Microstrip Patch Array for GPS Application

ECE 770 Radio-Wave Systems
Course Project
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Project Description

Description taken from project outline:

This project requires us to design a low-profile transmitting antenna to be placed on a highly conducting box of 35 cm x 35 cm x 5 cm. The box will eventually be placed on the top of a truck such that the antenna will always be facing the Zenith (on the assumption that the satellite with which the antenna is communicating is in the Zenith).

The antenna should operate at a frequency of 1575 MHz with the following constraints:

1. The footprint should not exceed 25 cm x 25 cm.
2. The vertical profile (total height above the ground plane of the box) should not exceed 10 cm.
3. The antenna feed (transmitter) has an input impedance of 50 Ohms.

Initial Design

Based on the project description, I interpreted it as a task to design a microstrip patch antenna for a vehicle's GPS system. I aimed to design a low-cost aftermarket GPS patch array for this application using a RO4003 substrate. This substrate material was chosen for its lower fabrication costs, while maintaining high performance and relatively low loss for microwave and millimetre applications [1]. Selecting this substrate to be 1 mm, I can expect it to be low-cost, but the trade-off would be the efficiency of the antenna. If the antenna is more than 50% efficient it should suffice.

According to [2], the antenna should operate at a frequency of 1575 MHz (also outlined in the project description) as well as a 2-20 MHz bandwidth for GPS microstrip antennas. However, because there are no given specs in the project outline, I will present an antenna with an approximate 10-12 MHz bandwidth as a middle ground. The gain of the antenna should be about 2-5 dB [2]. Because I am using a thinner substrate, I will create an antenna array to improve the gain and directivity of the antenna. The highly conducting metal box will be placed underneath the microstrip patch array to act as a reflector, also improving the gain and directivity of the antenna.

An image of the proposed array is shown in Figure 1. In the array, 2 patches are connected in series which is fed in parallel with another 2 patches in series. This design was chosen for its simple and compact feed network which would allow for an easier fabrication process.

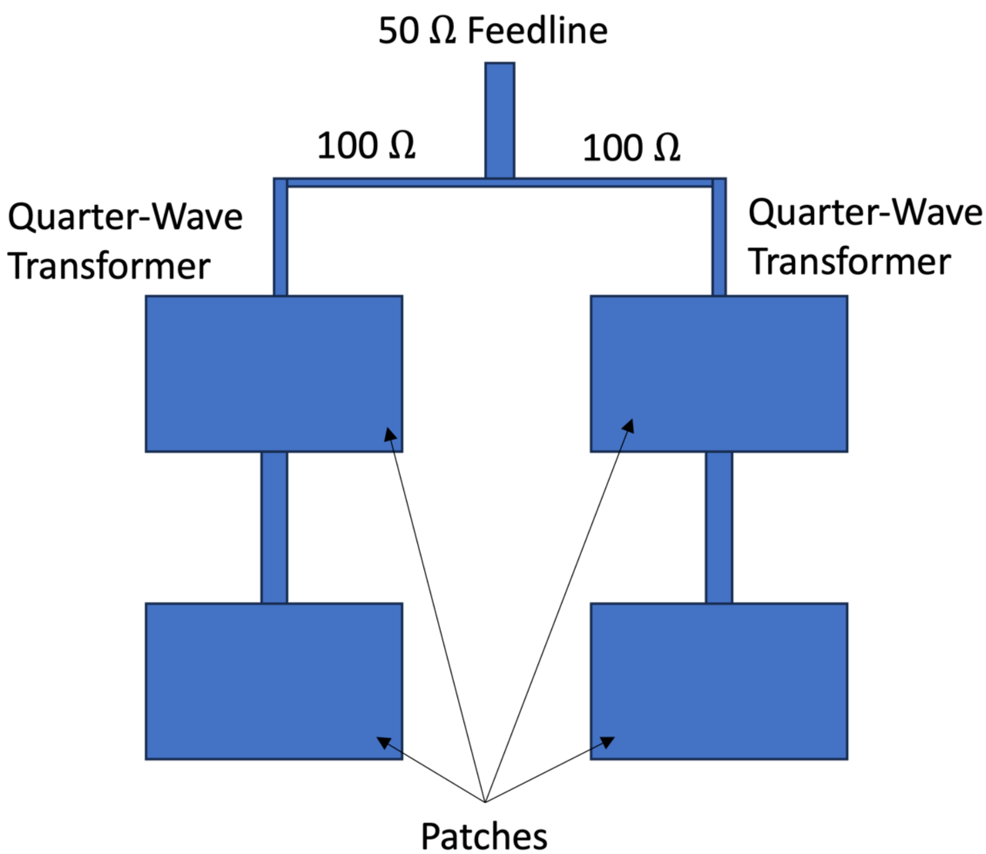

Figure 1: GPS Microstrip Patch Array

The initial lengths and widths of each component can be calculated for a general idea when creating the HFSS design presented later in this report. I used the online microstrip patch antenna, microstrip line, and the wave port size calculators provided by [3]. The dielectric constant or relative permittivity of the Rogers 4003 substrate provided in the HFSS material database is approximately 3.55. The input parameters and calculated results for a simple microstrip patch antenna are shown in Figure 2 - Figure 5.

A quarter-wave transformer was used to match the 50 Ω feedline to the input impedance of the patch antenna. Using the microstrip patch antenna calculator, the input impedance along the edge of the patch was found to be 204.75 Ω. Performing a quick calculation, we obtain the characteristic impedance of the quarter-wave transformer to be approximately

