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ECEN 5634
Lab 6 Report

Part II

Q1: We first measured the S-parameters of Circuit 1 (a shunt open stub). We found that S_{11} had a dip at 4.42 GHz, and S_{21} had a dip at 2.36 GHz. The dip in S_{11} occurs when the stub is half a wavelength long (or a multiple of half a wavelength), because then its impedance is the same on either end, which means the microstrip line "sees" a shunt open circuit, which is as if it is not there at all. The dip in S_{21} occurs when the stub is a quarter of a wavelength (or an odd multiple thereof), because then the stub looks like a short circuit to the microstrip, so the reflection coefficient is -1. If we calculate the length of the stub based on the dip in S_{21}, we get $l = \frac{c_0}{4f\sqrt{\varepsilon_r}} = \frac{3*10^8}{4*2.36*10^9\sqrt{4.4}} = 15.2\ mm$. If we calculate it based on the dip in S_{11}, we get $l = \frac{c_0}{2f\sqrt{\varepsilon_r}} = \frac{3*10^8}{2*4.42*10^9\sqrt{4.4}} = 16.2\ mm.$

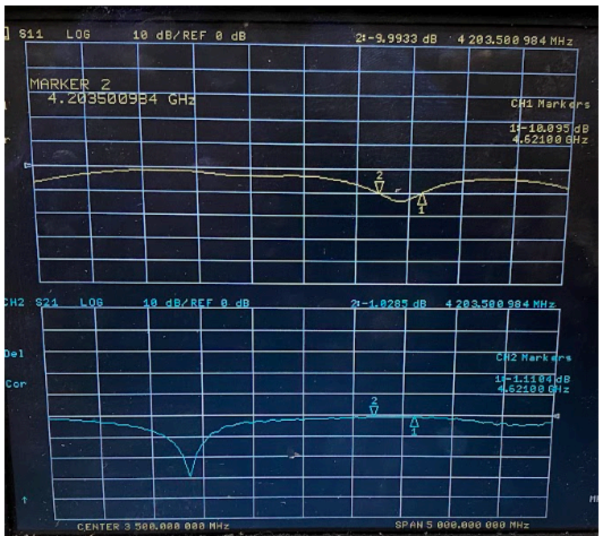

Figure 1: S-parameters of Circuit 1 measured by the VNA. Markers are at -10 dB.

Q2: The stepped-impedance low pass filter works because the low impedance (wider) sections act like shunt capacitors, and the high impedance (narrower) sections act like series inductors. Both of these lumped elements will block high frequency signals while allowing low frequencies to pass. The wider sections are like capacitors because there is an increased area of the top conductor, which increases the capacitance between it and the bottom conductor. This also explains why the impedance of the wider sections is lesser (since $Z_0 = \sqrt{\frac{L'}{C'}}$). The narrower sections are like inductors because the capacitance decreases, which is equivalent to the inductance increasing.

We checked that the circuit is lossless by calculating $||S_{11}||^2 + ||S_{21}||^2$ at a single frequency, where we measured $|S_{11}|$ = -0.1 dB = 0.989 and $|S_{21}|$ = -60 dB = 0.001. We calculated $||S_{11}||^2 + ||S_{21}||^2 = 0.978$, which is close to 1. It is not exactly 1 because the circuit is not ideal, there is resistance in the conductor and conductance in the dielectric that lead to losses.

Q3: Circuit 3 is also a stepped-impedance low pass filter. It has insertion loss $IL = 1\ dB$, corner frequency of 1.73 GHz, pass band width of 0.73 GHz, attenuation of -31 dB in the stop band, and design frequency at 1.13 GHz. It is different from Circuit 2 physically in that it has less extreme changes in the microstrip width (the narrower sections are less narrow and the wide sections are less wide compared to Circuit 2), and that its narrow and wide sections are not all the same (the center high impedance section is a little wider and longer than the others). Our measurements show that it has a lower insertion loss, is better matched at the design frequency, and has higher stop band attenuation. It also has a slightly lower design frequency and slightly higher corner frequency compared to Circuit 2.

