extracting impedance versus frequency.

III. BACKGROUND MATERIAL:

A) HP4396B Network Analyzer

The network analyzer measures signal amplitude and phase verses frequency. By using the network analyzer, high frequency verification of electronic component behavior is possible. A simplified block diagram of the network analyzer is shown in Fig. 1.

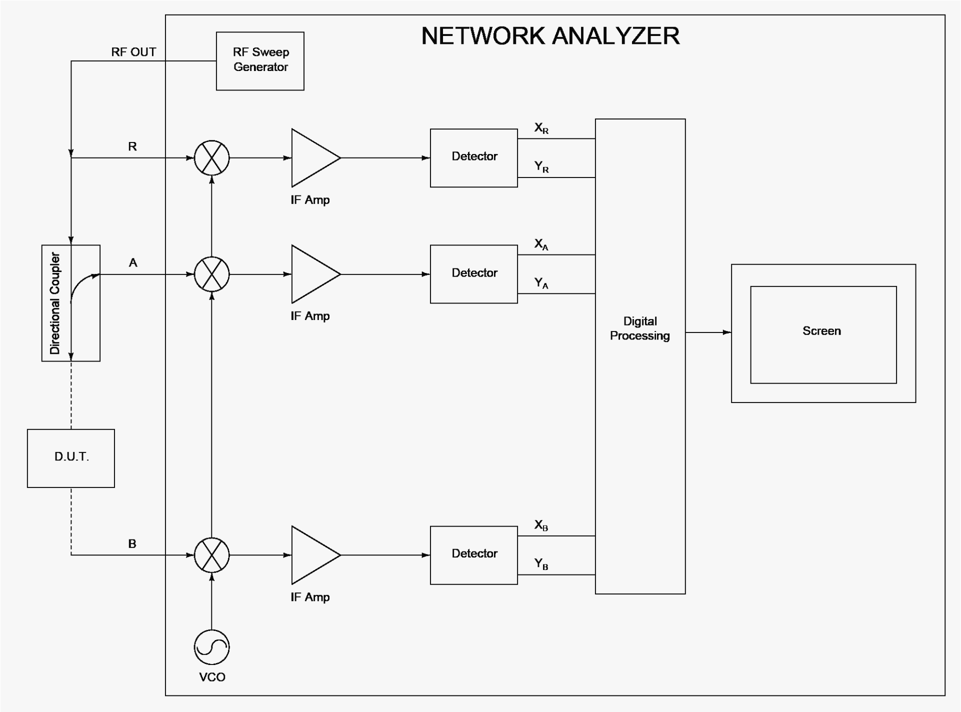

Figure 1. A three receiver network analyzer setup to measure S_{11} and S_{21}.

The 4396B network analyzer contains three superheterodyne receivers to detect the R (reference), A (reflection), and B (transmission) inputs. The detectors at the end of the superheterodyne receivers demodulate the inputs into real and imaginary components, X + jY, which contain magnitude and phase information. The RF output port of the 4369B is a sweep generator which sweeps all frequencies in the range that is being measured.

To make measurements, external equipment has to be used along with the 4369B. In the setup shown in Fig. 1, the external directional coupler allows the network analyzer to perform S_{11} and S_{21} measurements of the device under test (DUT). To measure S_{22} and S_{12}, the DUT connections are reversed. To ease S parameter measurements, the 85046A S-parameter test set contains directional couplers and switches to automatically do a full two-port measurement.

B) Port Extensions

Every time the network analyzer is turned on, or frequency settings are changed, a calibration must be done. Shorted, opened and matched load terminations are used to calibrate the network analyzer. Once the calibration is done, measurements can proceed at the phase plane or at the connector terminations. Usually the phase plane is changed as shown in Fig. 2.