$$Z_0 = \sqrt{Z_L Z_{in}} = \sqrt{50 * 204.75} = 101.18\ \Omega.$$

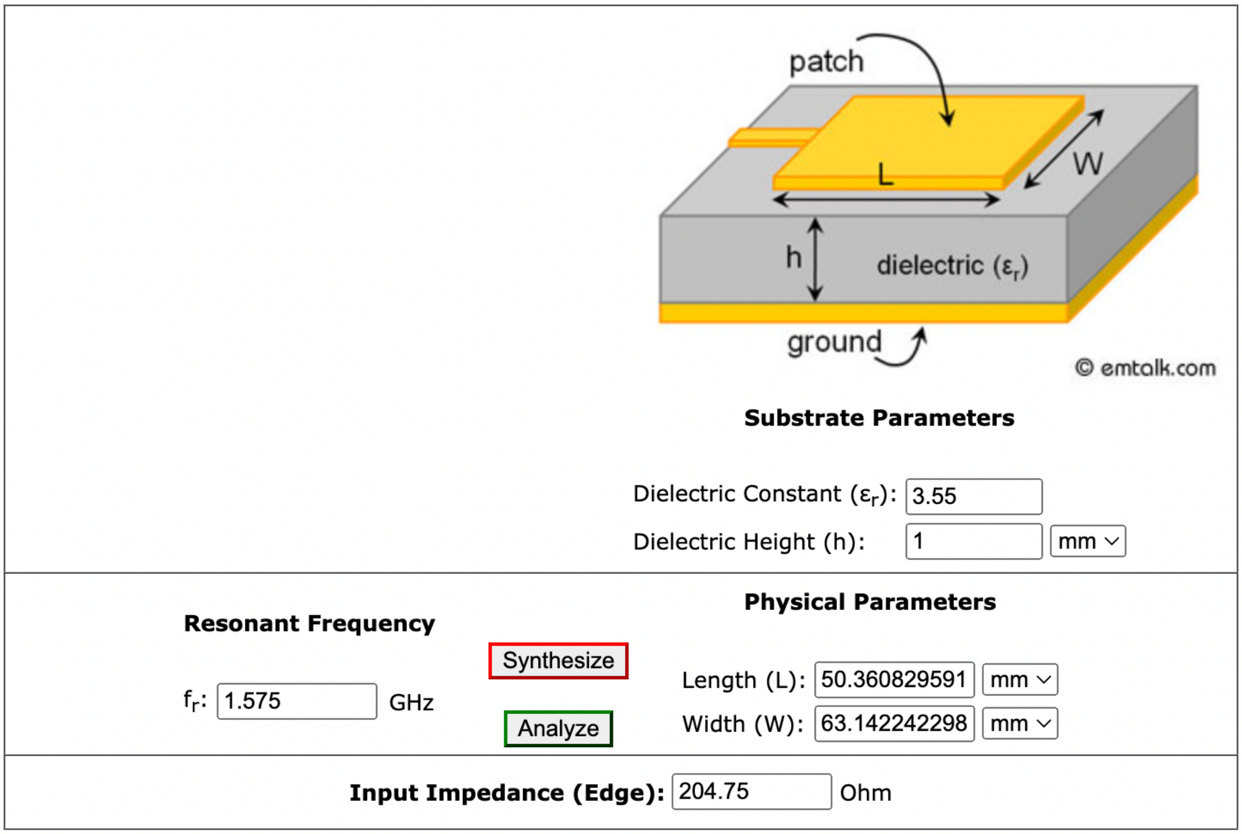

Figure 2: Microstrip Patch Antenna

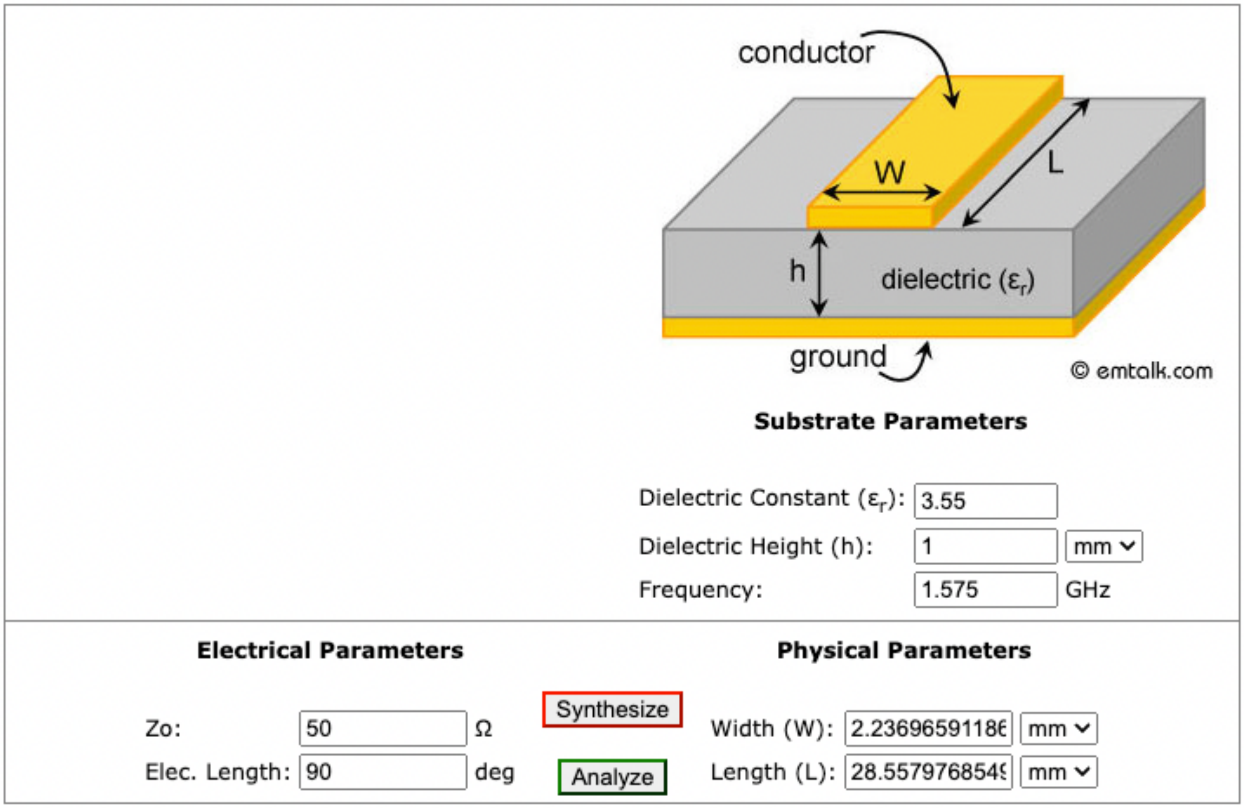

Figure 3: 50 Ohm Microstrip Feedline

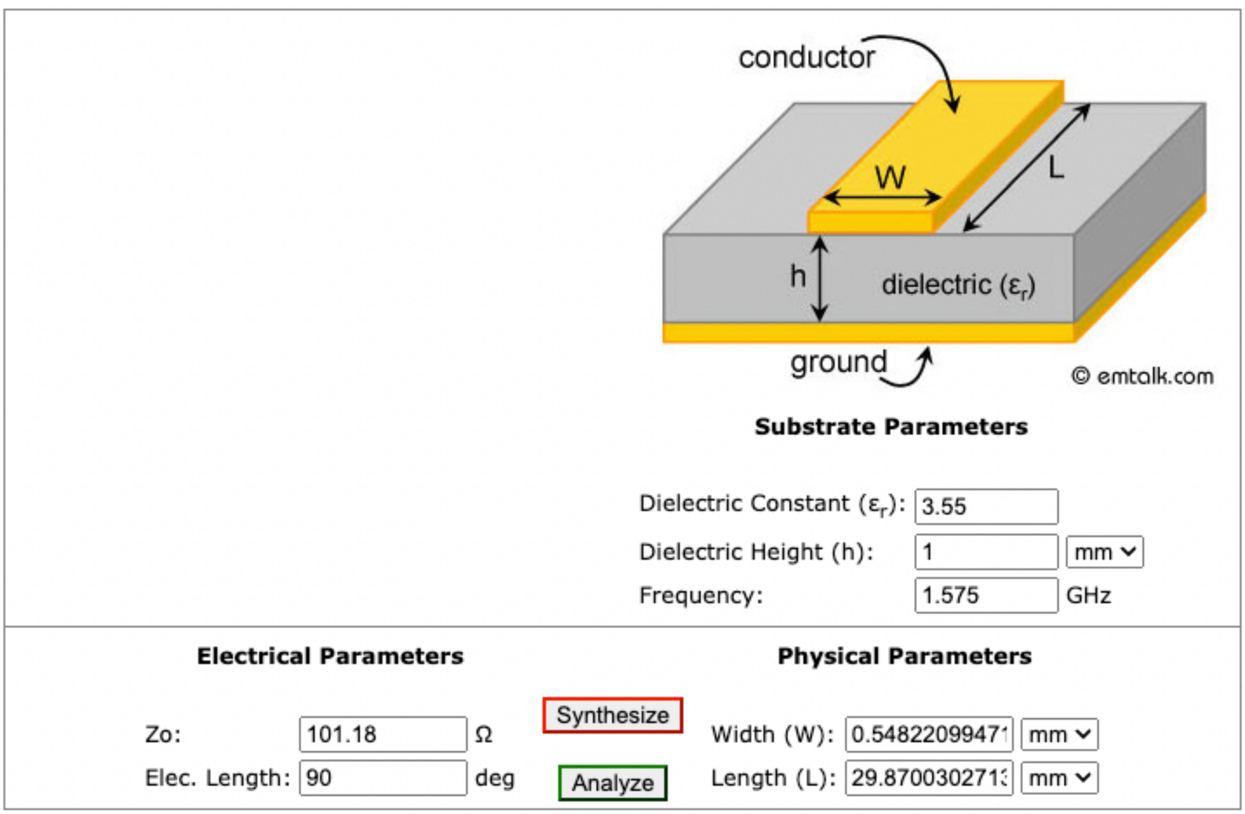

Figure 4: Quarter-Wave Transformer Microstrip Line

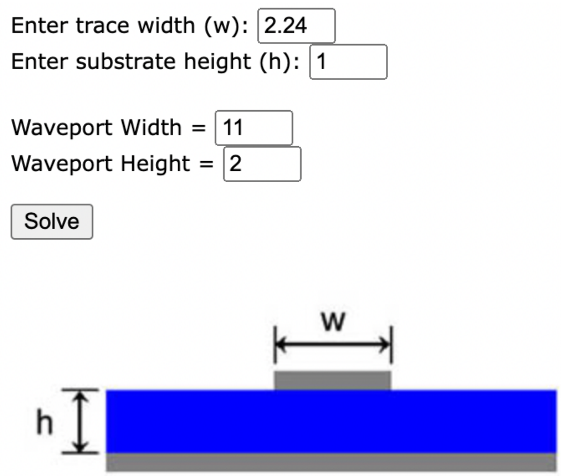

Figure 5: Wave Port Size

After calculating the parameters for the simple microstrip patch antenna for the first phase in the design, the HFSS model was created (next section). For the second phase, a transmission line was added to connect 2 patches in series. This transmission line was 204.75 Ω to match the two patch antennas. In the third phase, I fed two patch antennas in parallel using a 100 Ω line connected to the 50 Ω one. Matching the 100 Ω line to the input impedance of the patch antenna using a quarter-wave transformer, I obtained