Q4: Circuit 4 is a low pass filter implemented with shunt open stubs, and it has an insertion loss of 0.2 dB, a corner frequency of 3.94 GHz, a pass band range of 2.94 GHz, stop band attenuation of -50 dB, and design frequency of 2.05 GHz.

Q5: Circuit 6 is a high pass filter using shunt short stubs, and it has an insertion loss of 0.75 dB, a corner frequency of 1.91 GHz, pass band range of 4.09 GHz, attenuation in the stop band of -20.4 dB, and design frequency at 2.37 GHz.

Q6: We did not measure Circuit 7 with the VNA, but we noticed that it is a series combination of Circuits 4 and 6. Since it has both a high pass and low pass filter, we believe it is a band pass filter that likely has corner frequencies near those of Circuits 4 and 6 (1.91 GHz and 3.94 GHz).

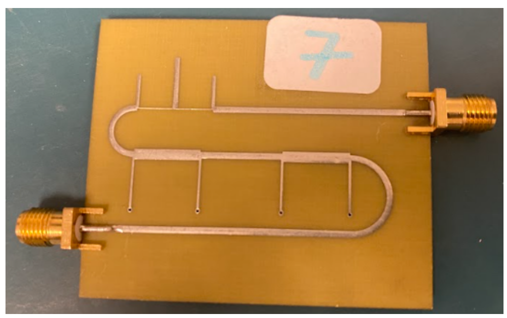

Figure 2: Circuit 7. The top section (open stubs) are the same as Circuit 4 (LPF), and the middle section (short stubs) are the same as Circuit 6 (HPF).

Circuit	Function	Insertion Loss (+dB)	Corner Frequency (GHz)	Pass Band Range (GHz)	Stop Band Attenuation (dB)	Design Frequency (GHz)
1	Band Pass	1	2.86, 5.42	0.41*	-27.5	4.42
2	Low Pass	3	1.69	0.69	-75	1.30
3	Low Pass	1	1.73	0.73	-31	1.13
4	Low Pass	0.2	3.94	2.94	-50	2.05
6	High Pass	0.75	1.91	4.09	-20.4	2.37

Table 1: Summary of Two-Port Network Parameters.

*Note that for every circuit, we defined pass band range as in the lab manual (between corner frequencies, or between corner frequency and maximum or minimum frequency of VNA) with the exception of Circuit 1. In this case, we used the -10 dB bandwidth on S_{11} since it was much smaller than the -3 dB bandwidth on S_{21}.

Part III

Q7: Circuit 9 is a 3 dB power splitter, which splits power incident at port 1 evenly between ports 2 and 3, or combines power from ports 2 and 3 into port 1. To fully characterize three-port networks, 9 measurements must be made (assuming that a single measurement of an S-parameter consists of both its magnitude and angle). This is because there are three rows and three columns in the scattering matrix, so there are a total of 9 complex S-parameters.

Q8: We first measured $|S_{11}|$. We found that this circuit is designed to operate at 3.19 GHz, and the 10-dB bandwidth is 2.8 GHz (2.71 GHz to 5.51 GHz).

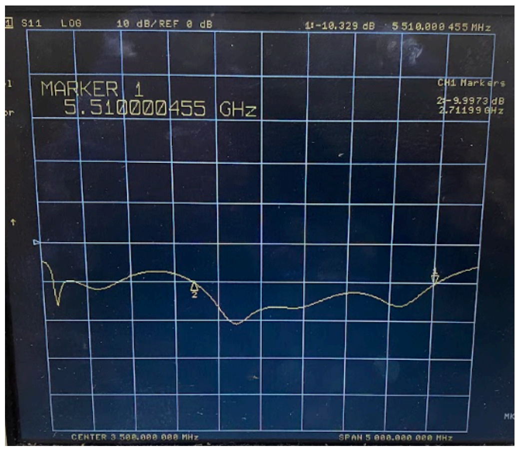

Figure 3: $|S_{11}|$ of Circuit 9, with markers at -10 dB.

Q9: We then measured the transmission coefficient from port 1 to port 2. We found that $|S_{21}|$ = -3.14 dB at its maximum and is around -3.3 dB at the design frequency. An ideal power splitter would have half of the power going into port 2 and half into port 3, which is -3 dB. This circuit is very close, so it does work well as a power splitter.