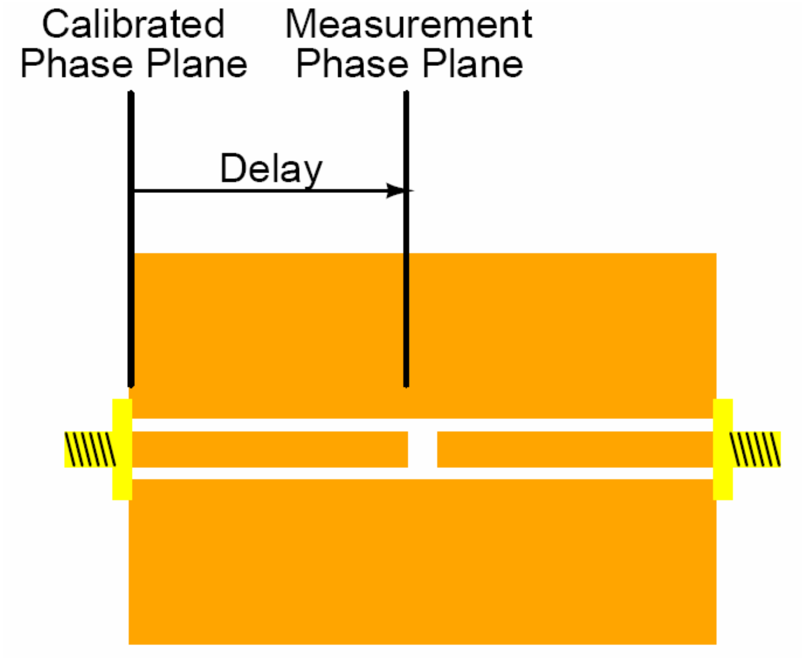

Figure 2. Adjusting the phase plane on a microstrip test fixture.

To change the phase plane, a time delay can be programmed into the network analyzer. When using a test fixture, de-embedding is used to move the point of measurement to where component leads are placed. There are numerous and complicated ways of performing de-embedding but one of the simpler ways is by using the Port Extension Option on the network analyzer. The port extension option changes the phase plane for all frequencies being measured. It is similar to using a slotted line. Port extensions allows the operator of the network analyzer to move the point of detection anywhere along a transmission line. Since the test fixture being used is made of several transmission lines, the port extension option will eliminate time delay measurement errors.

In this lab, we are going to measure an impedance, Z, connected to the microstrip line of Fig. 2 which is a transmission line consisting of a strip conductor and a ground plane separated by a dielectric medium. Once properly set up, as described above, the network analyzer will measure S_{11} which for a one-port corresponds to Γ_o. The relationship between Γ_o and Z is given in Eqns. 1 and 2.

$$\Gamma_o = \frac{Z - Z_o}{Z + Z_o} \tag{1}$$

$$Z = Z_o \frac{1 + \Gamma_o}{1 - \Gamma_o} \tag{2}$$

where

Z_o = characteristic impedance of the transmission line,
Z = terminating impedance.

C) Passive Elements

The network analyzer is used to accurately measure electronic components and systems of components. Every component behaves nonlinearly with respect to frequency. Resistors, capacitors and inductors each have a high frequency cutoff, that is, a point where they will resonate. A circuit model for a resistor is shown in Fig. 3 and a plot of the impedance versus frequency is shown in Fig. 4.

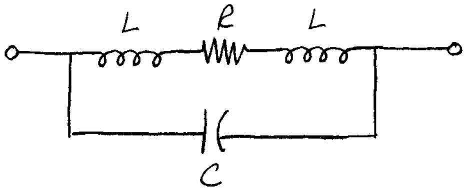

Figure 3. Equivalent circuit for a resistor.

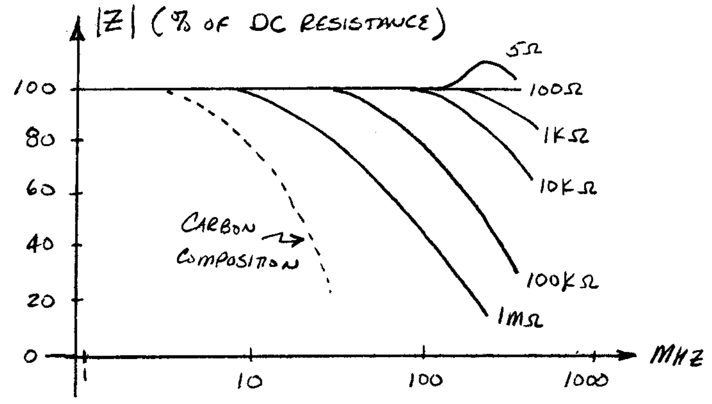

Figure 4. Impedance of a metal film resistor verses frequency.

At high frequencies, the resistor does not perform as a resistor anymore. For large values of resistance, the model in Fig. 3 is dominated by the parallel combination of R and C with the impedance of L being negligible. For low values of resistance, the model in Fig. 3 is dominated by the parallel combination of L and C with the resistance being negligible. This has a resonant frequency which can result in the maximum impedance exceeding the value of R as shown in Fig. 4. The formula for one lead inductance is given in Eqn. 3.

$$L = 2\,\ell\left[2.3\log\left(\frac{4\ell}{d}-0.75\right)\right] \tag{3}$$

where

d = Diameter of the wire in cm. and for a gauge of x is equal to $2.54(10^{-3}) \bullet 2^{[50\text{ AWG} - x\text{ AWG}]/6}$
ℓ = Length of one lead in cm.
L = Inductance of one lead in nH.