$$Z_0 = \sqrt{Z_L Z_{in}} = \sqrt{100 * 204.75} = 143.09\ \Omega.$$

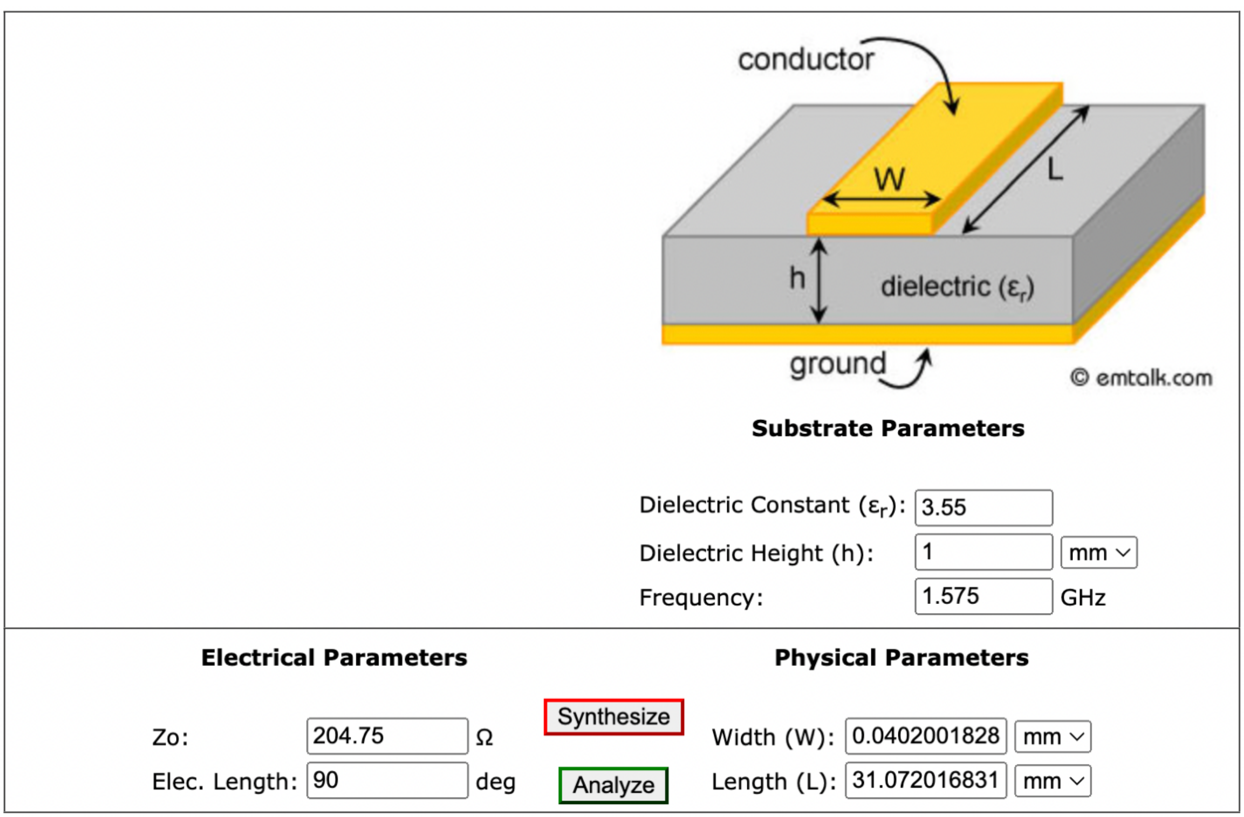

Figure 6: Microstrip Line Connecting 2 Patches in Series

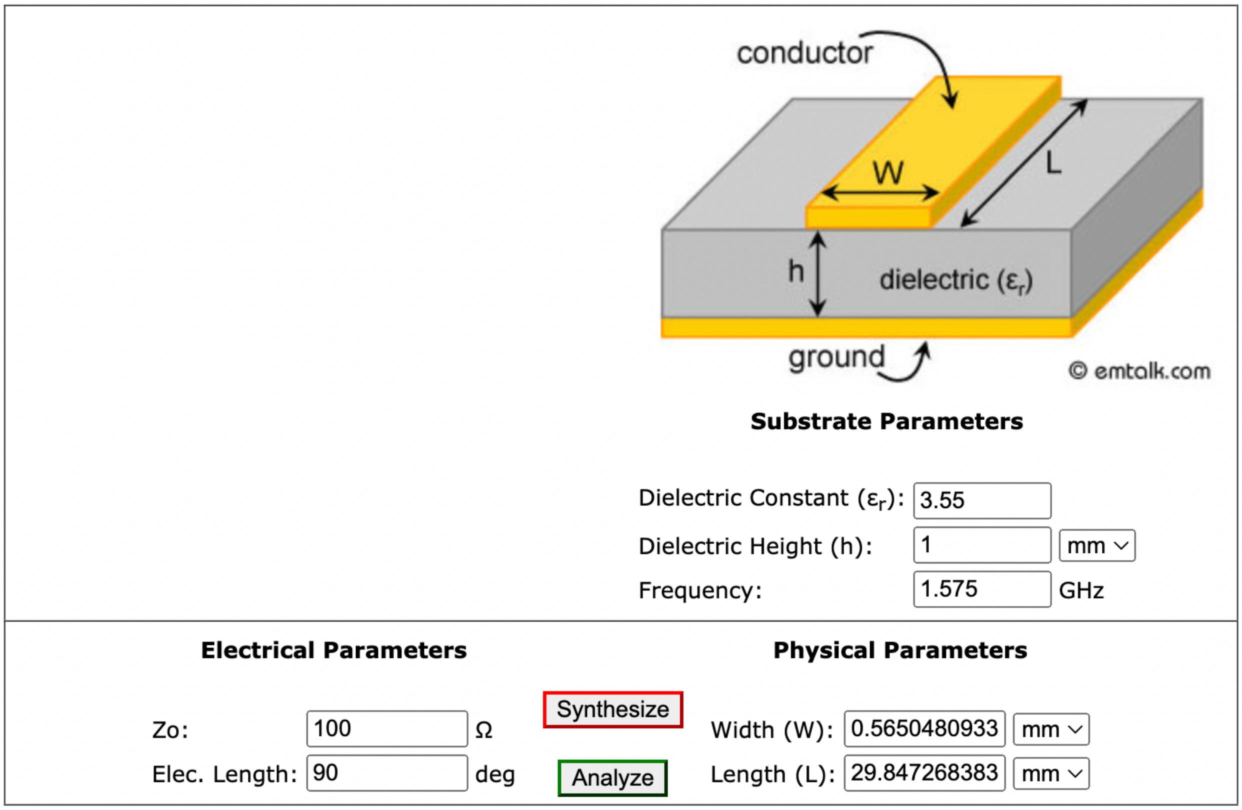

Figure 7: 100 Ohm Microstrip Line

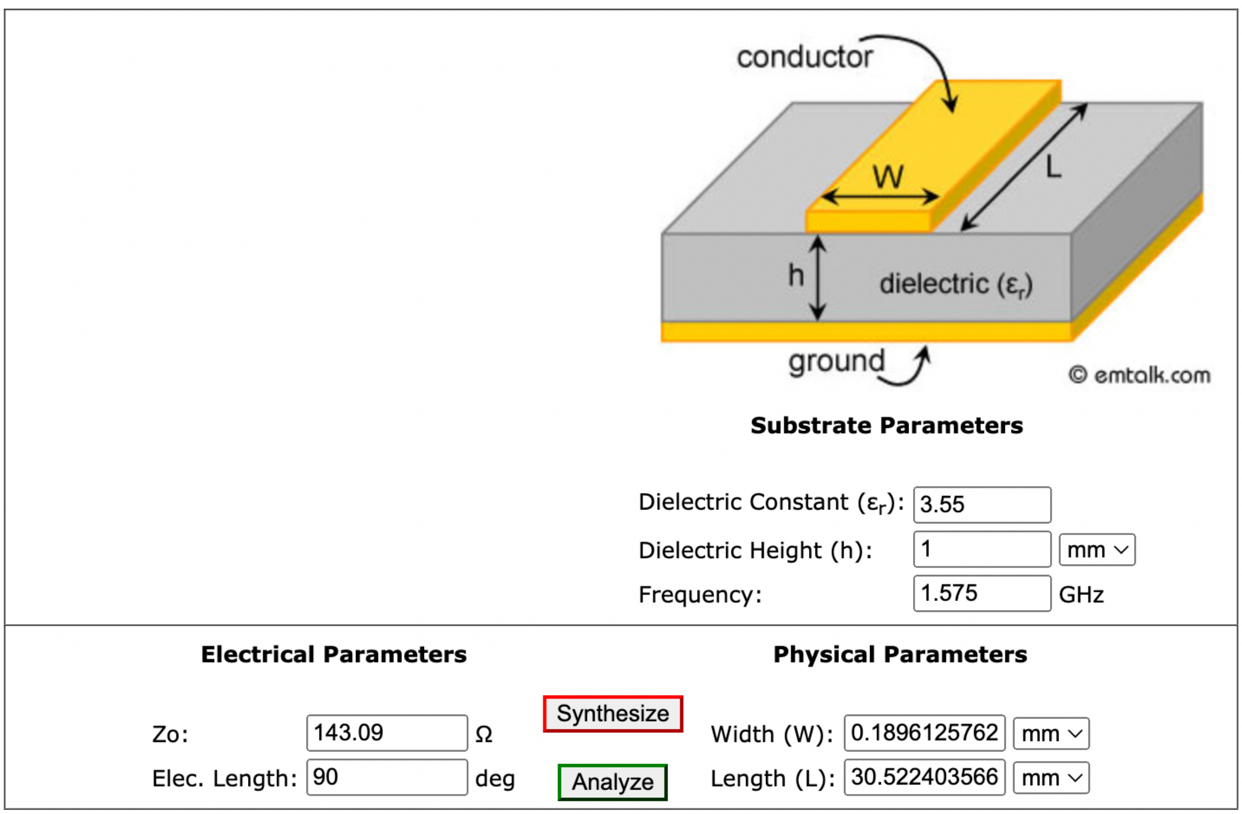

Figure 8: Quarter-Wave Transformer Microstrip Line (in Array)