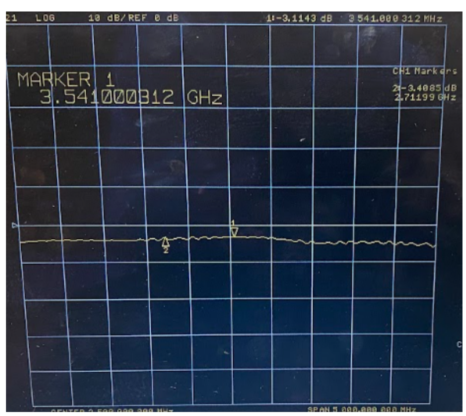

Figure 4: $|S_{21}|$ of Circuit 9.

Q10: We next connected the VNA to ports 2 and 3 to measure the isolation between the two ports and the reflection coefficient at each. We found that the transmission coefficient between ports 2 and 3 had a minimum magnitude of -10.9 dB, and a magnitude at the design frequency at about -7 dB. This circuit functions moderately well as a power combiner, since its isolation could be better. Some of the power from port 2 goes into port 3 (and vice versa) so it does not all go into a sum at port 1. Additionally, the matches on both ports 2 and 3 could be improved because then less of the incident power would be reflected at each input port.

This circuit is reciprocal, because when we switched the direction of the measurement on the VNA, we found that the S-parameter plots looked the same. It is also lossless (or very nearly there) because when we configured it as a power splitter, we found that almost close to half the power went into port 2. It is not matched, because although port 1 is well matched at the design frequency ($|S_{11}| < -20$ dB), the other two ports are not (at 3.19 GHz, $|S_{22}| = -6$ dB and $|S_{33}| = -5$ dB).

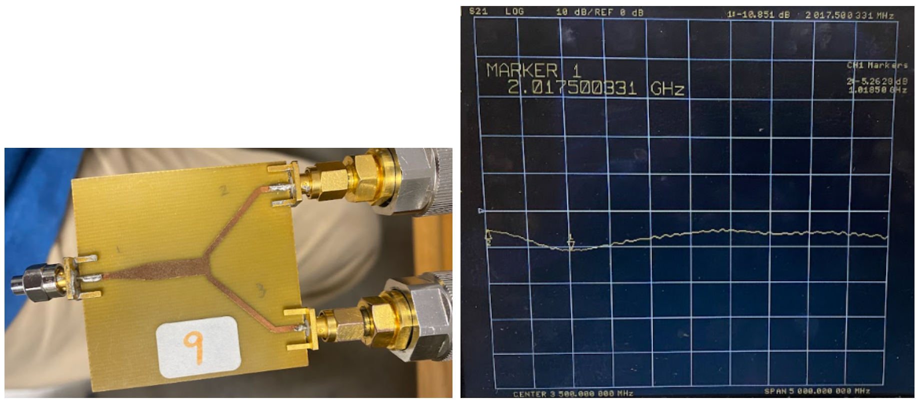

Figure 5: Circuit 9 with matched load at port 1 and VNA connected to ports 2 and 3 (left) and $|S_{32}|$ of Circuit 9 (right).

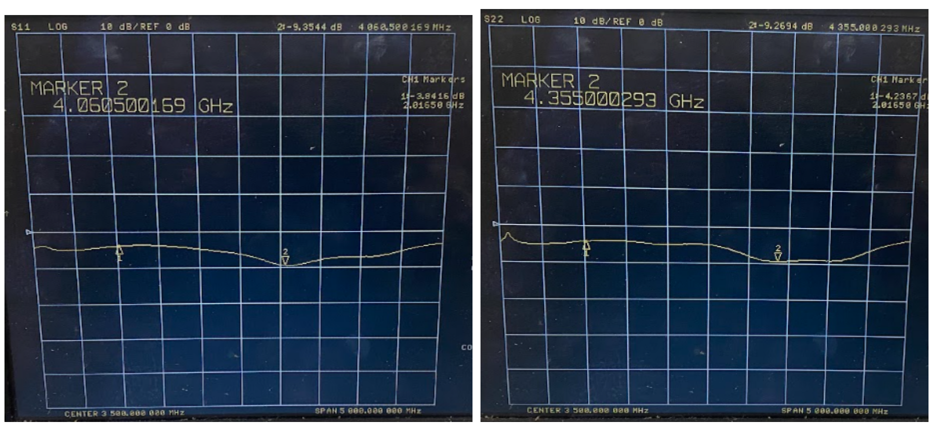

Figure 6: $|S_{22}|$ of Circuit 9 (left) and $|S_{33}|$ of Circuit 9 (right).

