Introduction to RF Measurement and Nonideal Components
The Vector Network Analyzer
UCSB - ECE145A/ECE218A – Winter 2007

Goals:

      (a) Introduction to the vector network analyzer and measurement
of S-parameters.

          1. Learn to calibrate the network analyzer. This will be described in the lab demo. (Note. Please treat the cal kit with respect. Don't leave the standards sitting on the bench. Return them to the box.)

          2. Understand the use of port extensions.

          3. Understand use of Smith Chart and rectangular displays

      (b) Observation of transmission line behavior in PCB layout.

      (c) Understanding non-ideal behavior of RF components.

Safety Precautions:

      (a) Observe static precautions when working with the network analyzer. Wear the wrist strap.

      (b) Never connect a network analyzer directly to a circuit carrying dc. Make sure your circuit is dc blocked, or you will destroy the NA.

Reading: Refer to HP 8751A Network Analyzer User's Guide (RBR and in lab - do not remove!)

Calibration of the NA: It should not be necessary to recalibrate unless a day or more has passed since the last cal or you have changed the frequency range (START, STOP). If you change the range, then the instrument must be calibrated again for the new range.

1. Set the required frequency range with the START, STOP Keys (Stimulus menu).
2. CAL menu. >MORE. Turn off PORT EXTENSIONS.
3. CAL menu. >Cal Kit > USER KIT [ECE_145] > RETURN.
4. Select Full 2 Port. Follow the sequence as prompted by the buttons, attaching the short, open and load standards sequentially.
5. CAUTION: DO NOT ROTATE THE BODY OF THE STANDARDS WHILE TIGHTENING THE CONNECTOR! THIS WEARS OUT THE CENTER PIN AND WRECKS THE STANDARD. THE KIT COSTS ABOUT $5000! AVOID OVERTIGHTENING - USE THE TORQUE WRENCH.
6. Skip the Isolation step.

Another tip: DON'T hit the PRESET green button. This erases the calibration!

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Part I
Non Ideal Component Behavior

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Reading: The Characteristics of Circuit Elements at High Frequencies. M. McWhorter, Chap. 1 of M. McWhorter, D. Scherer, H. Swain, EE344, High Frequency Laboratory, Stanford University, 1995. This is on the RBR electronic website.

You have been provided with a test board in your tool kit. It consists of an SMA launcher block and a short length of circuit board. The copper tape is designed for 50 ohm impedance (The width is approximately 0.185" for 50 ohms on Duroid with $\varepsilon r=2.3$). You will be using this test board throughout the quarter to characterize lumped components (resistors, capacitors, inductors) needed for your projects. The reason for measuring components is to enable you to have realistic and accurate models that can be used in the design and simulation of your circuits. **This greatly increases the likelihood that your project will work as expected.**

To measure components on the test board, you must extend the network analyzer reference plane (of port 1) to the board edge so that you will measure the S_{11} of the component without shifting the phase through the short length of 50Ω transmission line. Note that this does not change the basic calibration of the analyzer, but just shifts the reference plane. [1]

Procedure. FORMAT menu. Select Smith Chart. CAL menu > MORE > Port Extensions ON. Select port 1 extension. Use the rotary dial or keypad to enter delay. Attach the open circuit extension block and dial in the extra delay until S_{11} looks as much like a dot as you can get at the right side of the plot. Setting the reference place with the open board helps compensate for the fringe capacitance across the open end of the board. Then, your component measurements will not include this additional capacitance.

Include the results of the following tasks in your lab report:

1. Use the network analyzer to measure S_{11} between 5 MHz and 500 MHz (or higher) on a Smith Chart for the following components:

      a. 15 ohm chip resistor. Solder this resistor across the end of your test extension board (the one in your toolbox, not the open circuit standard board!) These are the same material and length as the short/open boards.

      b. 0.1 uF chip capacitor. Remove the resistor and replace with this capacitor.

      c. 0.1 uF leaded capacitor. Remove the chip capacitor and replace with the leaded cap. Keep leads as short as possible.

      d. 10 uH leaded inductor. Keep leads as short as possible.

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[1] "Port Extension is another mathematical adjustment that affects the data as though the measurement test ports were extended by a certain amount. It is commonly used to remove the delay of adapters or a fixture that is attached to the test port cables after a coaxial calibration is performed".

