Lab 5

Lab Link: https://pages.hmc.edu/mspencer/e157/fa24/labs/05.pdf

GitHub with files and scripts: https://github.com/kavidey/e157/tree/main/lab_05

Theory Questions

1. Assume that you measure the S parameters of two antennas connected to the ports of a VNA. One is a well-characterized calibration antenna, so you know it's gain, Gcal. You know the distance between the antennas, r, the S-parameters and the frequencies they were measured at Sxx and ω, and the power level you've specified for the VNA, P1. Write a formula for the gain of the non-calibration antenna. You may not assume S11 or S22 are zero in this measurement, though they are small.

$$P_{RX} = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi r}\right)^2, \ \lambda = \frac{2\pi v}{\omega}$$

$$P_{RX} = P_1 G_{TX} G_{cal} \left(\frac{\lambda}{4\pi r}\right)^2$$

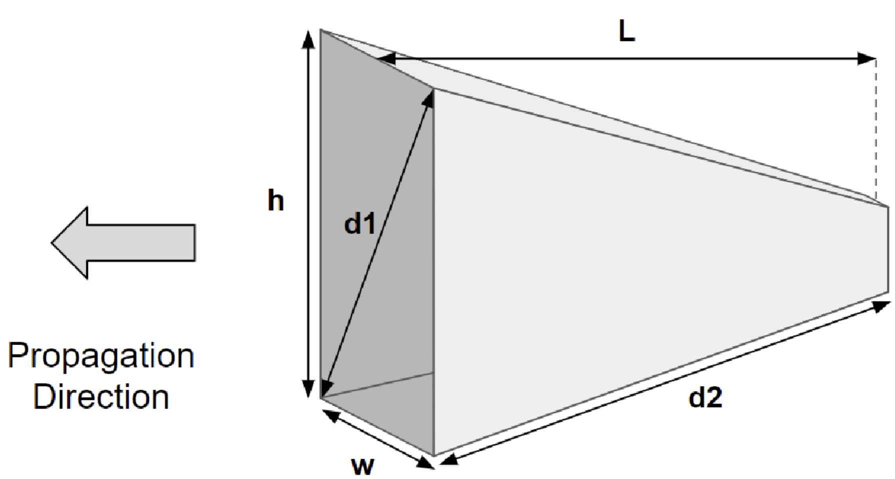
$$|S21|^2 = G_{TX} G_{cal} \left(\frac{\lambda}{4\pi r}\right)^2$$

$$G_{TX} = \frac{|S21|^2}{G_{cal}} \left(\frac{4\pi r}{\lambda}\right)^2$$

or in dB:

$$G_{TX} = S21 - G_{cal} - 20\log\left(\frac{\lambda}{4\pi r}\right)^2$$

2. What dimension of the antenna in Figure 1 would you use to calculate when it enters far field? What formula would you use to find when it enters far field?



The dimension D of the antenna is h. To calculate when the far field starts I would use:

$$\max\left(\frac{2D^2}{\lambda}, 10D, 10\lambda\right)$$

3. Find and read the datasheet for the BBHA9120LF Double Ridged Horn antenna, which is the calibration antenna in our chamber. What are the gain and VSWR of the antenna at 2.4GHz? Use these results to find is |S11| of the antenna at that frequency. http://www.schwarzbeck.de/en/antennas/broadband-horn-antennas/double-ridged-hornantenna/408-bbha-9120-lf-double-ridged-broadband-horn-antenna.html

   The antenna gain at 2.4 GHz is 12.49 dBi and the VSWR is around 1.5.

$$|S11|^2 = |\Gamma| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} = 0.2$$

$$\text{RL} = 20\log(S11) = -14\text{dB}$$

4. Read the specifications page for the PWTC 48-8 anechoic chamber. What are the maximum and minimum frequencies supported by the absorbers used in the chamber? Determine the frequency at which the test turntable leaves the far field of the calibration antenna. You will need to combine the size of the calibration antenna with the usable internal dimensions of the anechoic chamber to find this frequency. (Note: I think our chamber has a little extra room because of the deal we cut buying it, so make sure to re-measure when you get in lab.)

   https://web.archive.org/web/20191005160829/https://www.ramayes.com/Portable_Wireless_Test_Chambers.htm

   The chamber supports frequencies from 0.7 GHz to 50 GHz

GHz	.7	1	3	6	10	18	36
Absorption (dB)	25	30	37	45	50	50	50

   Separate from the absorbers, there is 100 dB Shielding Effectiveness from 14 KHz to 6 GHz.