Part IV

Q13: To fully characterize a four-port network such as Circuit 11, 16 measurements are required. This is because the scattering matrix has four rows and four columns, so there are 16 S-parameters in total. This assumes that 1 measurement consists of both the real and imaginary part of S.

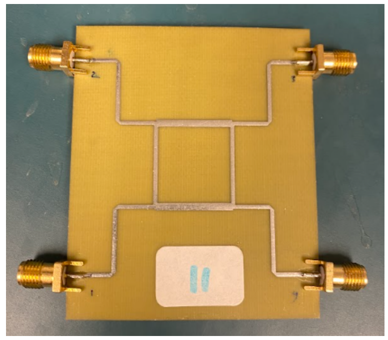

Figure 7: Circuit 11, a hybrid coupler.

Q14: While connecting the VNA to two of the ports of Circuit 11, we place matched loads on the other two ports. If we had no matched loads, we could still characterize the circuit, as long as we had known loads to place on the other ports, with at most one of these being an open or short. We would then measure the 2x2 scattering matrices of each configuration of two ports and renormalize these to the actual loads placed on the other ports. Once we did this for all connections of two ports, we would assemble the complete 4x4 scattering matrix and renormalize it back to 50 Ω to get the true S-parameters in standard form. This is the method described in “A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a 2-Port Network Analyzer” by John C. Tippet and Ross A. Speciale.

We assume that this network is symmetrical such that if we fed it at any port, the responses at the port on the same side, at the port directly across the circuit, and at the port diagonally across the circuit would be the same, so we only need to measure from port 1 to each of the other three ports.

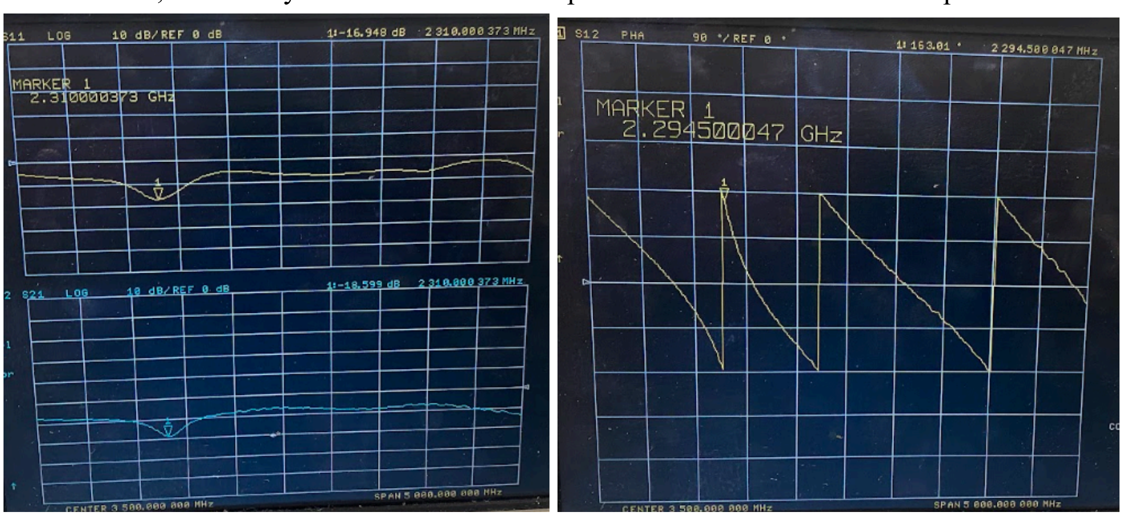

Figure 8: Circuit 11 S_{11} and S_{21} magnitude plots (left) and S_{21} phase plot (right).