Refer to "*Importing Measured Data into ADS*" on the course website. Transfer your measured result for each sample into ADS so your measurement can be compared with an equivalent circuit model simulation.

2. *How does each component's behavior differ from the ideal element? Determine if possible a self-resonant frequency for the component.*

3. *Propose an equivalent circuit model for each component that could represent the measured behavior.* Refer to "*ADS Tutorial #1*" on the course web page. Use Agilent ADS to plot S_{11} and the magnitude/ phase or real/imaginary parts of the impedances of your modeled components and compare your modeled results with the measurement data.

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Part II
Transmission Lines

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Include the results of the following tasks in your lab report:

Prototyping board. Circuits in this lab will be constructed on rectangular pieces of single sided printed circuit board, typically 2" wide. The board material will be 0.062" thick duroid with a dielectric constant of approximately 2.3. The bottom side, or ground plane, is covered with copper. Circuits are constructed on the top side by interconnecting components with strips of copper foil. This portion of the lab explores the transmission line properties of these microstrip transmission lines.

1. Use LINECALC (a transmission line simulation tool included with Agilent ADS) to design a distributed transmission line stub that provides the following impedance at 500 MHz:
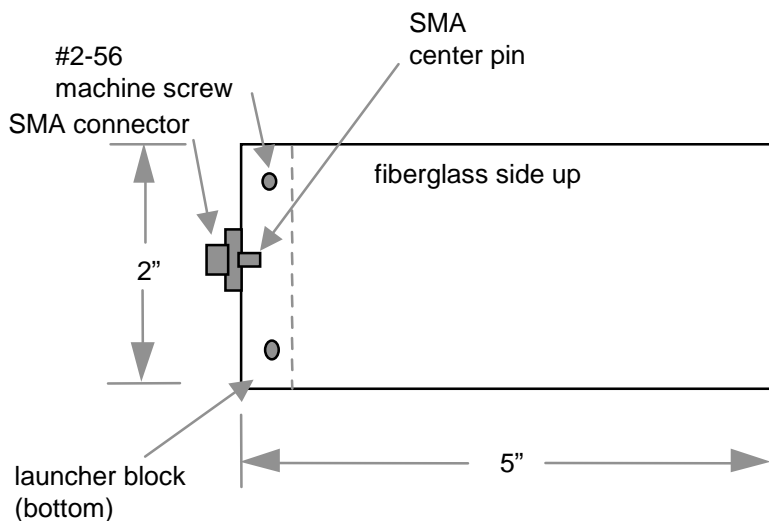   a) Capacitive reactance of – j60Ω.

Fig. 1. prototyping board

Build the stub using copper tape on the 0.062" thick duroid board material. Use an Exacto knife and copper tape to construct a microstrip line with the appropriate length and width. Taper one end and solder to one of the SMA connectors. Examples of open and shorted stubs are shown in Figs. 2 and 3.

Plot S_{11} on the Smith Chart from 50 (or130) to 1000 MHz and use markers to display the impedance at 500 MHz and at the frequencies corresponding to $\lambda/8$ and $\lambda/4$.

2. Next, build a 50 ohm through line between connector 1 and 2. Measure S21 magnitude and phase over the same frequency range.
Answer the following questions:

   a) Can you observe any loss on these lines?
   b) Determine the phase velocity, effective dielectric constant, and Zo for each test structure from your measurements.
   c) If there is disagreement between your design and measurement, propose an explanation. Perhaps simulation with Sonnet could lend some insight.
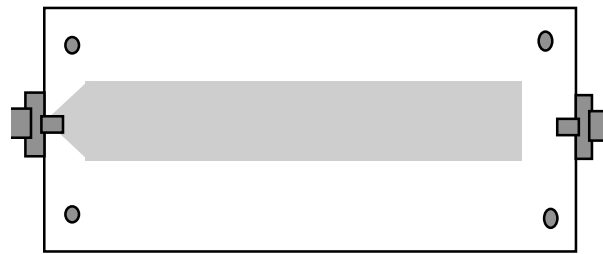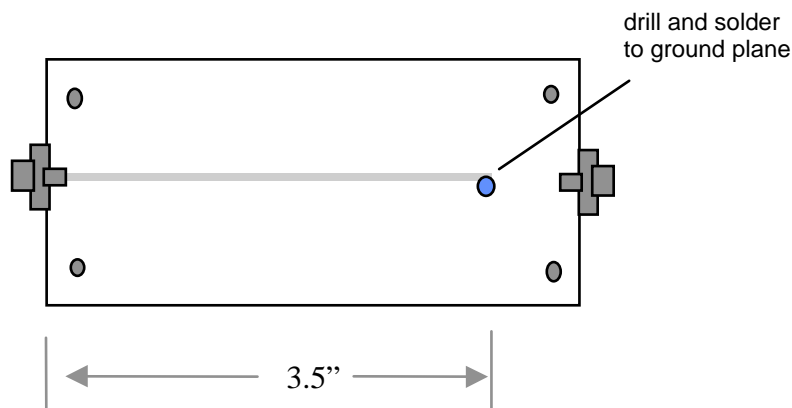
Fig. 2. Example: microstrip open-circuited stub.