A circuit model for a capacitor is shown in Fig. 5. Likewise at high frequencies, the capacitor does not perform as a capacitor anymore. The dominating terms are the effective series resistance (ESR) and the total lead inductance (L).

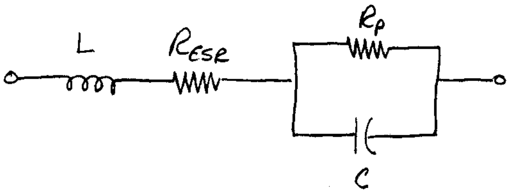

Figure 5. Equivalent circuit for a capacitor.

At some frequency, all capacitors will series resonate with their lead inductance above which the capacitor turns into an inductor. Just below resonance, the capacitor's impedance value will change drastically. The Q of a capacitor is defined in Eqn. 4 below.

$$Q = \frac{X_C}{R_{ESR}} \tag{4}$$

Ideally, the Q of a capacitor should be infinity but in reality the nonzero value of the R_{ESR} makes Q finite. With a finite Q, the point of resonance for the capacitor is broadened making the capacitor's impedance value change further away from resonance as shown in Fig. 6.

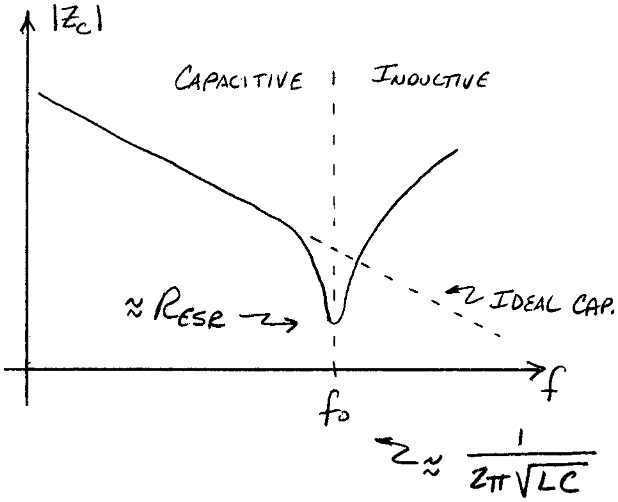

Figure 6. Impedance of a capacitor verses frequency.

Inductors are also non-ideal, the equivalent circuit for an inductor is shown in Fig. 7.

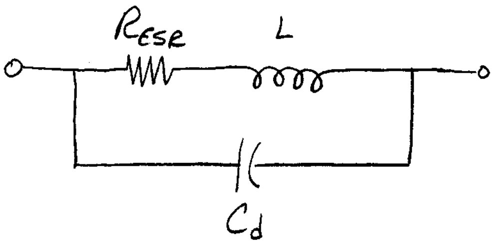

Figure 7. Equivalent circuit for an inductor.

The inductance will parallel resonate with its parasitic capacitance C_d. Just below resonance, the inductor's impedance value significantly changes and above resonance the inductor turns into a capacitor. The Q of an inductor is defined in Eqn. 5.

$$Q = \frac{X_L}{R_{ESR}} \tag{5}$$

Because the inductor has finite Q, its point of resonance will have a bandwidth and thus the inductor impedance value will change as frequency approaches resonance as shown in Fig. 8.

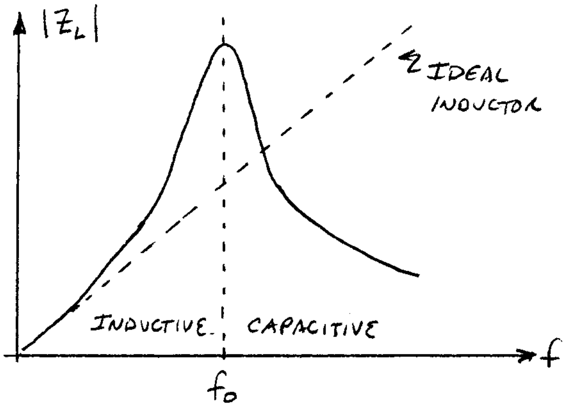

Figure 8. Reactance of an inductor verses frequency.