Design Parameter Summary

Table 1: Initial Design Parameters

Parameter	**Value (mm)**
Patch Length	50.36
Patch Width	63.14
50 Ω Line Length	28.56
50 Ω Line Width	2.24
Quarter-Wave Transformer (1) Length	29.87
Quarter-Wave Transformer (1) Width	0.55
100 Ω Line Length	0.57
100 Ω Line Width	29.85
Quarter-Wave Transformer (2) Length	30.52
Quarter-Wave Transformer (2) Width	0.19
204.75 Ω Line Length	31.07
204.75 Ω Line Width	0.04
Port Width	11
Port Length	2

Where (1) is the quarter-wave transformer used in the simple single microstrip patch antenna and (2) is the quarter-wave transformer used in the microstrip patch array.

HFSS Design

The HFSS design was split into a few phases, starting with a simple single patch antenna, before creating the 2x2 patch array with the reflector. This was to help tune and determine the impedance matching of the feed networks for the array. There are five stages in total: the single patch, the series patch array, the parallel patch array, the 2x2 array combining the series patch and parallel patch arrays, and finally the 2x2 array with the reflector.

Single Patch

The single microstrip patch antenna model was created in HFSS and is shown in Figure 9. The results for the S11, Z11, and gain plots after tuning the patch and transmission lines are shown in Figure 10 - Figure 12. The peak gain, peak directivity, and efficiency are tabulated in Table 2. We can see from the plots that the patch and lines are well matched, and the efficiency is higher than the goal of 50% set in the initial design objective. The peak gain in the zenith is about 4.9 dB, which is almost as much as the gain specified by [2].

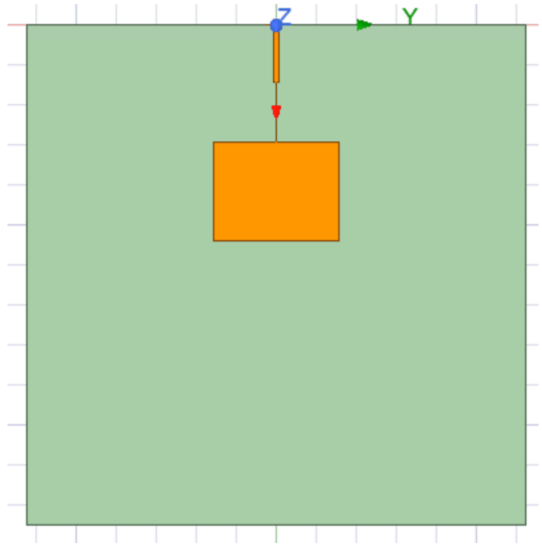

Figure 9: Single Microstrip Patch Antenna in HFSS

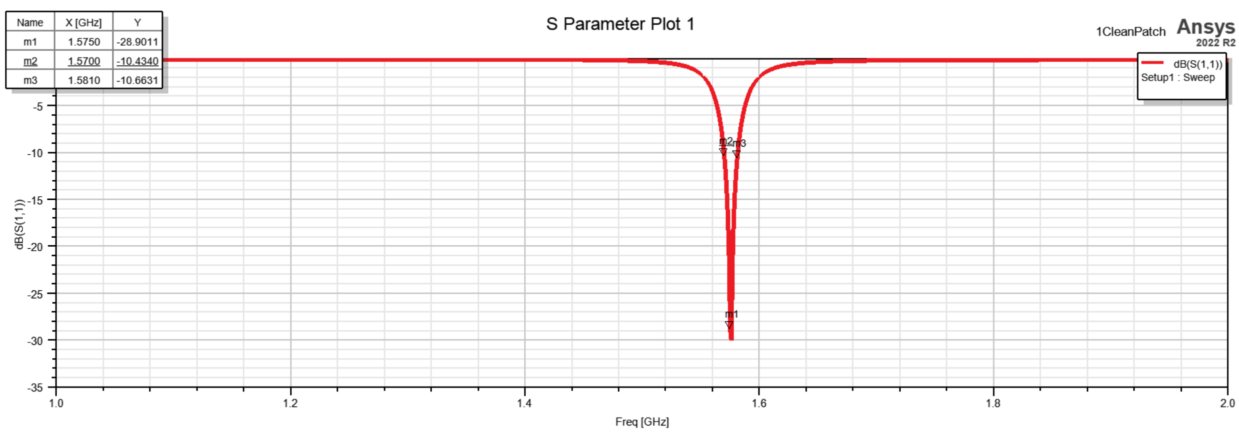

Figure 10: S11 of Single Microstrip Patch Antenna

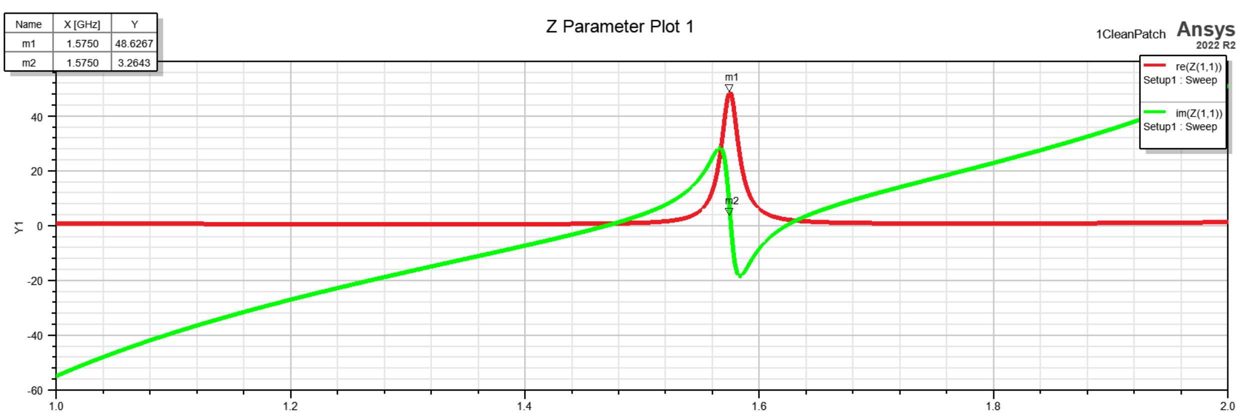

Figure 11: Z11 of Single Microstrip Patch Antenna

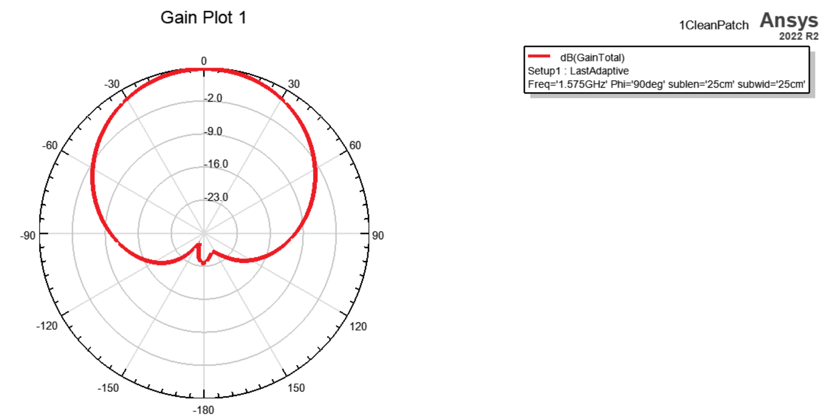

Figure 12: Gain Plot of Single Microstrip Patch Antenna

Table 2: Efficiency of Single Microstrip Patch Antenna

Frequency (GHz)	**Peak Gain (dB)**	**Peak Directivity (dB)**	**Efficiency (%)**
1.575	4.921852	7.037190	61.44

The S11 dip occurs at 1575 MHz, with a value well below -10 dB. To determine the operating bandwidth, we look at the two frequency points at which the graph passes through -10 dB. Looking at the S11 graph, we can see that the graph has a very narrow bandwidth of approximately 10 MHz or less. Going forward with the design, if the S11 dip is below -10 dB, we can consider that as well matched. Together with the Z11 plot, the two plots show that I have a well-matched feeding network so far as the reactance of the plot is quite small and the real part is close to 50 Ω. With more fine tuning, the resistance and the reactance of the antenna could be improved.

