Microwave Multiport Networks

In this lab you will characterize several different multiport microstrip and coaxial components using a network analyzer. Some of these components do not have a counterpart at low frequencies, while others have analogues in the low-frequency region. The purpose of this lab is to learn how to perform multiport network analysis, how to diagnose circuit functionality and how to evaluate the quality of your measurement.

**PART I – CALIBRATION**

We begin by performing a two-port 3.5mm SOLT (short-open-load-thru) calibration of the Agilent 8753ES network analyzer (refer to the analyzer instructions for details). Use a frequency range of 1 GHz to 6 GHz. This calibration consists of a one-port (or reflection) calibration for both ports, as well as a transmission calibration in which a "thru" standard is connected between ports 1 and 2 of the network analyzer. In this case, a "thru" is just a direct connection between the (male) connector at port 1 and the (female) connector at port 2. There is a third stage, called an isolation calibration, which can be omitted for purposes of this class. After you complete the calibration, check the calibration by observing all $S$-parameters when each of the calibration standards is connected. Save the calibration so that you can compare calibrated and uncalibrated measurements, while not having to repeat the calibration each time.

**PART II – TWO-PORT NETWORKS**

In this part of the lab, you will measure the performance of some two-port microstrip circuits using the network analyzer. Make plots of the relevant $S$-parameters in a frequency range you determine to be relevant, somewhere between 1 GHz and 6 GHz. It is up to you to choose which plots are relevant. (Including plots of all parameters in the lab can result in a reduced grade.)

**Q1:** Circuit #1 is a very simple two-port circuit. At what frequencies do the transmission and reflection coefficients have dips? Explain why: how long is the shorted stub at those frequencies? Measure the stub and, assuming the dielectric is 30 mils = 30 x 24.5µm thick, calculate the relative permittivity of the substrate. Use Eq.(1.42) in the notes. *Note:* This circuit was designed by a student to operate at 2.4 GHz, but the student did not know the permittivity of the substrate. Did he/she underestimate or overestimate the permittivity w.r.t. the real value?

The following circuits are various types of filters. For all of the circuits, when you discuss performance and comparisons, please pay attention to the following parameters:

1. What is the corner frequency?
2. How large is the insertion loss in the pass-band?
3. How large is the stop-band attenuation?
4. At what frequency does the stop band start?

You may need to state how you define the different parameters.
Q2: Circuit #2 is a low-pass filter? Explain how the circuit works based on physical principles and draw a simple equivalent lumped element circuit. Can you check if the circuit is lossless? Try calculating $|S_{11}|^2 + |S_{21}|^2$ at a frequency point – do you get close to unity? Remember that the $S$-parameters are defined w.r.t. voltage, i.e. the value in dB is $20 \log |S|$. Explain any errors in your measurement.

Compare uncalibrated and calibrated measurements for this circuit.

Q3: Turn calibration back on and measure Circuit #3. What is the functionality of Circuit #3, and how is it different from Circuit #2? Quantify in terms of (1) to (4) above and comment on the pass-band ripple. Draw the lumped-element low-frequency analogue of this circuit as well and compare to that of Circuit #2.

Q4: Measure Circuit #4 and explain its functionality. Save relevant S-parameters and evaluate criteria (1) to (4) from above. What is the lumped-element equivalent circuit and how would you obtain the equivalent lumped-element values? How is the circuit behavior different from that of a lumped-element equivalent?

Q5: Quantify the performance of Circuit #5 and compare it to Circuit #4.

Q6: Measure Circuit #6, explain its functionality and quantify all relevant parameters.

Q7: Circuit #7 is a bandpass filter. Explain how it is designed based on your knowledge of the previous circuits. Quantify all relevant parameters such as pass-band insertion loss, stop-band attenuation, bandwidth.

Q8: Circuit #8 is a coupled-line bandpass filter. Quantify all relevant parameters and compare it to Circuit #7.