In lab, we will wind our own inductors by using the equation for an air core inductor shown below.

$$L = \frac{0.394\, r^2\, N^2}{9\, r + 10\, \ell} \qquad \textbf{(6)}$$

where

r = Coil radius in cm.
N = Number of turns
ℓ = Coil length in cm. provided that $\ell \geq 0.67r$
L = Inductance in μH.

D) Pre-Lab Report

Before coming to lab, meet with your lab partner and calculate the number of turns N if r = 1/8" and l = 1/4" to make a 300 nH air core inductor. Make two copies of your calculations. Submit one derivation per group to the lab instructor at the beginning of lab. This pre-report will be graded as part of your Lab VI grade.

IV. EQUIPMENT REQUIRED:

1	Agilent 4396B Network Analyzer
1	Agilent 85064A/B S-Parameter Test Set
1	RF Test Fixture Measurement Board
1	SMA Calibration Kit

V. PARTS REQUIRED:

1	1.5" floppy disk
1	Metal Film Leaded Resistor (R_S) = 100 Ω
1	Leaded Ceramic Capacitor (C_S) = 68 pF
1	Spool of Varnished 22 AWG Copper Wire

VI. LABORATORY PROCEDURE:

A) Turning On and Calibrating the Network Analyzer

1. The 4396B should be set up to look like the photo shown in Fig.9. If not ask your instructor for help.

DO NOT ATTEMPT to make the connections shown in Fig. 9. A special torque wrench is need to make the cable connections to the S-Parameter Test Set. These cable connections cost $1000 each and can be easily damaged.

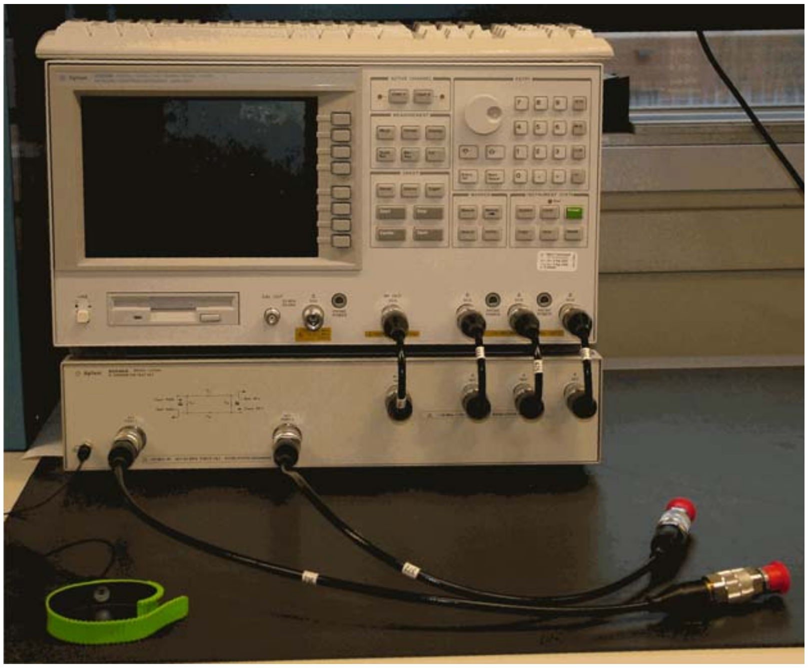

Figure 9. Network Analyzer and S-Parameter Test Set

Turn ON the 4396B power button located below the screen.

> **Caution**: The 4396B is static sensitive, so use the grounded wrist straps that are attached to the network analyzer.

2. Press the green **Preset** button, this will reset the network analyzer.

3. Select the frequency range to span from 10 MHz to 600 MHz.

   a. Press the **Start** button in the Sweep group.
   b. Type in **10** and then **M/μ** for a 10 MHz start frequency.
   c. Press the **Stop** button
   d. Type in **600** and then **M/μ** for a 600 MHz stop frequency.

4. The IF bandwidth for the network analyzer receivers must be set to 1KHz to make sure that components with large Qs can be measured.

   a. Press the **BW/Avg** button.
   b. Select the **IF BW** option on the screen.
   c. Type in **1KHz** using the keypad.
   d. Every measurement must be averaged to reduce noise.
   e. Select the **AVERAGING** option on the screen and make sure that **ON** is in upper case letters.

5. Before every calibration, which is every time the network analyzer is turned on, steps 1 through 4 must be done. There are many ways to calibrate a network analyzer, the approach used in this lab will be to have three standards, a 50 Ω load, Short and Open as shown in Fig. 10.