drill and solder
to ground plane

3.5"

Fig. 3. Example: microstrip shorted stub.

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Part III
Impedance Matching

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1. <u>Quarter wave impedance transformer.</u> Design, build and evaluate a quarter-wave series microstrip line impedance transformer to match a shunt 15 ohm chip resistor to 50 ohms at 450 MHz. Use the layout shown in Fig. 3 to terminate the microstrip line. Measure and plot the magnitude and phase of S_{11} on rectangular plots with frequency swept from 50 (or 130) to 500 MHz. Place markers at 450 MHz and at the actual quarter wave frequency. Also plot VSWR over the same frequency range. This can be done on ADS.

     a) Over what frequency range are you able to keep the VSWR below 2.0?

     b). Compare simulation with measurement. If there is disagreement between your design and measurement, propose an explanation.

<u>Notebooks</u>. Use a 3 ring binder for your lab notebook. Number pages and date them as you insert them into your notebook. Include any pen plots or computer generated plots in your notebook.

<u>Report.</u> This is intended as an introduction to network analyzer measurement techniques and components. A report will be required, but need not be as detailed as the design project reports. A brief description of each measurement and plots of measured data compared with simulated designs or nonideal component models will be sufficient.

Parts List for Lab #1: Network Analyzer Measurements and Component Evaluation

2ea	2" x 5" x 0.062" DUROID PC board
1	0.1 uF leaded ceramic capacitor
1	10 uH leaded inductor
2 ea	6" lengths of wide (about 10mm) copper tape
2 ea	6" lengths of narrow (about 3mm) copper tape
1 ea	Male SMA + launcher block
1 ea	Female SMA + launcher block

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Two techniques for measuring Zo and vp of a transmission line.

1. Open Stub. Use the layout shown in Fig. 2 to create an open stub. Looking on the network analyzer at low frequencies, S11 should look like an open, at the right real axis of the Smith Chart, in this case at $\Gamma = 1 \angle 0^o$. Now, increase frequency until the phase changes by 90 degrees (180° clockwise rotation since the Smith Chart angle corresponds to $2\beta l$). At this frequency, the line is one quarter wavelength long.

The phase velocity can be determined from the physical length of the line. At this particular length l, and frequency ω, $2\beta l = \pi$. From the definition of $\beta = \omega/v_p$, the phase velocity can be obtained:

$$v_p = \frac{2\omega l}{\pi}$$

Zo can be obtained by measuring the reactive part of the impedance at half of the frequency above. At this $\lambda/8$ frequency, the impedance measured (neglecting losses – imaginary part) should be – jZo (open stub is recommended – lower unknown parasitics) because the impedance looking into an eighth-wave lossless open line is

$$jZ_{in} = -jZ_0 \cot(\pi/4).$$

2. Through line. When the frequency is set so that the phase of S21 is 180°, the line is one-half wavelength long. From the physical length, you can determine phase velocity. The magnitude of S21 gives the transmission loss.

At half that frequency, you have a quarter-wave line which will act as an impedance transformer, transforming the 50 ohm termination into a measured impedance Z_{in}. The transmission line characteristic impedance, Z_{line}, can be determined from the real part of S11 at that frequency. Given a Zo = 50 ohms for the network analyzer ports, the impedance looking into the quarter wave line, Z_{in}, is
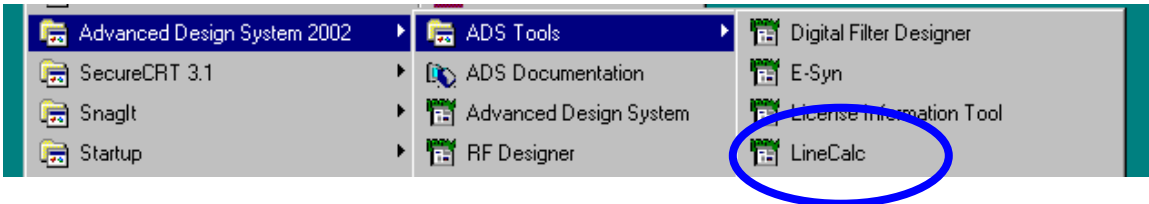
$$Z_{in} = Z_0 \frac{1 + \Gamma_{in}}{1 - \Gamma_{in}}$$