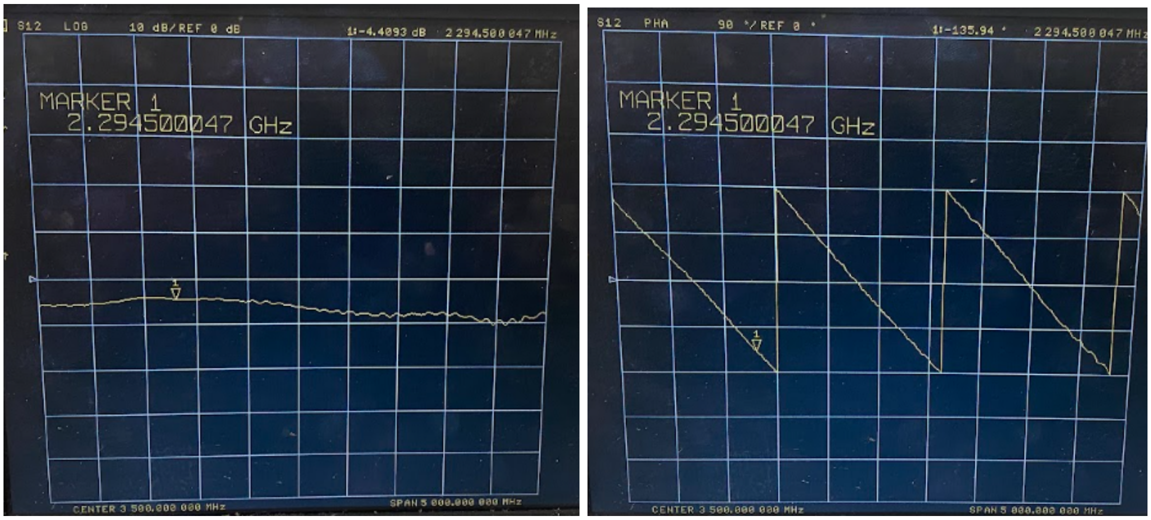

Figure 9: Circuit 11 and S_{13} magnitude plot (left) and S_{13} phase plot (right).

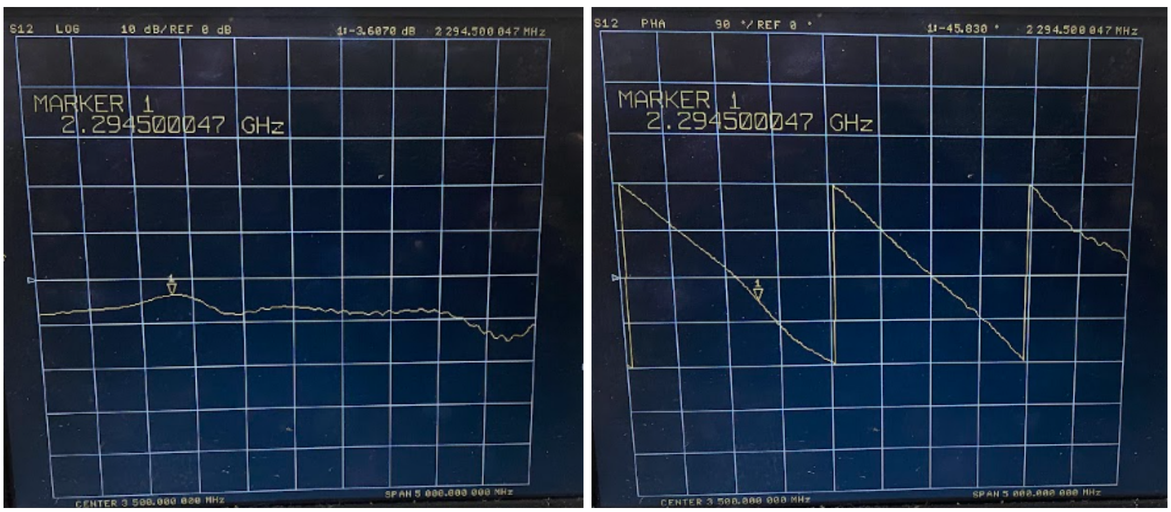

Figure 10: Circuit 11 and S_{14} magnitude plot (left) and S_{14} phase plot (right).