Figure 10. SMA female calibration standards (50 Ω load, Short, Open)

Obtain the SMA (Sub-Miniature version A) female calibration standards (50 Ω load, Short, Open) from your instructor. The Open has an "O" written on its base. The Short has an "S" written on its base. The 50 Ω termination has a black underside base.

> **Caution**: The calibration standards are very fragile and expensive. Do not turn the standard to tighten it on the connector, turn the connector instead. Do not over tighten.

Obtain an SMA cable as shown in Fig. 11 to connect between the S-Parameter N-type cables and the calibration standards.

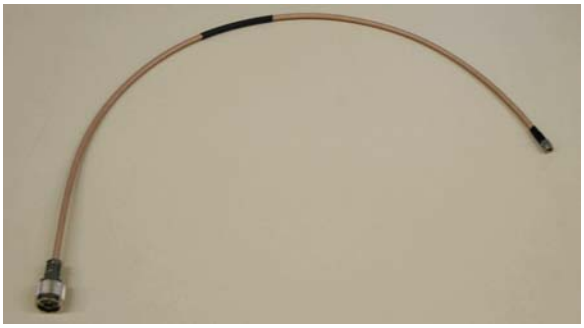

Figure 11. SMA cable

Make the cable connection to the Type N connector on Port 1, again by gently turning the cable connector. The next steps list how the calibration is done.

a. Press the **Cal** button in the Measurement group.
b. Select the **CAL KIT** [7mm] option.
c. Select the **N 50 Ω** option and then press **Return**.
d. Select **CALIBRATE MENU**
    1) Select **S_{11} 1-PORT**.
        a) Connect the open termination (which has an "O" written on its base) to the SMA male cable connected to Port 1 of the S-Parameter Test Set. Again, turn the connector instead of turning the termination.
        b) Select **OPENS**.
        c) Select **OPEN[F]**.
        d) After the measurement is done, the analyzer will beep. Select **DONE OPENS**.
        e) Remove the open and connect the short circuit termination. There has an "S" written on its base.
        f) Select **SHORTS**.
        g) Select **SHORT[F]**.
        h) After the measurement is done, select **DONE SHORTS**.
        i) Remove the short circuit termination and connect the 50 Ω termination which has a black underside base.
        j) Select **LOAD**.
        k) After the measurement is done, select **DONE 1-PORT CAL**.
        l) Remove the 50 Ω termination and put all of the terminations back into the calibration kit.

6. The network analyzer is now calibrated. The calibration is good as long as the frequencies being measured stay within the start and stop

frequency range of the calibration and the IF bandwidth is greater than when calibrated.

B) De-Embedding the Test Fixture

1. This is a two week lab. When time runs out for the first week, go to section F) and G). Pick up where you left off the following week.

Obtain an RF measurement board and go to a soldering station in the ECE 404 lab. Solder a short circuit to the end of one of the one inch long transmission lines and surrounding large copper fills as shown in Fig. 12. The center copper strip should be soldered to the larger copper sections on both sides of the center copper strip. Be careful so that you don't short the next transmission line.

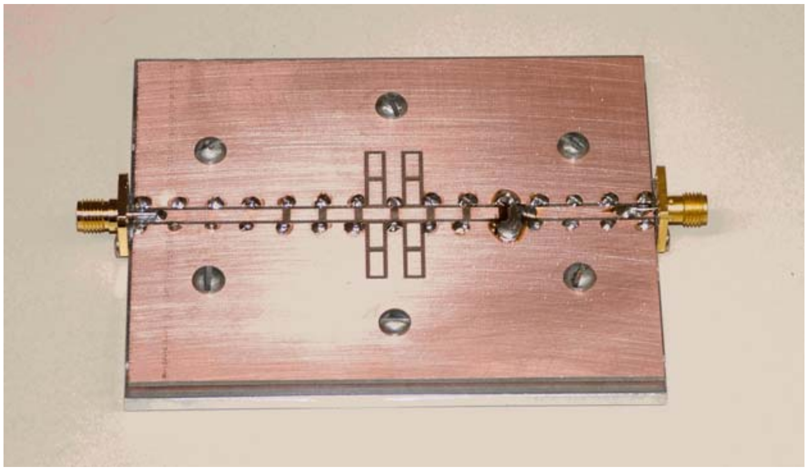

Figure 12. RF measurement test fixture with a short soldered

Connect port one of the network analyzer to the RF measurement board with the short at the end of its transmission line by gently turning the cable connector.