If the unknown line impedance Z_{line} is other than 50 ohms, Γin $\neq$ 0. Then,
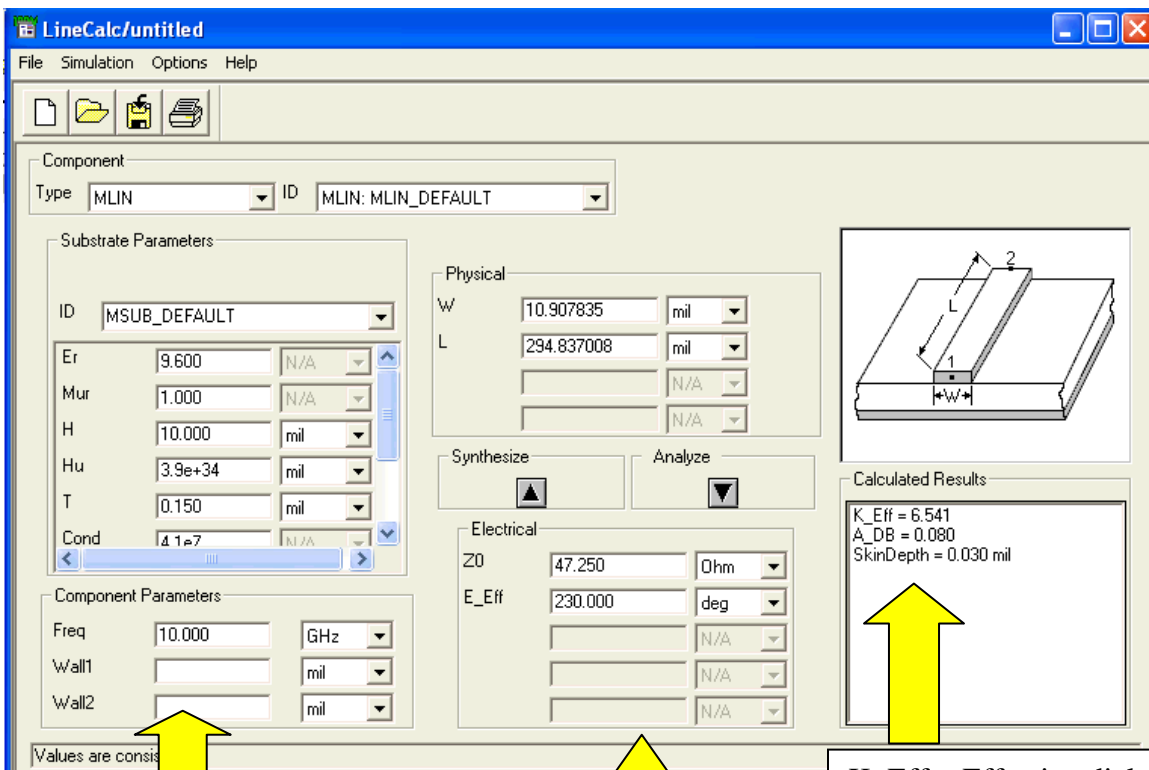
$$Z_{line} = \sqrt{Z_0 Z_{in}}.$$

LINECALC

To start LINECALC,

Select MLIN for the microstrip model.

Enter on the left:
relative dielectric constant, Er, (2.3 for Duroid)
board thickness, H, (62.5 mils)
Conductor thickness, T (use default)
Design frequency (used to calculate attenuation
A_DB and SkinDepth)

K_Eff = Effective dielectric constant
vp = c/sqrt(K_Eff)

Then choose either synthesize or analyze function giving either electrical or physical line specifications respectively. Electrical length (E_Eff) can be entered as either degrees or radians. E_Eff (degrees) = length in wavelengths * 360°