Calculating the voltage standing wave ratio (VSWR) gives us

$$VSWR = \frac{1+\Gamma}{1-\Gamma} = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+1.288\times 10^{-3}}{1-1.288\times 10^{-3}} = 1.003.$$

The VSWR is another parameter that can tell us how closely matched the patch is matched to the transmission line. The minimum value of the VSWR is 1 and is the ideal case, where no power is reflected back at the edge of the patch. In this case, for my simple patch antenna I have a VSWR of 1.003, representing a very well-matched antenna.

The efficiency in Table 2 was calculated using the peak gain and peak directivity in Watts.

$$Efficiency\ (\%) = 10^{(Gain-Directivity)/10} = 10^{(4.921852-7.037190)/10} = 61.44\%$$

2x1 Series Array

After ensuring that the single patch antenna was well matched to the feed line and quarter-wave transformer, a second patch of the same size was added to the top of the substrate. The two patches were connected with a 204.75 Ω as specified in the initial design (Figure 13). The simulations were run again with this connection and the S11, Z11, and gain plots are shown in

Figure 14 - Figure 16. From these results, we can see that the antenna is still well matched with these lines with very minimal tuning required. However, there is a noticeable drop in the efficiency of the antenna (Table 3) compared to the single patch, but it is still greater than the 50% efficiency outlined in our design objective. This may suggest that the series array is not as efficient as other array layouts. However, with the series layout, there has been an improvement in the gain and directivity of the antenna. The VSWR also indicates a well-matched antenna.

$$VSWR = \frac{1+\Gamma}{1-\Gamma} = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+1.975\times10^{-3}}{1-1.975\times10^{-3}} = 1.004.$$

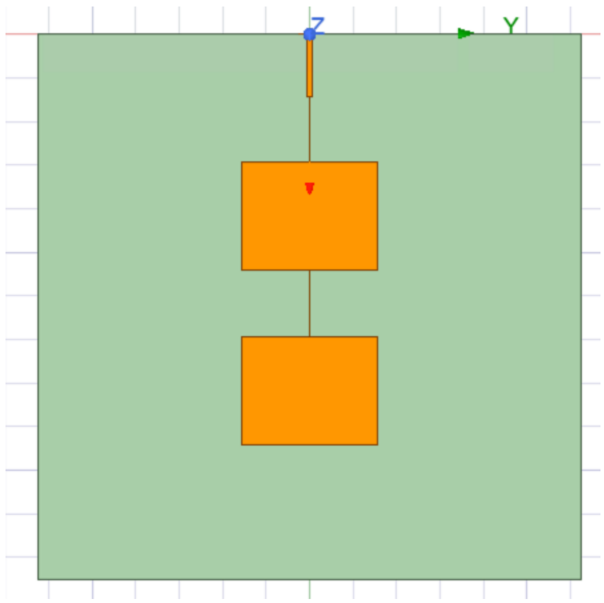

Figure 13: Series Microstrip Patch Array in HFSS

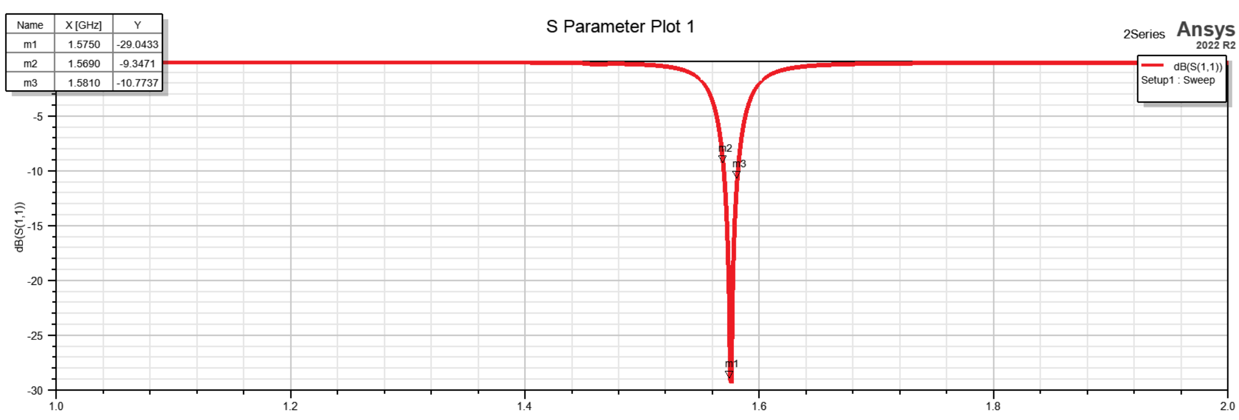

Figure 14: S11 of Series Microstrip Patch Array

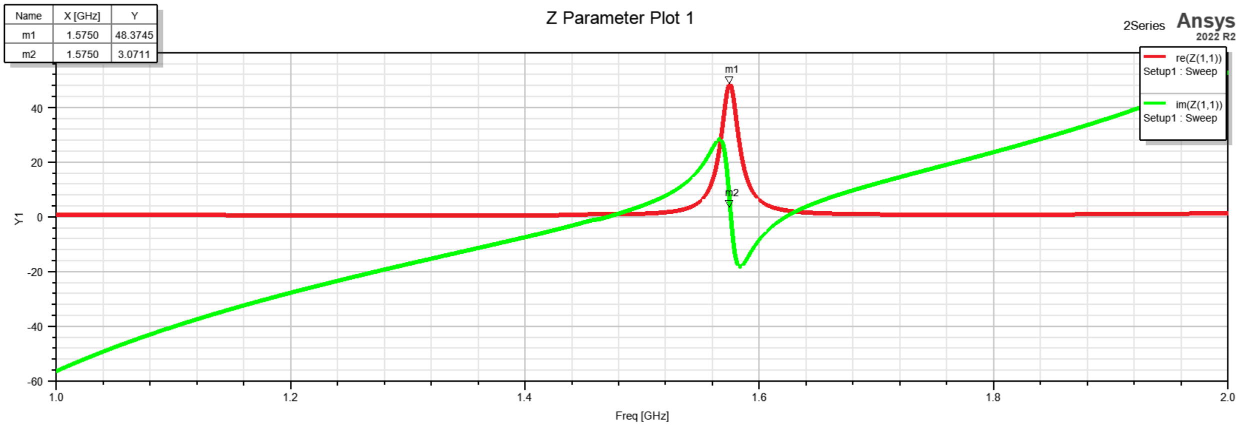

Figure 15: Z11 of Series Microstrip Patch Array

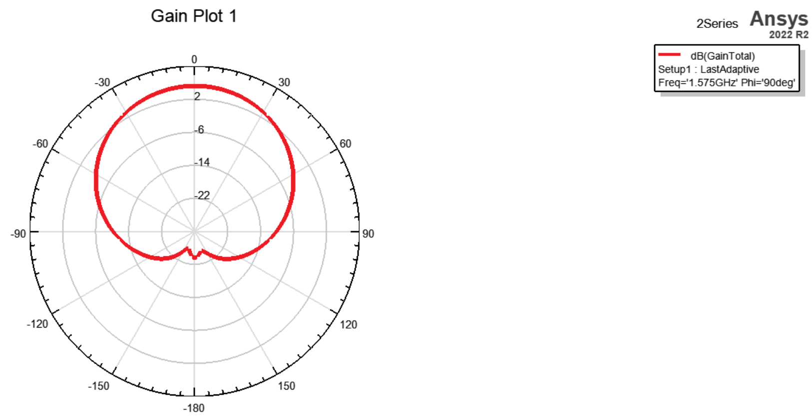

Figure 16: Gain Plot of Series Microstrip Patch Array

Table 3: Efficiency of Series Microstrip Patch Array

Frequency (GHz)	**Peak Gain (dB)**	**Peak Directivity (dB)**	**Efficiency (%)**
1.575	5.321903	7.550026	59.87

2x1 Parallel Array

Before proceeding to put two series arrays together in parallel, a 2x1 parallel patch array was tested to ensure the feeding network was correct. An image of the parallel patch array is shown in Figure 17. After some tuning of the original numbers calculated in the initial design, I was able to obtain a well-matched antenna with the S11 dip at 1575 MHz (Figure 18) and sufficient bandwidth of about 15 MHz. This tuning required me to shorten the length of the 100 Ω line until the edges of the patches were about half a wavelength away from each other. The Z11 plot (Figure 19) also shows a resistance relatively close to 50 Ω, and a reactance of approximately 0. The efficiency of the antenna is also better than the simple patch antenna and the series patch antenna. This could suggest that if I made a 2x2 parallel patch array, it would be more efficient than the 2x2 series/parallel patch array that I aimed to design for this project. The gain and directivity of the parallel patch antenna is also better than the 2x1 series patch array, which is another suggestion that if I made a 2x2 parallel patch array the specs would be much better than what I have initially proposed. The VSWR of my parallel patch array is approximately 1, indicating a well-matched feed network.