2. Currently the network analyzer thinks that measurements are taken at the end of the cables where the calibration standards were connected. The measurement board that is used contains a microstrip transmission line. By using the port extension option of the network analyzer, the point where measurements can be taken is shifted along the transmission line of the measurement board. The port extension option requires knowledge of the length of the transmission line that is being corrected.

To know the exact transmission line length is very difficult to determine. An approach to not needing to know the transmission line length is to short the end of the transmission line and adjust the port extension until all measurement points show as a dot on the left of the Smith Chart which corresponds to zero resistance.

Once the proper port extension length is found, the measurement fixture is de-embedded from the measurement. As a note, using port extensions for de-embedding can only be used when the measurement fixture represents a transmission line.

3. Port extensions will now be added to compensate for the measurement board.

   a. First make sure the Smith Chart is showing on the display by pressing **Format** in the Measurement group and then selecting the **SMITH CHART** option on the screen.
   b. Press the **Cal** button
   c. Select the **MORE** option
      1) Select **PORT EXTENSIONS**
         a) Select **PORT EXTENSION ON**
         b) Select **EXTENSION PORT 1**
         c) Now add 200 ps for the port extension delay, which will have to be keyed in as 0.200 ns.
         d) If more delay needs to be added to the port extension, do this by turning the dial next to the keypad clockwise until all data points are located on the left side of the Smith Chart which corresponds to zero resistance.
   d. Record the final value of the port extension delay in the Lab Report.

C) Resistors at High Frequency

1. Disconnect the measurement board and go back to the soldering station in the ECE 404 lab. Un-solder the short circuit. Obtain from your lab instructor the metal film resistor Rs.

   Obtain a wire gauge from your lab instructor. Measure the wire gauge of Rs by trying to pass the diameter of the resistor lead through the smallest slot in the wire gauge without forcing it through. Record the value in the Lab Report.

   Bend the leads of the resistor close to the body as shown in Fig. 13. Bend the tips the resistor leads approximately 1/8" and solder to the end of the transmission line on the measurement board as shown in Fig. 13. Reconnect your wrist strap and reconnect your board to the network analyzer.

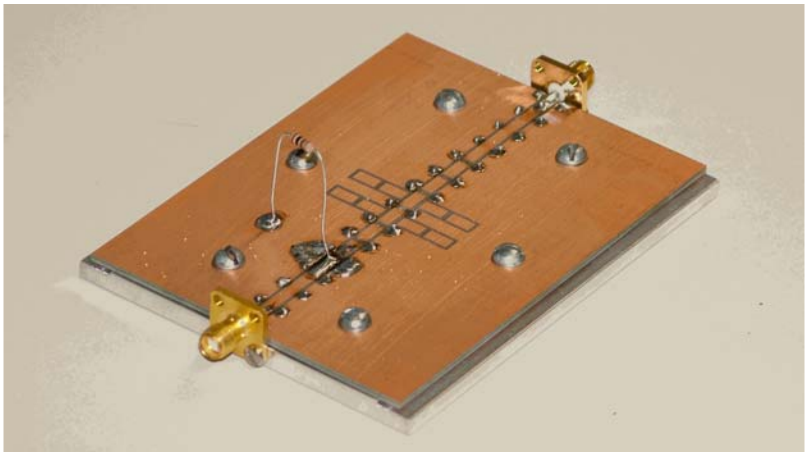

Figure 13. Soldering the resistor, with long leads, to the test fixture.

2.
- a. The resistor leads add inductance, to see the effect of inductance look at the phase of $S_{11} = \Gamma_o$.
  - 1) Press the **Format** key.
    - a) Select the **PHASE** option.
- b. Use the scaling options of the network analyzer to zoom into the data.
  - 1) Press the **Scale/Ref** button.
    - a) Select the **AUTOSCALE** option.
- c. The network analyzer also has marker options that allow easier visualization of data points. The marker will display the current value of any data point on the screen. The knob can be used to move markers anywhere along the data trace.
  - 1) Press the **Marker** button.
    - a) Rotate the knob to select different frequency data points.
    - b) Use the marker to figure out how the scales per division for the x- and y- axis are set. Comment in the Lab Report.
- d. As seen in Eqn. 1, if the impedance of the resistor is purely real then the phase of S_{11} should be zero since $Z = R_S > Z_o = 50\ \Omega$. In a parallel RLC circuit, the angle of the parallel impedance changes sign at resonance. This also causes the phase of S_{11} to change sign since Z_o is real. From the data of the phase of S_{11} displayed on the network analyzer, is there a frequency where the resistor has resonance?
- e. Print the screen onto a 1.5 inch floppy disk
  - 1) Insert a floppy disk into the network analyzer.
  - 2) Press the **Save** button.
    - a) Select the **GRAPHICS** option.
    - b) Type a file name on the keyboard which is sitting on the top of the network analyzer.
    - c) Hit Enter on the keyboard and the screen will be

saved to the floppy disk in TIFF format.

