ECE4122 DESIGN PROJECT

Eric Horng 26935449

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Introduction

Antennas are electromagnetic transducers that both convert electrical signals into free-space electromagnetic waves (transmission) and convert free-space electromagnetic waves into electrical signals. This allows devices to wirelessly communicate with each other and form the basis of many technologies we used today such as mobile phones, Wi-Fi and television.
Antennas come in different forms such as horn, patch, wire and waveguide slots, providing different performance characteristics and features. Antennas can be arranged into arrays, giving different directivity and gain characteristics as the electromagnetic waves interfere constructively and destructively.

In this project, a 2-patch antenna array is designed according to the specifications given in Table 1 and Table 2, centered around an operating frequency of 2.4 GHz. A patch antenna and 3-db power divider is modelled in CST microwave studio, integrated to create a 2-element linear array, and tuned using a parametric sweep to give desired performance characteristics.

Parameter	Notation	Value
Substrate Material	-	FR4
Substrate Height	h	1.6 mm
Substrate Relative Permittivity	ε_r	4.3
Patch Material	-	Copper
Copper Thickness	t	0.017 mm
Ground Plane Material	-	Copper
Array Configuration	-	2 -elements linear array
Resonant Frequency	f_r	Your assigned design frequency
S_{11} at Resonant Frequency (with ±10% tolerance)	S_{11} (dB)	< -10 dB
Realized Gain at Resonant Frequency	$G_{realized}$	> 5 dB

Table 1. Design requirements of patch antenna array

Parameter	Notation	Value
Substrate Material	-	FR4
Substrate Height	h	1.6 mm
Substrate Relative Permittivity	ε_r	4.3
Track Material	-	Copper
Ground Plane Material	-	Copper
Copper Thickness	t	0.017 mm
Design Frequency	f_r	Your assigned design frequency
S_{11} in [f_r (GHz)-0.5GHz, f_r(GHz)+0.5 GHz]	S_{11} (dB)	< -10 dB
S_{21} in [f_r (GHz)-0.5GHz, f_{res}(GHz)+0.5 GHz]	S_{21} (dB)	≈ -3 dB
S_{31} in [f_r (GHz)-0.5GHz, f_r(GHz)+0.5 GHz]	S_{31} (dB)	≈ -3 dB

Table 2. Design requirements of 3-db power divider

Background Theory

Microstrip Patch Antennas and Arrays

Microstrip patch antennas are comprised of two conducting layers separated by a dielectric substrate (Figure 1). These antennas radiate through fringing fields [1]. As the antenna patch is charged, an electric field is created in the substrate between the patch and ground plane, with maxima on the edges of the patch. These fields extend beyond the patch hence radiate perpendicular to the patch. Microstrip antenna are valued due to their low cost, portability and high efficiency [1].

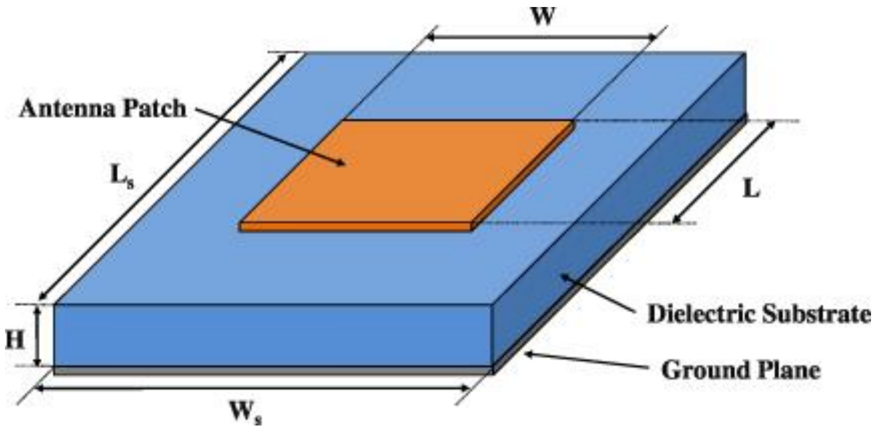

Figure 1. Microstrip patch antenna structure [2]

Impedance Matching, Reflection Coefficient and Return Loss

Impedance matching between the antenna and the transmission line is important to provide maximum power transfer. If the impedance between the transmission line and antenna is different, then a proportion of the power in the line is reflected off the antenna input port. The amount of reflection off the antenna in decibels is denoted as Return Loss and can be calculated through:

$$RL = 20\log_{10}\frac{1}{\Gamma}\ db$$

where

$$\Gamma = \frac{Z_A - Z_0}{Z_A + Z_0}$$

Γ is known as the Reflection Coefficient and is the ratio between the antenna input impedance Z_A and the transmission line impedance Z_0. The network parameter S11 is the negative of RL. In general, a larger RL is, the better the antenna is matched to the feed (conversely, the more negative S11 is, the better the matching).

Radiation Pattern

The radiation pattern of an antenna is the intensity of radiation in the space around the antenna. Different types of antennas have different radiation patterns which provide different characteristics at points around the antenna. For a microstrip patch antenna, the radiation pattern is in the shape of an elongated ‘balloon’ with two side lobes as shown in Figure 2.

Figure 2. Radiation pattern for a microstrip patch antenna [3]

Directivity

The directivity of the antenna is the direction and power transfer in which the intensity of radiation is largest. An antenna with a high directivity focuses most of its radiation in one direction, while an antenna with low directivity radiates most of its power around itself in a spherical shape.

Gain

The gain of the antenna is similar to the directivity except it takes into account the associated ohmic losses of the antenna. The gain is the product of the directivity and the efficiency of the antenna. The efficiency of the antenna is the ratio of the power provided to the antenna and power radiated. Energy loss due to finite conductivity and lossy substrates result in an efficiency less than 1.