   Assuming the distance between the test turntable and the calibration antenna is $x = 2m$ and $D = h = 185$ mm (the height of the antenna), we have the following equations.

   We need to calculate the far field boundaries described by each of the following equations

$$\max\left(\frac{2D^2}{\lambda}, 10D, 10\lambda\right)$$

   Equation 1

$$x = \frac{2D^2}{\lambda} = \frac{2D^2 f}{c}$$
$$f = \frac{xc}{2D^2}$$
$$f = \frac{2\text{ m} \cdot 3 \times 10^8 \text{ m/s}}{2D^2} = 8.7655 \text{ GHz}$$

   Equation 2 (hard limit)

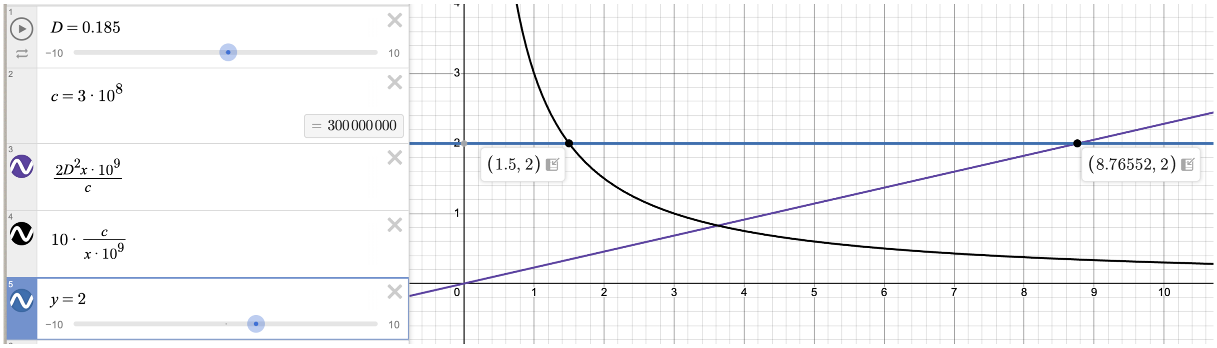
$$10D = 0.185 \text{ m} \cdot 10 = 1.85 \text{ m}$$

   Equation 3 (can go a bit below this)

$$x \leq 10\lambda = 10\frac{c}{f}$$
$$f \geq \frac{10c}{x}$$
$$f \geq \frac{10 \cdot 3 \times 10^8 \text{ m/s}}{2 \text{ m}} = 1.5 \text{ GHz}$$

The minimum frequency is around 1.5 GHz (but we can go a bit lower probably to 0.7 GHz)

The maximum frequency is 8.77 GHz



https://www.desmos.com/calculator/9fo6o1iflr, x axis is in GHz

Lab Notebook

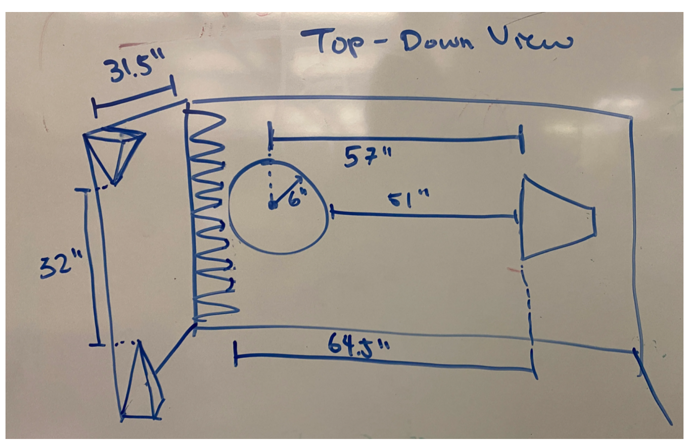
@November 11, 2024

Relevant device datasheets:

- https://web.archive.org/web/20191005160829/https://www.ramayes.com/Portable_Wireless_Test_Chambers.htm
- https://www.keysight.com/us/en/product/8753D/network-analyzer-30-khz-to-3-ghz.html
- http://www.schwarzbeck.de/en/antennas/broadband-horn-antennas/double-ridged-hornantenna/408-bbha-9120-lf-double-ridged-broadband-horn-antenna.html
- https://www.tp-link.com/us/support/download/tl-ant2409a/

1. Measure 2.4 GHz Antenna

Started by measuring the dimensions of the anechoic chamber:

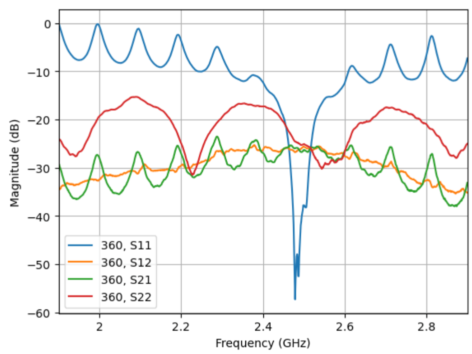


Using the math (+desmos plot) from theory question and the measured antenna dimensions, we calculated that the true frequency bounds are 2.07 GHz to 6.35 GHz.

