Lab Exercise T: TRL Calibration and Probe-Based Measurement

In this project, you will measure the full phase and magnitude S parameters of several surface mounted components. You will then develop circuit models for these components. To find these models, you need both magnitude and phase of the S parameters.

Prelab

Before coming to the lab complete Table 1 as directed below.

Overview

Figure 2.1 illustrates a surface mount component soldered on a printed circuit board (PCB). We want the S parameters of the component only with reference planes at its edges. However, there is a length of PCB and the connection from the network analyzer to the PCB that make up the fixture that supports the component. To remove the effects of the fixture from the measurement and move the reference planes to the component edges, we can use the TRL calibration technique.

These measurements will use the Agilent 5071B system because of its TRL calibration capability. You will use a probe system to precisely connect to the fixtured filters. The purpose of this exercise is to give you experience using the TRL calibration scheme and using a probe based measurements. The TRL calibration and the probe based measurement are really independent of each other. In other words, you could use a TRL calibration for measurements in a connectorized fixturing scheme, or you could use an SOLT calibration with a probe based measurement. For the purposes of this lab, you will use the TRL and probe together because it is easier to fabricate the TRL standards than SOLT standards for the probe based measurement. Probe based measurements are routinely used to measure microwave integrated circuits.

The probes are illustrated in Figure 2.1. They are GGB Picoprobes model 10 and consist of three 125 µm thick wires each sharpened to a point. Their center to center separation (pitch) is 1.0 mm. The two outer wires connect to the shield of the coax feed.
while the center wire connects to the coax center conductor, so the probe forms a ground- signal-ground connection. The probe (coax and G-S-G fingers) is lowered onto the fixture conductor using a microscope and micro-positioner. The TA will show you how to do this. These probe tips are \textit{VERY FRAGILE}. They are very easy to break. \textit{Do not touch the probe tips.}

The TRL calibration requires at least three standards as shown in Figure 2.2. They are the “THRU”, “REFLECT”, and “LINE”. All three consist of coplanar transmission lines. You can assume that the transmission lines on the standards have a characteristic impedance of 50Ω and that they have the same transverse dimensions as the transmission lines in the component fixtures. The length of the THRU sets the reference plane of the measurement. In this case the length of the THRU is set to 2L so that the reference plane is at the component edge. The REFLECT is just a short circuited coplanar line. The LINE standard is a length Δ longer that the Thru. You will have two LINE standards; choose the appropriate one to use for your measurement.

The particular characteristics of these standards are:

- Substrate, 1.27mm, $\varepsilon_r = 11.5$, Duroid 3010; (Manufacturer specifies $\varepsilon_r = 10.2$, but CPW behaves more like $\varepsilon_r = 11.5$; it may be anisotropic)
- CPW, gap = .63 mm, strip = 1.62mm;
- Distance from probe pattern to filter edge = L = 12.2 mm.

For the line impedance to be 50Ω the PCB must be sitting on top of a foam layer, and the foam layer should be sitting on top of an absorber layer (to damp stray resonances).

Plan to make measurements from 500 MHz to 2.5 GHz.

The Δ values of the LINE standard are given below. Before coming to the lab, finish filling out Table 1, by calculating the frequency range over which the line standards will give a valid calibration. The Δ in the LINE standard is chosen such that at the center of the frequency band, Δ corresponds to 90º of electrical length. At the lower end of the acceptable frequency band ($F_{\text{min}}$), Δ should be no less than 20º in electrical length. At the higher end ($F_{\text{max}}$), Δ should be no more than 160º. Calculate $F_{\text{min}}$ and $F_{\text{max}}$ for these limits and enter them in the table. Calculate the time delay associated with the two line standards and enter it in the table.