f. Select the Smith Chart format.
    1) Press the **Format** button.
        a) Select the **SMITH CHART** option on the screen.

g. At the top of the Smith Chart, the real and imaginary part of Z is calculated using Eqn. 2 (assuming Z_o = 50 Ω). If the imaginary part is positive then an equivalent inductance is calculated. By moving the marker, notice how the real part of R_S changes verses frequency. Print the Smith Chart to floppy disk.

h. By moving the marker to 10 MHz, record the real and imaginary part of the measured resistor as well as the equivalent inductance.

i. Measure the straight length of one lead. Using Eqn. 3, calculate the inductance of this one lead using your data from VI-C-1. Double this value and record as L_{Rs}. Using the calculated lead inductance, calculate the expected resonant frequency if the stray capacitance is 0.5 pF. Record.

j. Is there a frequency where the real part diverges by more than 10% from its 10 MHz measured value? If not what is the value at 600 MHz.

k. Using your 10 MHz value of the real part as a constant independent of frequency and the calculated value of total lead inductance from part i., calculate the impedance Z of your resistor in rectangular form at 300 MHz. Record in the Lab Report. Calculate S_{11} in polar form using Eqn. 1 with Z_o = 50 Ω and record.

l. Measure the magnitude and angle of S_{11} at 300 MHz. This should compare well with k. if not ask your instructor for help.
    1) Press the **Format** key.
        a) Select the **LIN MAG** option, read the value of the magnitude of S_{11} and record.
        b) Print to the linear magnitude screen to the floppy disk.
    2) Press the **Format** key.
        a) Select the **PHASE** option, read the value of the angle of S_{11} and record.

3. Disconnect the measurement board and go back to the soldering station. Un-solder your resistor. Reduce the resistor lead size and find frequency where the real part diverges by 10% from its 10 MHz measured value? Don’t forget to reconnect your wrist strap.

D) Capacitors at High Frequency

1. Obtain from your lab instructor the leaded ceramic capacitor C_S. Unsolder the resistor and solder C_S to the end of port one of the measurement board (with short leads).

a. Reset the averaging by pressing the BW/AVG button and selecting the Averaging Restart option. Repeat the Phase measurement of S_{11} to find resonance.
   1) At what frequency does resonance occur?
   2) Record the value at 10 MHz.
   3) Print the phase screen to the floppy disk

b. Repeat the Linear Magnitude of S_{11} measurement.
   1) Record the value at 10 MHz.
   2) Print the linear magnitude screen to the floppy disk.

c. Repeat the Smith Chart measurement for capacitance.
   1) Record the capacitance at 10MHz. Calculate the magnitude and angle of S_{11} at 10 MHz. This should agree with the measured values in a. and b., if not ask your instructor for help.
   2) Where does the capacitance stray 10% from its 10 MHz value? This is roughly the upper useable frequency of the capacitor.
   3) Using the information given by the Smith Chart, find the capacitor Q at 10, 50, 100, 150 and 200 MHz.

E) Inductors at High Frequency

1. Wind an air core inductor using the number of turns calculated in the prelab (Use 22 AWG varnished wire and the smaller diameter shaft of the tuning tool as the winding block as shown in Fig. 14).

Figure 14. Winding an inductor.

2. Unsolder the ceramic capacitor and solder the inductor to the end of port one of the measurement board.
   a. Repeat the Phase measurement of S_{11} to find resonance.
      1) At what frequency does resonance occur?
      2) Record the value at 10 MHz.
      3) Print the phase screen to the floppy disk
   b. Repeat the Linear Magnitude of S_{11} measurement.
      1) Record the value at 10 MHz.
      2) Print the linear magnitude screen to the floppy disk.
   c. Repeat the Smith Chart measurement for inductance.
      1) Record the inductance at 10MHz. Calculate the magnitude and angle of S_{11} at 10 MHz. This should agree with the measured values in a. and b., if not ask your instructor for help.
      2) Where does the inductance stray 10% from its 10 MHz value? This is roughly the upper useable frequency of the inductor.
      3) Using the information given by the Smith Chart, find the inductor Q at 20, 40, 60, 80, 100 MHz.