Next we did a full 2-port calibration of the VNA and fixturing. Port 1 was connected through the left side of the chamber to a long SMA cable that we left inside. The end of that cable was attached to the AUT after calibration. Port 2 was connected through the right side of the chamber to a short SMA cable that connected to the receive horn after calibration.

To do the calibration, we followed the procedure on pg 277 of the user manual. We ran a "Full Two-Port Error Correction" with the *HP85033D: 3.5mmD* calibration kit selected. We did a full SOLT calibration, omitting the isolation calibration step. Power was set to -5 dBm and 801 points were captured across the a 1 GHz span from 1.9 GHz to 2.9 GHz. This is the same calibration procedure used in parts 2 and 3, with only the start and stop frequency changed.

With the antenna facing forward, we measured the following S parameters:



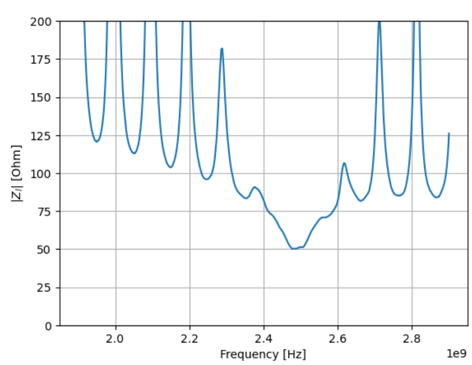
Note that the mismatch between S12 and S21 which in theory should perfectly overlap is due to impedance mismatches between the tplink antenna and VNA. Notice how S21 and S12 do overlap around the 2.4-2.5 GHz region where the impedance is well matched and the antenna is intended to be used.

We can calculate the magnitude of the input impedance from S11 (return loss) using:

$$RL = 20\log_{10}(|\Gamma|) \implies |\Gamma| = 10^{RL/20}$$

$$\Gamma = \frac{Z_l - Z_0}{Z_l + Z_0} \implies Z_l = Z_0\frac{1+\Gamma}{1-\Gamma}$$

Which gives the following plot:

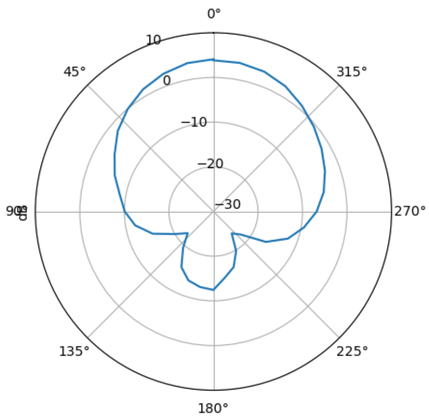


The impedance matching around 2.5 GHz is very good, but it quickly explodes to a much higher input impedance at other frequencies.

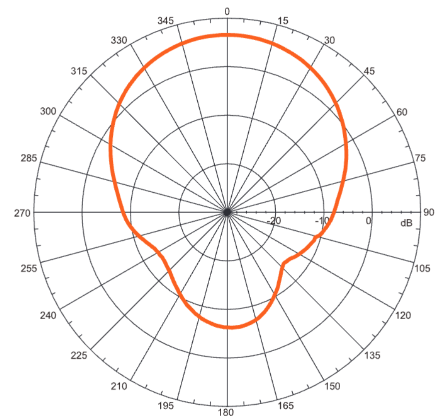
Using the turntable we measured the following radiation pattern. Gain was calculated using the equation we derived in theory question 1:

$$G_{TX} = S21 - G_{cal} - 20\log\left(\frac{\lambda}{4\pi r}\right)^2$$

We plugged in G_{cal} from the horn datasheet, r as the antenna-antenna distance from the chamber diagram above, and λ calculated using a frequency of 2.4 GHz. This resulted in the following radiation pattern (at 2.4 GHz):