<table>
<thead>
<tr>
<th>Standard label</th>
<th>Standard type</th>
<th>Δ (mm)</th>
<th>$E_{\text{eff}}$</th>
<th>Delay (ns)</th>
<th>$F_{\text{min}}$(GHz)</th>
<th>$F_{\text{max}}$(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THRU</td>
<td>delay</td>
<td>0</td>
<td>5.5</td>
<td>0</td>
<td>0</td>
<td>999</td>
</tr>
<tr>
<td>SHORT</td>
<td>short</td>
<td>0</td>
<td>5.5</td>
<td>0</td>
<td>0</td>
<td>999</td>
</tr>
<tr>
<td>LINE1</td>
<td>delay</td>
<td>20.23</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LINE2</td>
<td>delay</td>
<td>6.62</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textit{Procedure}

1. Once you have calculated the band of operation of your standards, you will use those values to set up the vector network analyzer (VNA) for your TRL calibration. The Agilent 5071B has a built-in VBA macro that guides you through the entire calibration process. The TA will show you how to invoke and run this VBA macro.
2. Set the frequency range for the measurement that you will make. Use a linear sweep. Set the power level to -10 dBm or less in order to get accurate results (particularly important when measuring the short standard).

3. Follow the TA instructions to perform the TRL calibration. During the calibration, you will contact the probes with the line, reflect, thru standards illustrated in Figure 2.2. You can do the calibrations in any order. It’s a little more convenient to do the THRU cal last because after you implement the cal, you can check to see that the measurement of the THRU is a zero phase line with 0 dB of attenuation. You should check the short standard, also. It should have a magnitude within a few tenths of 0 dB and a phase of just under 180 degrees.

4. Measure the LINE standard again and record the phase delay at a few frequencies. Determine the effective dielectric constant of the CPW line. Record also the attenuation per mm at several frequencies. You may want to download the phase delay data to diskette in a CSV format.

5. Measure the 915 MHz filter and download the S parameters to diskette. Note especially the in-band loss. Use the attenuation you measured in step 4 above to estimate the in-band loss you would have measured if the calibration set the reference planes at the probe tips.

6. Measure the surface mount inductor (Figure 2.3) and download the S parameters to diskette. Look at the Smith Chart graph of S11 on the network analyzer and estimate the inductance.

7. Measure the surface mount capacitor (Figure 2.3) and download the S parameters to diskette. Look at the Smith Chart graph of S11 on the network analyzer and estimate the capacitance.
Figure 2.2 TRL calibration standards: (a) Thru, (b) Reflect, (c) Line
Circuit Modeling of Chip Components

After completing the lab, use the S parameter measurements to find a circuit model for the component between the reference planes shown in Figure 2.3. Note that the measurements you made of this structure may not be accurately modeled by a simple inductor or capacitor. There are complicated electromagnetic fields in these components and calling them an inductor or capacitor only describes their gross behavior. Suggested models for the two components you are measuring are shown in Figure 2.4. (C_b is not necessarily the same in both models.)

![Circuit Models](image)

**Figure 2.4** (a) A lumped element model of the measured inductor and (b) a model for the measured surface mount capacitor.

First find the lumped element model in Figure 2.4a. Do this by inputting your measured S parameters into a circuit simulator such as Serenade or ADS. Remove the taper from your measured results by putting negative lengths of transmission line on either side of the two port box representing your measured results. Estimate the
impedance $Z_{cpw}$ as being 50 ohms and the length to be a little less than $L_d/2$. Use the circuit simulator to convert the resulting S parameters to y parameters. Find expressions for $1/y_{21}$ in terms of $R$, $L$ and $C_a$. Choose values for these three elements so that your modeled $1/y_{21}$ matches the measured values. $R$ and $L$ will dominate at low frequencies; $C_a$ adds a correction for higher frequencies. You may actually see the “inductor” resonate at high frequencies and become capacitive. Plot on the same set of axes measured and modeled real and imaginary $y_{21}$ versus frequency. Compute the Q of the inductor versus frequency. Calculate $C_b$ by using $y_{11} + y_{21}$ or $y_{22} + y_{12}$. Do this at a few frequencies. $C_b$ should be the same independent of frequency if the model topology is correct. For the overall model (including the transmission lines modeling the taper) plot the measured and modeled $|S_{21}|$ versus frequency on the same axes. On a different set of axes, plot the phase of $S_{21}$ for the measured and modeled circuits. Do the same for the magnitude and phase of $S_{11}$.

Follow a similar procedure for modeling the capacitor.

**Report**

Use Serenade, ADS, or similar software tool, to determine the theoretical loss/mm and effective dielectric constant of the CPW line. Compare to what you measured.

Show the analysis you used to determine the model of the components in Figure 2.3 (as described above) and comment on quality of the models as shown by the plots you made above. Would adding some resistance in series with the capacitor improve the model?