Part III – Three-Port Networks

Q9: What is the function of Circuit #9? How many measurements do you need to perform to characterize this circuit? How symmetric is this circuit? Is it lossless? Is it matched? Using an ohmmeter and a coaxial BNC to SMA (3.5mm) adapter, measure the impedances of the matched loads to be connected to ports 2 and 3 (for port numbers refer to circuit labels). What impedance would be seen at port 1 with matched loads connected to ports 2 and 3 if the matching circuit were absent?

Attach the matched loads to ports 2 and 3, and make a plot of $S_{11}$ from 1 GHz to 6 GHz. What frequency is the matching circuit designed for? How big is the 10-dB (about 2:1 VSWR) bandwidth of the matching circuit? Note: the 10-dB bandwidth is defined as the difference between two frequency points on a response curve that are 10 dB below the maximum response amplitude (or above the minimum, as appropriate).
Q10: Remove the matched loads from ports 2 and 3, and connect the test port cables from the network analyzer to them. Place a matched load at port 1 of the circuit. Instead of splitting the power supplied to port 1 between ports 2 and 3, while maintaining a match at port 1, the circuit is now connected as a power combiner. Look at the magnitudes of $S$-parameters $S_{23}$ (the isolation), $S_{22}$ and $S_{33}$ (input match at each port) on the display. What should these $S$-parameters be if the circuit is to function well as a power combiner?

Q11: Connect ports 1 and 2 of the network analyzer to ports 1 and 2 of Circuit #9, and terminate port 3 of this circuit with SMA coaxial matched loads. Measure the transmission coefficient $S_{21}$ from port 1 to port 2. Based on your answers to Q9 and Q11, does the circuit work well in reverse, i.e., can it efficiently combine the power input at ports 2 and 3 for output at port 1?

Q12: Circuit #10 is a Wilkinson power divider. Measure this circuit as a three-port and quantify:
   a) Power division (coupling coefficient);
   b) Return loss (how well the circuit is matched);
   c) Isolation between ports 2 and 3;
   d) Insertion loss between input and coupled ports;
   e) Bandwidth;
   f) Relative phase between the two coupled ports.

PART IV – FOUR-PORT NETWORKS

Q13: Use the network analyzer to characterize Circuit #11, the four-port microstrip hybrid directional coupler (as studied in your prelab homework). Measure the $S$-parameters for this circuit between 1 GHz and 6 GHz. Make use of all the symmetries you can to reduce the number of plots. Include plots of the amplitudes in your notebook, and look at the phases on the network analyzer. What is the phase difference between $S_{21}$ and $S_{31}$ at the center frequency? Compare un-calibrated and calibrated measurements.

Q14: There are only two ports on the network analyzer. What do you do with the rest of the ports in the circuit while you are doing the measurement? Trick question: if you had no matched loads, could you still characterize the circuit, and if yes, what would you do?

Q15: At the operating frequency, how large is the through, coupled, reflected and isolated-port power assuming 1mW (0 dBm) incident at port 1?

Q16: Sketch the circuit and label the ports as they are labeled on the circuit. What are the relative phases of $S_{11}$, $S_{21}$, $S_{31}$ and $S_{41}$ at the design frequency? Does this agree with the analysis from your prelab?

Q17: How large is the 3-dB bandwidth of the coupler? What is the 10-dB bandwidth equal to?

Q18: Characterize Circuit #12 between 1 GHz and 6 GHz. Make use of all the symmetries you can to reduce the number of plots. Compare the performance to Circuit #11:
   - What are the relative phases of $S_{11}$, $S_{21}$, $S_{31}$ and $S_{41}$ at the design frequency?
   - How large is the 3-dB bandwidth of the coupler? What is the 10-dB bandwidth equal to?
**PART V – COAXIAL COMPONENTS**

In this part of the lab, you will characterize a few coaxial components. Set the network analyzer for a frequency range of 100MHz to 6 GHz. Perform a full two-port calibration. Circuit #13 is a coaxial directional coupler. Circuits #14 and #15 are unspecified components whose functions you will determine using the network analyzer.

**Q19:** What range of frequencies is circuit #13 designed for? What are its coupling factor and isolation?

**Q20:** What does circuit #14 do, and why do you think so?

**Q21:** What does circuit #15 do, and why do you think so? [Hint: Compare $S_{21}$ with $S_{12}$.]