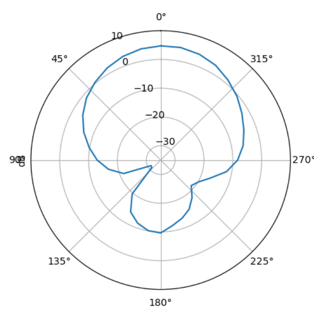


Gain of 4.07 dBi



Expected radiation pattern from datasheet. Source: https://static.tp-link.com/TL-ANT2409A_B_V1_Datasheet.pdf

At 2.4 GHz, the gain we measured is around 2 dB lower than the expected gain of 6 dBi from the datasheet radiation pattern. Recalculating the gain at 2.5 GHz, we get 4.7 dBi and the following radiation pattern:



The extra dB of loss likely comes from physical mis-alignment between the tplink and horn antenna (the horn antenna's polarization not being perfectly aligned to the tplink, or the tplink not being perfectly centered in with respect to the horn).

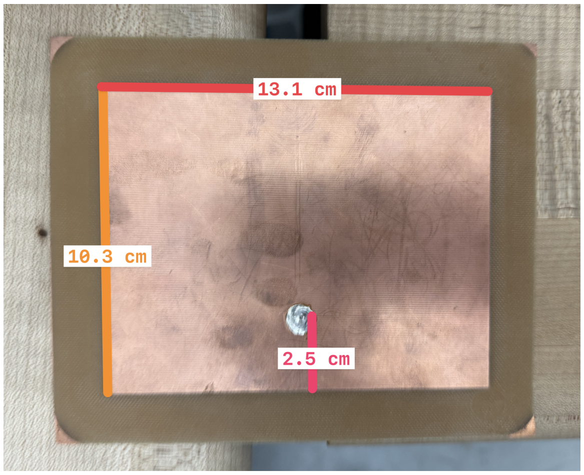
Based off of the gain of 4-5 dBi and the round forward facing shape of the radiation pattern we are guessing that this is a patch antenna. This also makes sense given the physical patch-like shape of the antenna.

2. Characterize a Patch Antenna

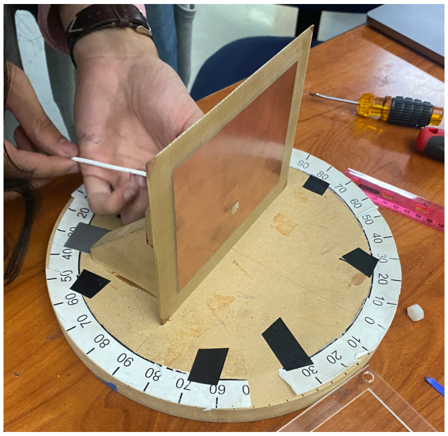
A machined patch antenna is sitting on top of the VNA. Use theory to predict its gain, input impedance, operating frequency and radiation pattern. Confirm with the anechoic chamber.

Patch Antenna Diagram

height: 10.3 cm, width: 13.1 cm, distance from edge to feedpoint: 2.5 cm

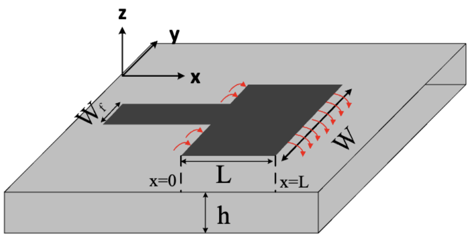


We mounted it to the anachoic chamber using the same stand as for the tplink antenna:



Patch Antenna Theory:

All equations and figures in the patch antenna theory section come from https://bpb-us-w2.wpmucdn.com/sites.gatech.edu/dist/6/733/files/2018/11/PatchAntennas.pdf unless other specified.



patch antennas form a standing wave in their vertical L dimension. The fringing fields electric and magnetic fields create a poynting vector that points out of the patch. The patch antenna we have uses a probe feed to improve the driving impedance.

Operating Frequency:

$$f_c = \frac{c}{2L\sqrt{\epsilon_r}}$$

plugging in $L = 0.103\ \mathrm{m}, \epsilon_r = 4, c = 3 \times 10^8\ \mathrm{m/s}$ we get:

$$f_c = 728.155\ \mathrm{MHz}$$

Note that $\epsilon_r = 4$ is the dielectric constant of FR4, the material the antenna PCB is made of.

https://www.antenna-theory.com/antennas/patches/antenna.php

Gain

We expect the gain to be at least 3 dBi, because all of the energy that would come out the "back" side of an isotropic antenna is coming out the front of a patch. In reality, the gain ends up being a bit higher (5-7 dBi) because the radiation pattern is slightly curved and focused towards the forward direction.