$$VSWR = \frac{1+\Gamma}{1-\Gamma} = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+0.0213}{1-0.0213} = 1.004.$$

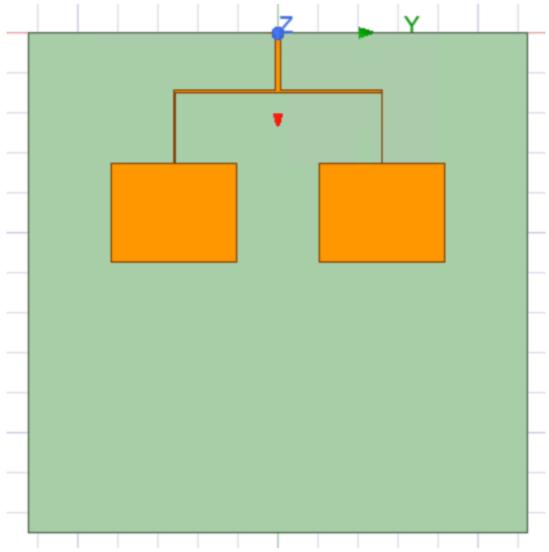

Figure 17: Parallel Microstrip Patch Array in HFSS

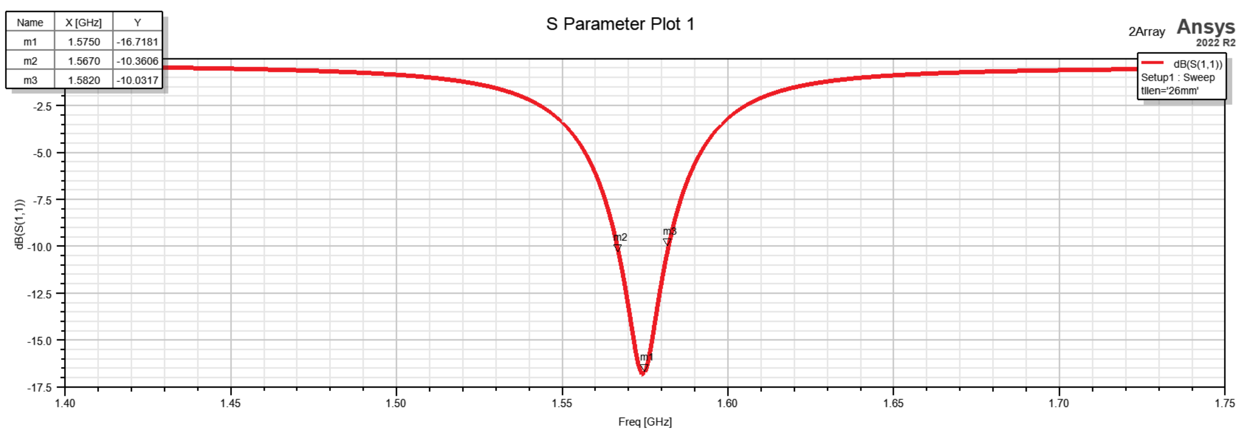

Figure 18: S11 of Parallel Microstrip Patch Array

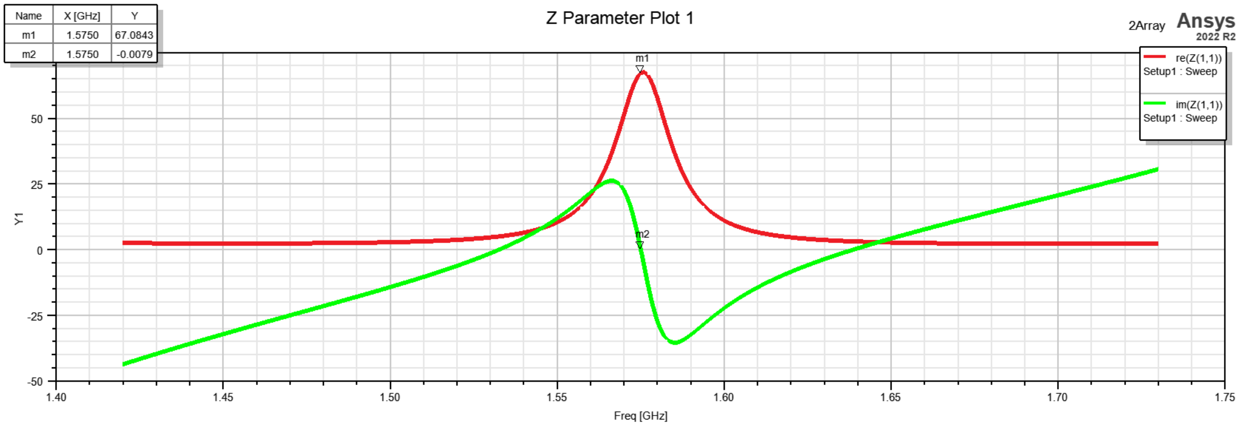

Figure 19: Z11 of Parallel Microstrip Patch Array

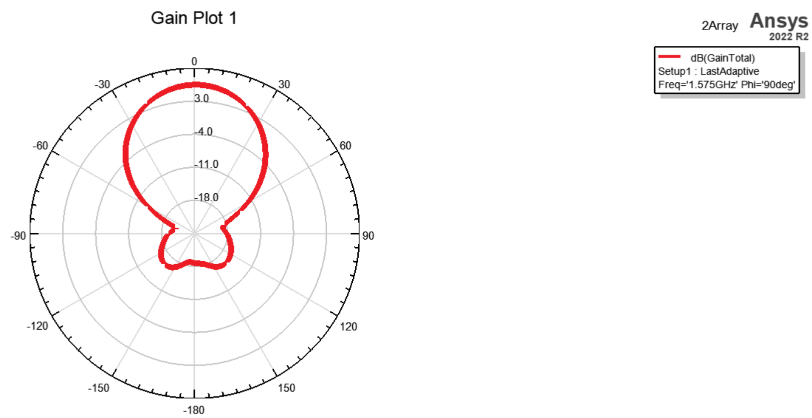

Figure 20: Gain Plot of Parallel Microstrip Patch Array

Table 4: Efficiency of Microstrip Patch Parallel Array

Frequency (GHz)	**Peak Gain (dB)**	**Peak Directivity (dB)**	**Efficiency (%)**
1.575	6.868742	8.806630	64.00

2x2 Array

Using what I learned from the 2x1 series and 2x1 parallel patch arrays, I combined the two to create 2 patches in series connected in parallel with another 2 patches in series. An image of the 2x2 array is shown in Figure 21. I took the parallel patch array and added the 204.75 Ω transmission lines to connect two more patches of identical sizes, as initially demonstrated in my initial design. This design was not tuned due to the time it took to run each simulation and the short timeline of this project. Looking at the S11 and Z11 plots (Figure 22 and Figure 23 respectively), the antenna is quite well-matched considering there was no tuning performed. There are two dips in the S11, but if the operating region is under -10 dB, the antenna can be considered well-matched. The VSWR of the antenna did increase, but only slightly.

$$VSWR = \frac{1+\Gamma}{1-\Gamma} = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+0.0527}{1-0.0527} = 1.111.$$

There is a noticeable improvement in the bandwidth of the array compared to the single patch antenna, while the efficiency has stayed approximately the same. If the 2x2 array was made up of parallel patches instead of a combination, the specs may be much better. However, the series array does help to make the design more compact. With more time and higher computational power, it would be possible to tune the antenna to obtain even better matching and higher specs (better gain, directivity, VSWR, etc.). It can be noted that the gain and directivity of the array are much better than the simple single patch antenna.