F) Data on Floppy

Log onto the PC at your lab bench and insert your floppy disk into the disk drive. Cut and paste your files to your M: drive. Leave the blank floppy disc for the next lab group.

G) Clean up

Leave your last element soldered on the measurement board. Write your names on the copper side of the measurement board with a felt-tip pen and return the board to your instructor. You will use this board in more experiments. Place your used parts in the parts box of the radio with your name on it. Return the box on one of the storage drawer.

If you are the last ones to use the soldering station, turn off the soldering iron. Turn off all equipment and brush off your bench.

H) Lab Report

Finish your Lab Report at home. Add the following sections to end of the Lab Report.

1. Print all of the plots saved to disc and label the section number labeled on each plot.

2. Using your data in the Table VI-D-1-c-3, plot C, R_{ESR} and Q versus

frequency. You can use any software or even a piece of graph paper.

3. Using your data in the Table VI-E-2-c-3, plot L, R_{ESR} and Q versus frequency. You can use any software or even a piece of graph paper.

4. Are there any other plots or calculations that you feel would help you to better understand the principles of this experiment? Include them in this section.

5. Write a conclusion for this experiment.

This is due at your next lab meeting.

Lab Report

Lab VI - Measurement of Passive Elements Using a Network Analyzer

Name: . . . .

Partner: . . . .

Date: . . . .

Lab Section Number . . . .

Lab Station Number . . . .

Code of Ethics Declaration

All of the attached work was performed by our lab group as listed above. We did not obtain any information or data from any other group in this lab or any other lab section.

Signature . . . .

VI-B-3-d

Port Extension Delay = ________________

VI-C-1

Lead wire gauge = ________________

VI-C-2-c

____

____

____

____

VI-C-2-d

____

____

VI-C-2-h

Real Part of R_S = ________________

Imaginary Part of R_S = j ________________

L_{Rs} = ________________

VI-C-2-i

Straight length of one lead = ________________

Calculation of lead inductance. Record results below.

Calculated L_{Rs} = ________________

% Error = ________________

where % Error = {(Measured - Calculated) / (Calculated) } x 100%

Calculation of resonant frequency. Record results below

Calculated resonant frequency = ________________

VI-C-2-j

0.9 x Real Part of R_S (10 MHz) = ________________

1.1 x Real Part of R_S (10 MHz) = ________________

Frequency = ___________ or Real Part of R_S at 600 MHz = ________

VI-C-2-k

Calculation and results recorded below.

Z = ________________ + j ________________

Calculation and results recorded below.

$|S_{11}|$ = ________________

$\angle S_{11}$ = ________________

VI-C-2-l

$|S_{11}|$ = ________________

$\angle S_{11}$ = ________________

VI-C-3

Real Part of R_S at 10 MHz = ________________

Imaginary Part of R_S at 10 MHz = j ________________

L_{Rs} = ________________

0.9 x Real Part of R_S (10 MHz) = ________________

1.1 x Real Part of R_S (10 MHz) = ________________

Frequency / value at which either occurs = ________________________

VI-D-1-a

Resonant frequency = ________________

$\angle S_{11}$ @ 10 MHz = ________________

VI-D-1-b

$|S_{11}|$ @ 10 MHz = ________________

VI-D-1-c-1

C @ 10 MHz = ________________

Calculation and results recorded below.

$|S_{11}|$ @ 10 MHz = ________________

$\angle S_{11}$ @ 10 MHz = ________________

VI-D-1-c-2

0.9 x C (10 MHz) = ________________

1.1 x C (10 MHz) = ________________

Frequency / value at which either occurs = ________________________

VI-D-1-c-3

Frequency	10 MHz	50 MHz	100 MHz	150 MHz	200 MHz
X_C					
R_{ESR}					
Q					

VI-E-2-a

Resonant frequency = ________________

$\angle S_{11}$ @ 10 MHz = ________________

VI-E-2-b

$|S_{11}|$ @ 10 MHz = ________________

VI-E-2-c-1

L @ 10 MHz = ________________

Calculation and results recorded below.

$|S_{11}|$ = ________________

$\angle S_{11}$ = ________________

VI-E-2-c-2

0.9 x L (10 MHz) = ________________

1.1 x L (10 MHz) = ________________

Frequency / value at which either occurs = _________________________

VI-E-2-c-3

Frequency	20 MHz	40 MHz	60 MHz	80 MHz	100 MHz
X_L					
R_{ESR}					
Q					