Input Impedance

We can predict the input impedance of a patch antenna at the edge as

$$Z_A = 90\frac{\epsilon_r^2}{\epsilon_r - 1}\left(\frac{L}{W}\right)^2 \qquad (1.9)$$

where $\epsilon_r = 4, L = 0.103\ \mathrm{m}, W = 0.131\ \mathrm{m}$. Giving us $Z_A = 296.73\ \Omega$.

$$Z_a(x = x_p) = Z_A(x = 0)\left[\cos\left(\frac{\pi x_p}{L}\right)\right]^2 \qquad (1.12)$$

where $x_p = 0.025\ \mathrm{m}$ is the distance from the edge to the feedpoint:

Plugging this in we get an expected output impedance of $Z_A(x = x_p) = 155.15\ \Omega$

Radiation Pattern

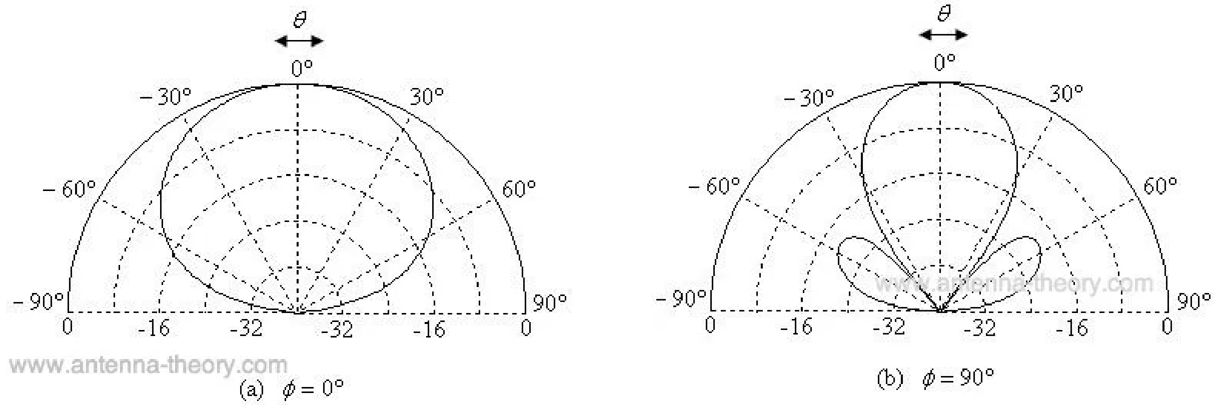
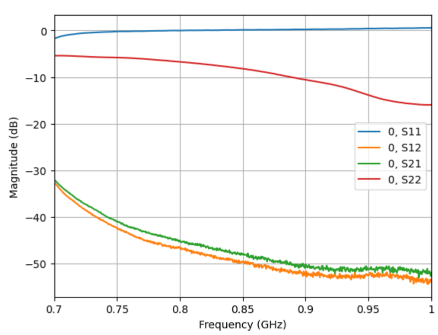
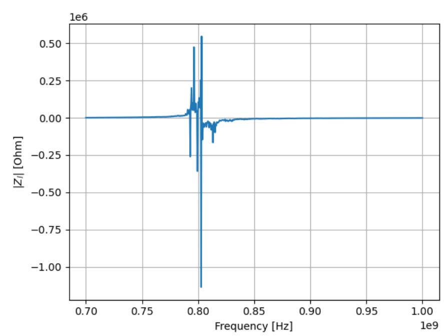


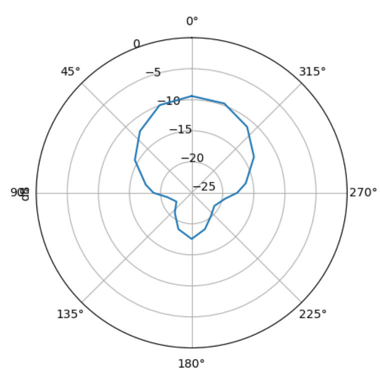
figure from: https://www.antenna-theory.com/antennas/patches/antenna.php

Our Data:

We initially measured the performance from 700 Mhz to 1 GHz (700 MHz is the lowest we can go without near-field loading effects and is below the resonant frequency of the patch antenna).