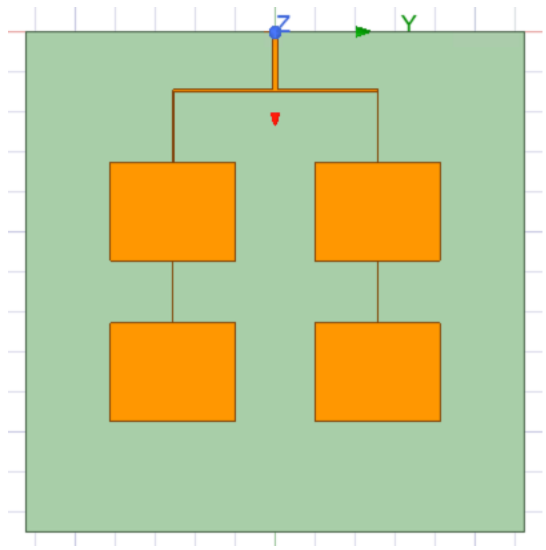

Figure 21: Microstrip Patch Array in HFSS

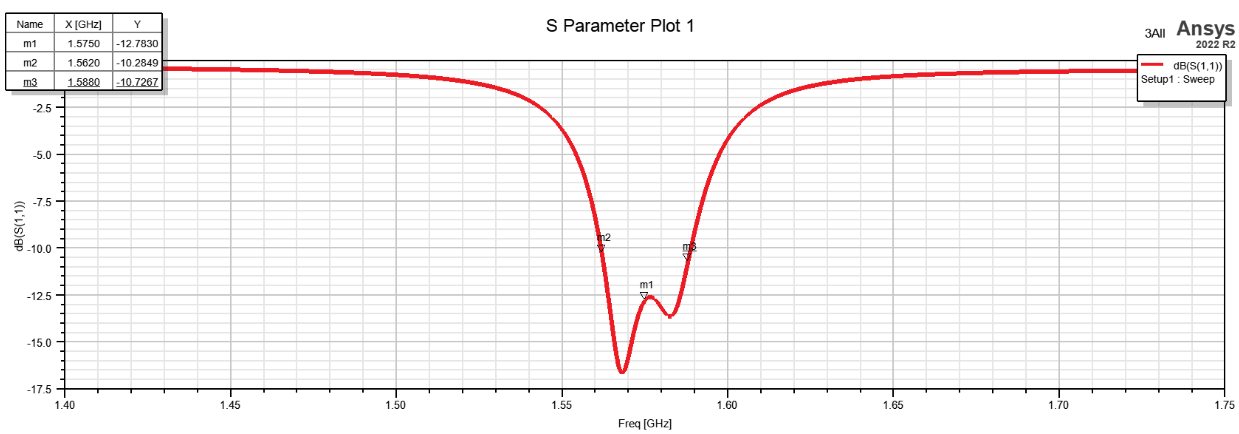

Figure 22: S11 of Microstrip Patch Array

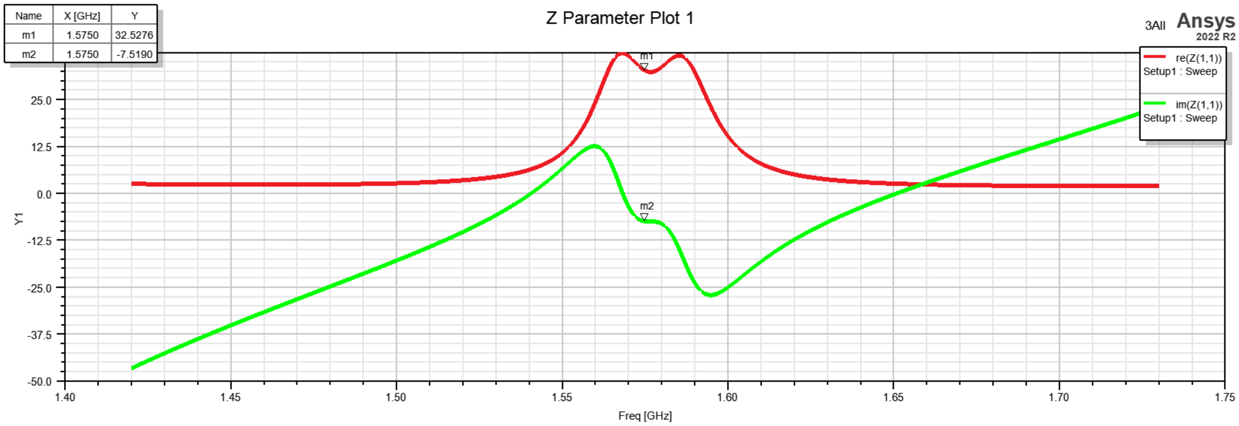

Figure 23: Z11 of Microstrip Patch Array

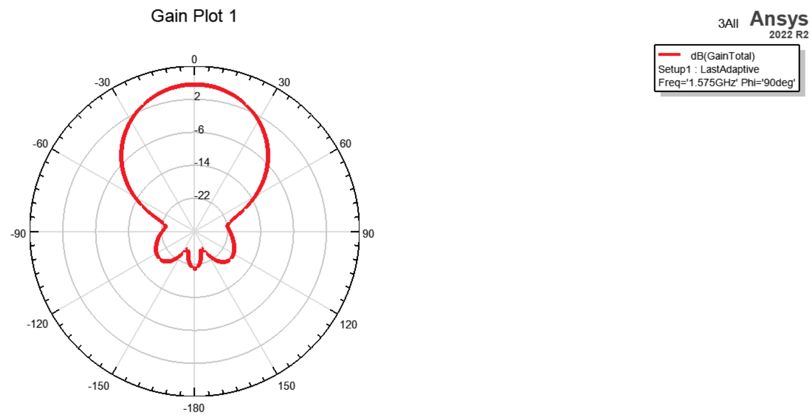

Figure 24: Gain Plot of Microstrip Patch Array

Table 5: Efficiency of Microstrip Patch Array

Frequency (GHz)	Peak Gain (dB)	Peak Directivity (dB)	Efficiency (%)
1.575	9.369575	11.503612	61.12%

2x2 Array with Reflector

The last stage of the design is to include the highly conducting box (reflector) that the antenna would be placed on top of. To reduce the computational complexity of adding a 35 cm x 35 cm x 5 cm copper box, I added only the top surface of the box as a 35 cm x 35 cm copper sheet (Figure 25). Otherwise, the simulation would take much longer to run. The patch array was centred above the box. The S11 and Z11 patterns (Figure 26 and Figure 27 respectively) were similar to the patterns without the reflector, but with a slight difference in values.

$$VSWR = \frac{1+\Gamma}{1-\Gamma} = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+0.0625}{1-0.0625} = 1.133.$$

Interestingly, the peak directivity and peak gain decreased with the reflector while the overall efficiency of the system remained the same. I expected the peak directivity and gain to increase with the reflector due to the redirection of the electric fields and constructive interference, but I am unsure why it decreased it this case. I tried troubleshooting this (in the challenges section) but haven't had much success with it.