Q15: At the design frequency (2.3 GHz), the amplitudes are $|S_{11}|$ = -16.95 dB, $|S_{21}|$ = -18.60 dB, $|S_{31}|$ = -4.41 dB, and $|S_{41}|$ = -3.61 dB. As we expect, the power is split between ports 3 and 4. The phase difference between S_{12} and S_{13} is (163°-(-136°)) = 298°. The phase difference between S_{14} (through) and S_{13} (coupled) is (-45°-(-136°)) = 90°, which means that this is a quadrature hybrid coupler.

Q16: The 10-dB bandwidth is 0.799 GHz (from 1.886 GHz to 2.685 GHz).

Q17: Circuit 12 is a rat-race coupler. We know this because between ports 2 and 3 is a length of line 3x as long as those between the adjacent other ports. If the length between ports 1 and 2, for example, is a quarter wavelength, then between ports 2 and 3 will be three-quarters. Compared to Circuit 11, the power will still be evenly distributed between the coupled port and the through port, with the isolated port receiving close to 0, but the phases will be different due to the extra length of line. For a rat-race coupler, we expect a 180° phase difference between the coupled and through ports instead of 90°.

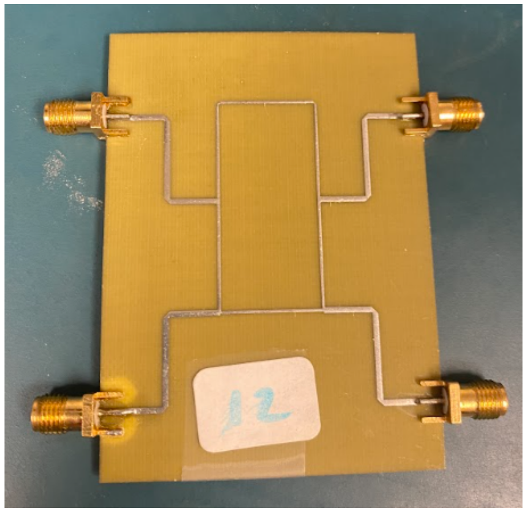

Figure 11: Circuit 12, a rat-race coupler.

Part V

Q18: Circuit 14 is a bandpass filter. We think this is the case because we found that the transmission coefficient sharply drops off at low frequencies and high frequencies, only allowing signals in a specific band to pass through. The design frequency is 2.1 GHz, the pass band is from 1.78 GHz to 3.20 GHz (1.42 GHz bandwidth), and the insertion loss is about 2 dB.

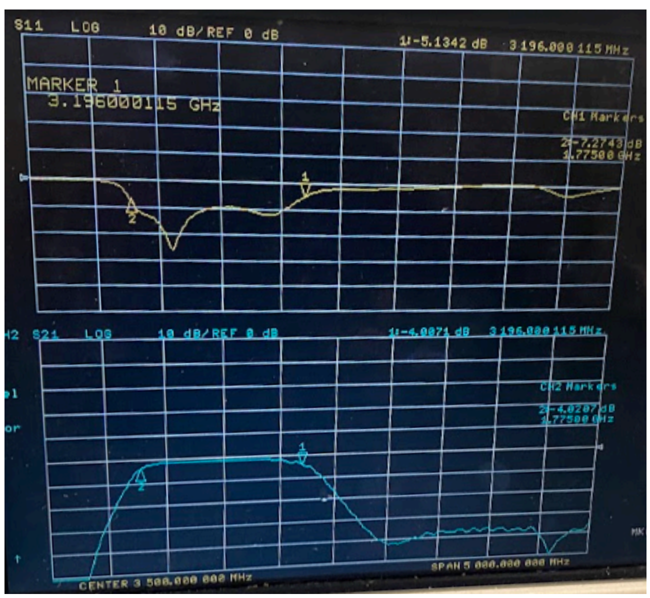

Figure 12: Circuit 14 S-parameters' magnitudes.