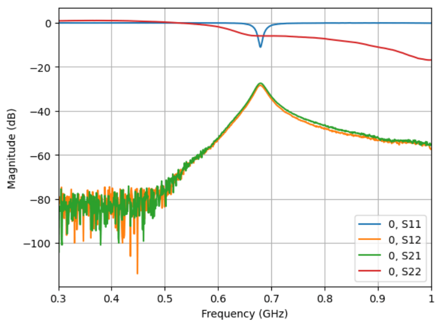
Gain: -9.41

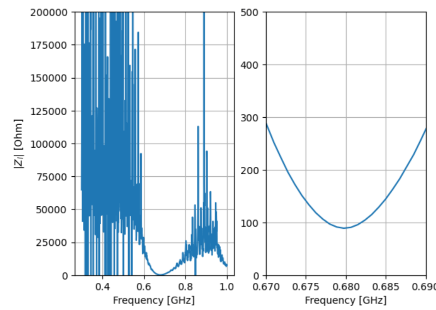
The low gain and lack of any dip in S11 implies that the antenna is not radiating and we are at the wrong frequency.

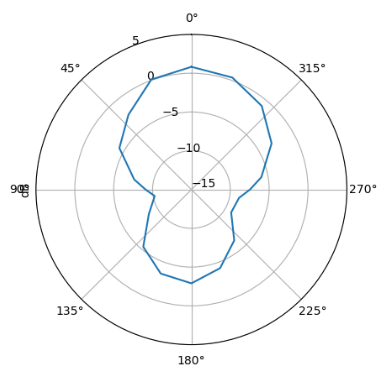
After talking to Prof. Spencer, we determined that there might have been an error in our calculations and logic. We assumed the antenna was radiating in the shorter, vertical direction and that the dielectric constant of FR4 was exactly 4. If we instead assume that the dielectric constant is closer to 4.5, we get that the actual radiating frequency is around 680 MHz.

Importantly, this is lower than the 700 MHz limit that the anechoic chamber is rated for, and also low enough that the patch antenna could be in the near field of the horn antenna creating unintended loading effects. All results should be considered critically.

Measuring the performance from 300 MHz to 1 GHz, we see a very clear dip in S11, combined with a spike in S21 at 680 MHz, implying that that is the true resonant frequency of the patch antenna.





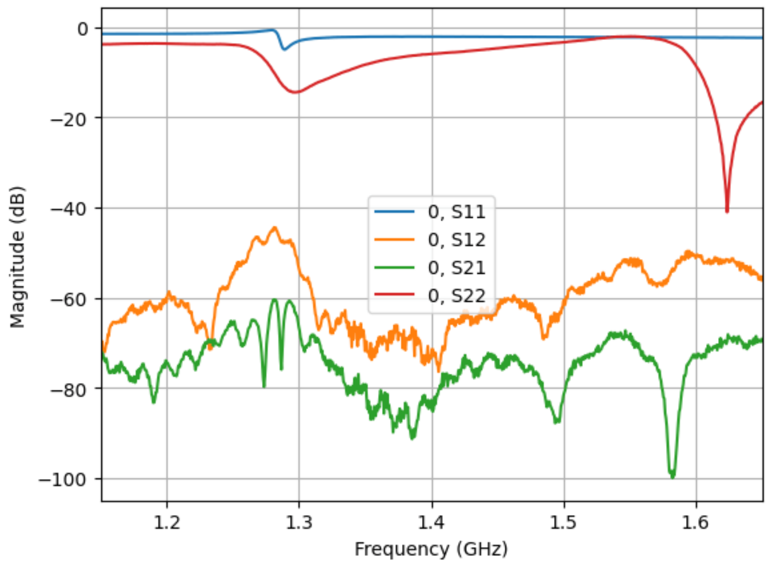


Gain: 0.82 dBm

Calculating the input impedance, we see that it is minimized at 680 MHz with a value of around 89 Ohms. This is around 60 Ohms lower than predicted 115 Ohms from the patch antenna theory, likely due to the inaccuracies of the physical connection between the SMA connector and the PCB, or unaccounted for factors in a DIY machined patch antenna.

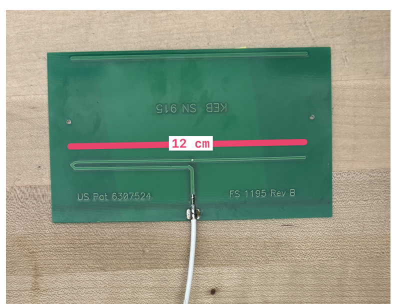
The measured gain is lower than expected at 0.8 dBm vs the expected 3+ dBm. Given the unideal conditions of this measurement: out of range of the anechoic chamber, near field loading, home-made antenna, this is a fairly reasonable result.