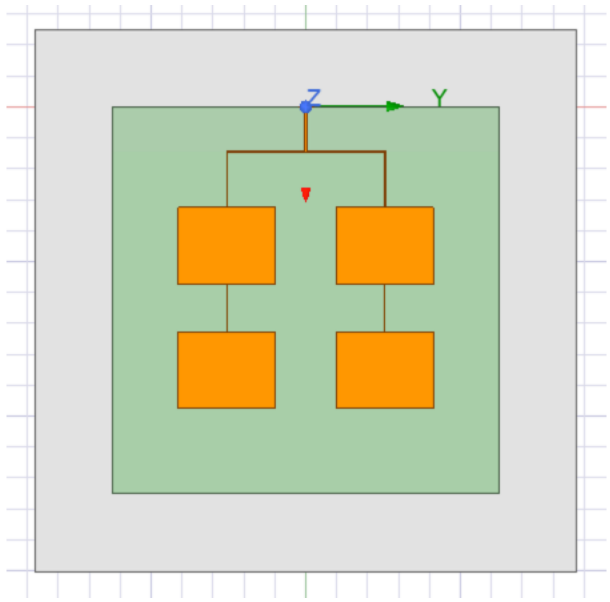

Figure 25: Microstrip Patch Array with Reflector in HFSS

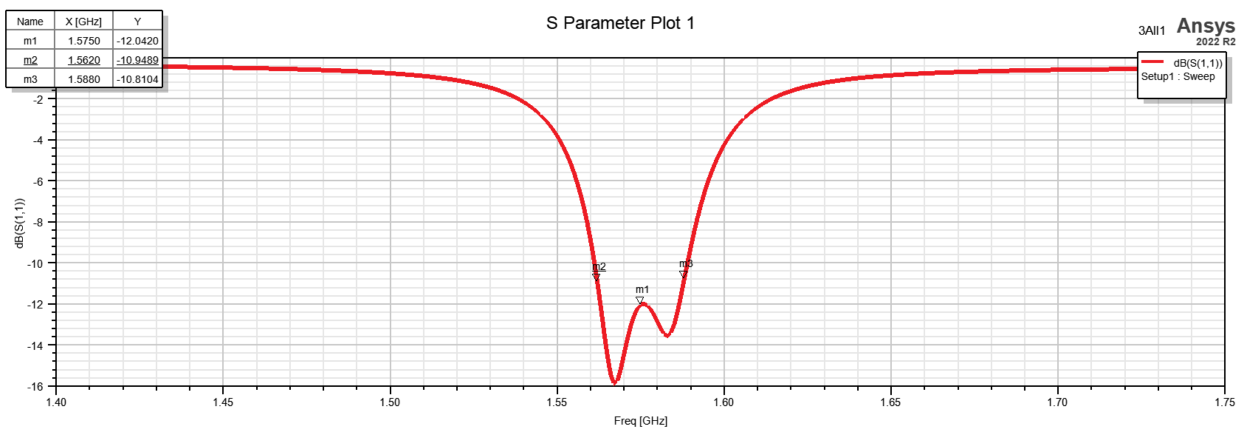

Figure 26: S11 of Microstrip Patch Array with Reflector

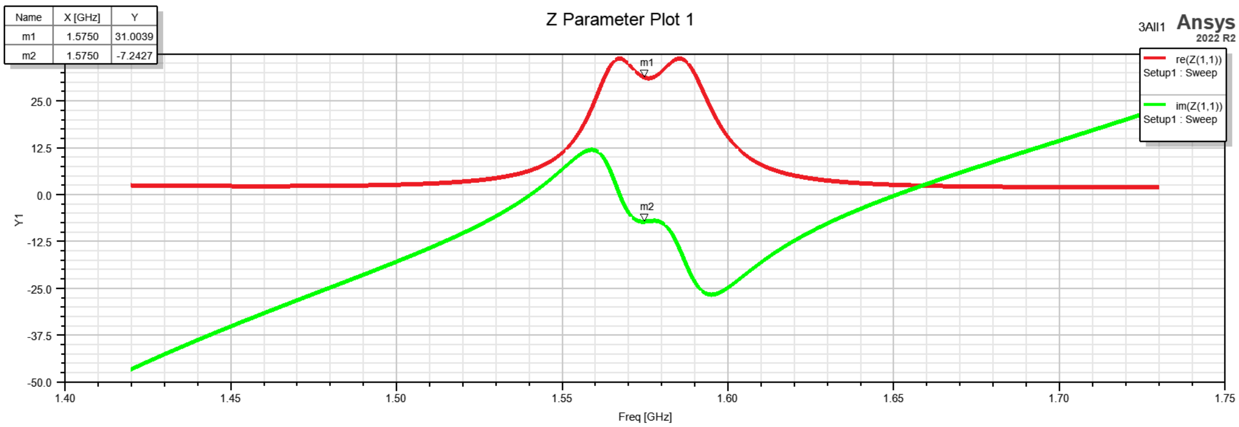

Figure 27: Z11 of Microstrip Patch Array with Reflector

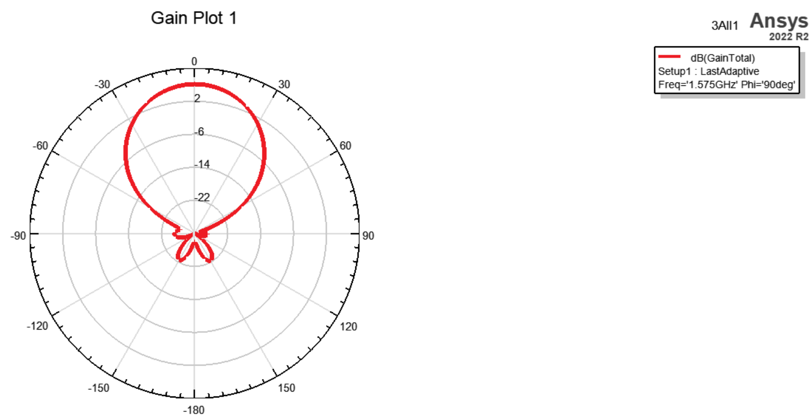

Figure 28: Gain Plot of Microstrip Patch Array with Reflector

Table 6: Efficiency of Microstrip Patch Array with Reflector

Frequency (GHz)	Peak Gain (dB)	Peak Directivity (dB)	Efficiency (%)
1.575	8.782792	10.891018	61.54%

Power at Satellite Receiver

Description taken from project outline:

If the transmitter provides 1 Watt to the antenna, what would be the power density (in Watts/m^2) at the satellite to which this antenna is assumed to be communicating with, if its altitude is 20200 km?

The power density at the satellite 20200 km away would be given by

$$p = \frac{P_T}{4\pi R^2}$$

where $P_T = 1\ W$ and $R = 20200\ km = 20{,}200{,}000\ m$. Substituting in the values, we obtain

$$p = \frac{1}{4\pi(20{,}200{,}000)^2} = 1.951 \times 10^{-16}\,\frac{W}{m^2}.$$

Because the transmitting GPS antenna has a peak gain in the direction of the zenith, we can multiply the power density by the antenna gain found through HFSS.

$$p = 1.951 \times 10^{-16} \cdot 10^{\frac{8.78}{10}} = 1.473 \times 10^{-15} \frac{W}{m^2}$$

Elsewise, in decibel milliwatts the power density is

$$p = -118.318 \frac{dBm}{m^2}.$$

Challenges

This project had many challenges because I decided to create an array instead of only a simple microstrip patch antenna on top of a reflecting box. Although the simple patch had its own challenges, I found the project to be much more challenging once the feed network was added in. There were many parameters to tune and optimize, which would have taken a lot of computing power and time if I wanted to sweep over everything to find the best fits.

For example, with the simple patch I was able to sweep over the length and width of the patch to determine the best S11 and Z11 responses that corresponded to a well-matched system. However, once I added in the second patch, the meshing time and computing time became much longer. With some time, I was able to determine a good length for the 100 Ω line so that the patches are approximately half a wavelength away from the edges of each other.

Once I added in the other two patches to form my 2x2 array, it took HFSS even longer to mesh the model and compute. Running it once with one parameter would take about 3-4 hours. Because of this, I was not able to tune the antenna like the 2x1 arrays and the simple patch antenna. It was not viable given the time constraints for this project. Also, with the more patches added, I required a higher number of passes, otherwise HFSS would not converge. This increased the simulation time by much more. It took much longer to mesh the structure to meet the convergence criteria than it took for solvers to run.

To address the computational speeds, I made a few modifications to the solution set-up and the solvers. The first thing I did to speed up the computations was to ensure that I was running a frequency sweep over at least ±10% of the operating frequency. This difference could be seen in my 2x1 parallel patch array S11 and Z11 plots and onwards. This did help to reduce the number of points HFSS had to solve for, but it still took a long time to run one simulation because of the meshing part.

The next thing I did was change the order of basis function to second order and select the Auto Select Direct/Iterative radio box in the Driven Solution Setup > Options. The second order was used to decrease the size of the meshing. I don't think I noticed any difference in the meshing times. Aside from computing speeds, I also had the issue of "fake convergences". To address these fake convergences, I had to increase the minimum number of converged passes to ensure that the mesh did converge properly. This took requirement made the meshing times much longer.

As a last resort, I tried changing the number of cores that HFSS could use and increase the RAM limit under Simulation > Analysis Configuration. Increasing the number of cores and the RAM limit did help with the solving speeds and I noticed a difference in the simulation times, but I still found it unfeasible to tune the parameters given the time constraints and computing power I had.

Finally, when I added the reflector to the bottom of the patch array, the peak directivity and the peak gain of the system decreased from when there was no reflector. As mentioned previously, I expected the reflector to improve the gain and directivity, so I was not sure why this was happening. I tried a series of things such as increasing my radiation box until I was out of RAM, but it did not affect the results much. I also tried changing the distance of the ground plane beneath the patch array, like 0 mm, 3 mm, etc., but it either increased or decreased the peak directivity and peak gain by a few decimals. Another thing I tried was to add a thickness to the box instead of using a sheet for the reflector, which also only improved the directivity and gain by a few decimals. Lastly, because I was using a copper sheet/box, I changed it to a perfect electrical conductor (PEC) and the results, again, did not change much.

Executive Summary

A microstrip GPS antenna operating in the L1 band of 1575 MHz would require a bandwidth of 2-20 MHz depending on its application with a gain of 2-5 dB. The proposed transmitting antenna would be facing the zenith and placed on top of a highly conducting box or reflector and then placed on top of a truck. To meet these specs, I aimed to design a low-cost 2x2 aftermarket microstrip patch array using copper on a 25 cm by 25 cm Rogers 4003 substrate with an efficiency of 61%. The array consists of two patches in series and fed in parallel with another two patches in series. This array layout was chosen for its compactness, simplicity, and ease of manufacturing and fabrication. The array is used to improve the gain and directivity compared to a simple single microstrip patch antenna. There were multiple stages to the design process, starting with a single patch antenna. Next, a feed network for a 2x1 series array and another one for a 2x1 parallel array were implemented. Finally, the two put together to create the 2x2 array and the reflector was introduced. The results at every stage were compiled and presented in this report, showing that the 2x2 array had the best performance in terms of gain and directivity, reaching a peak gain of 9.34 dB, compared to the other antennas created in the design process.

Bibliography

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