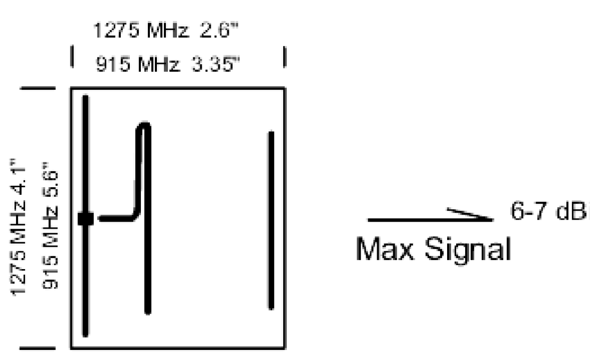
Taking another measurement at a much higher frequency wee see that there is also a resonant dip at around 1.3 GHz which is roughly twice the 680 MHz value we saw below.

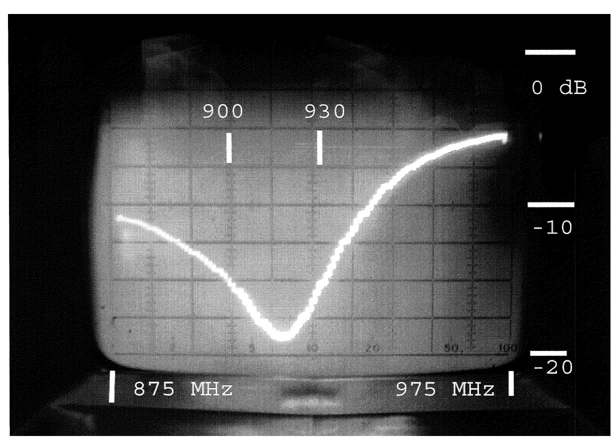


3. Characterize a weird antenna

For our weird antenna, we picked a 915 MHz Yagi antenna. The physical diagrams and S11 expected from the datasheet are below:

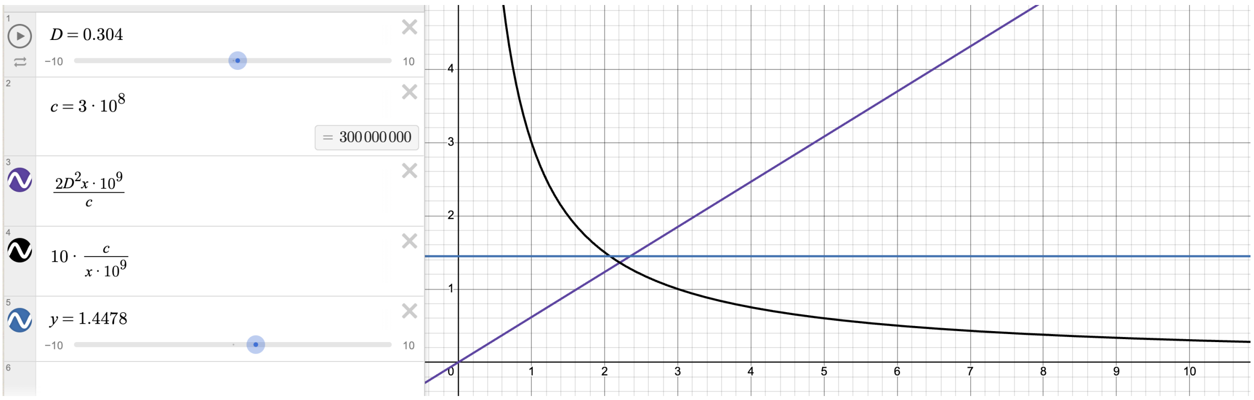






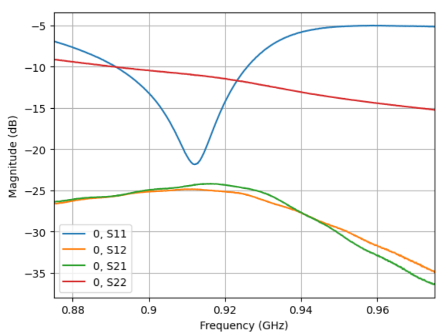
Datasheet and info from: https://www.wa5vjb.com/pcb-pdfs/Yagi900.pdf https://www.wa5vjb.com/products2.html. Note that we have the 915 MHz variant of the antenna.

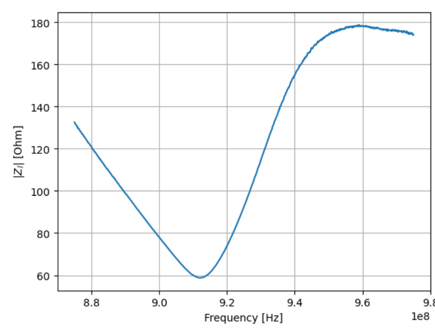
Calculating the far field boundary, we see that there is a small frequency range where it fits within the chamber



However these bounds are an over estimate, so we should still be ok, but results should be considered critically.

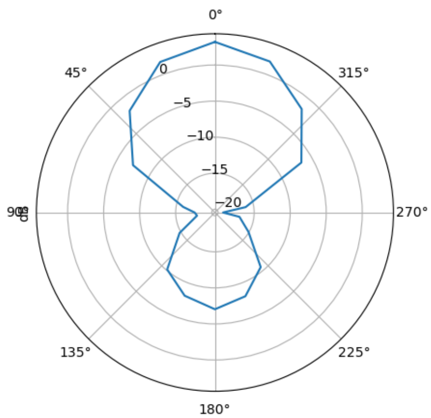
Measuring the antenna in the anachoic chamber using the same procedure from part 1, we get the following S parameters, input impedance, gain, and radiation pattern.



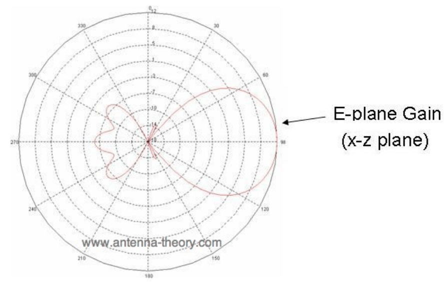


The dip in S11 closely matches what is expected from the datasheet. Additionally, the input impedance gets closes to 50 ohms at 915 MHz as expected.

Radiation pattern was calculated at 915 MHz



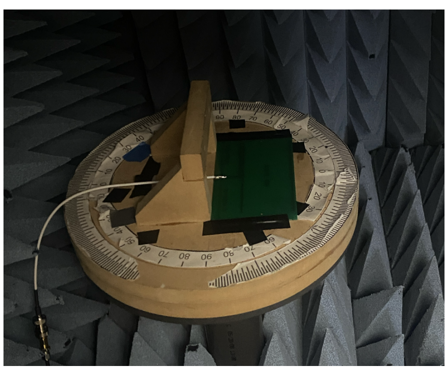
Gain is 3.2 dBi



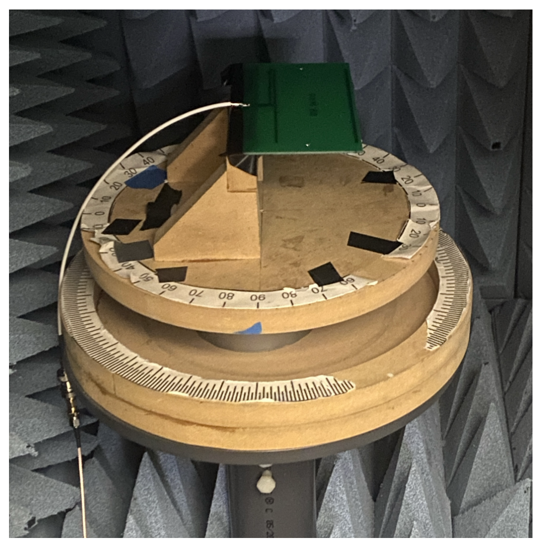
Source: https://www.antenna-theory.com/antennas/travelling/yagi3.php.

The radiation pattern matches what we expect from theory (the lack visible lobes on back is due to the coarseness of our measurement.

The gain is lower than expected at 3.2 dBi instead of 6-7, this is likely because of the difficulty of lining up the antenna vertically with the horn receive antenna, and the possible near field loading effects from the anechoic chamber size. If it is mis-aligned, we are measuring a slice that is not centered and will have a much lower gain. Additionally, the recieve horn antenna may be partially in the near field of the yagi antenna as seen in the calculations above, which would cause additional loading effects.



Initial attempt with antenna too low



Updated setup with antenna raised

Empirically, we tested alignment by stacking metal-free objects under the antenna to maximize the gain, however we did not perfectly center it, and raising the antenna up made it harder to set angles correctly in the chamber.

Note also that the yagi antenna is vertically polarized while the patch antennas from questions 1 and 2 were horizontally polarized, requiring us to rotate the receive horn.