Power Dividers

Power dividers reduce the complexity of antenna arrays as it allows the network to be powered by one input line. In the project, a 3-dB power divider is created to be fed into two patch antennas, which divides the power equally between the antennas. A power-divider's main purpose is to impedance match the power line and the antennas as you split the power line. Splitting a 50-ohm power line into two, creates two equivalent 100-ohm lines in parallel, resulting in an impedance mismatch between the 50-ohm antenna and the 100-ohm input split power line. Hence an impedance matching network is needed. For the project, a quarter length impedance transformer is used.

Design Procedure

The initial patch antenna dimensions were calculated using the equations found in Appendix 1:

$$Patch\ width = 0.0461\ m$$
$$Patch\ length = 0.0358\ m$$
$$50 - ohm\ microstrip\ feedline\ width = 0.0031\ m$$

The patch antenna was then modelled in CST Microwave Studio using dimensions in Table 1, and the initial dimensions from Appendix 1. The inlet length was initially set to 10 mm and a time-domain simulation was run to calculate S21, which provided performance characteristics which weren't within design specifications. A parametric sweep was then performed on the inlet length to get better impedance matching (i.e. increase S21) until a value less than -30 dB was achieved. Another parametric sweep was performed on the patch length and width to centre the resonance frequency around 2.4 GHz.

The dimensions of the 3-dB power divider was calculated using the CST impedance calculation tool, with a desired resistance of 70.7 ohms and desired phase of 90 degrees. The 3-db power divider was then integrated into the antenna network and the dimensions of the antenna and inlet optimized for our design specification. The final dimensions of the antenna are:

$$Patch\ width = 0.03715\ m$$
$$Patch\ length = 0.0291\ m$$
$$Inlet\ length = 0.007\ m$$

Simulation Results

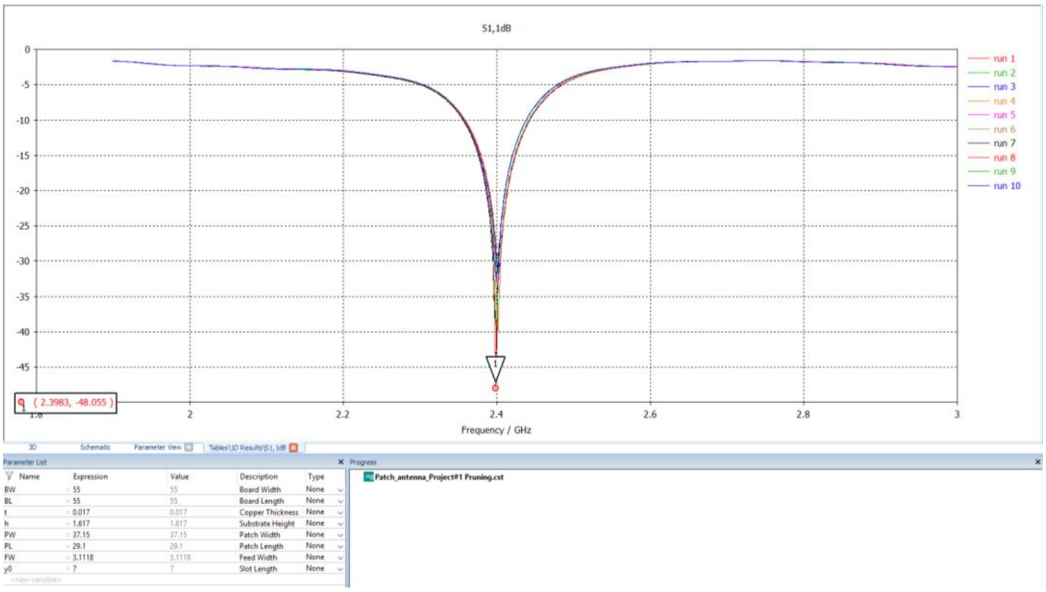

Figure 3. Simulated S11 of final design

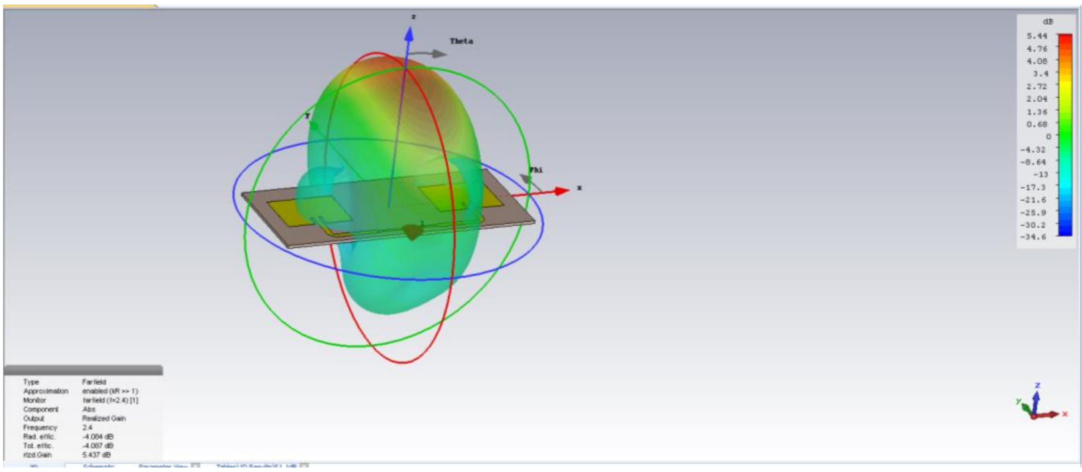

Figure 4. Simulated Far Field pattern and gain of final design

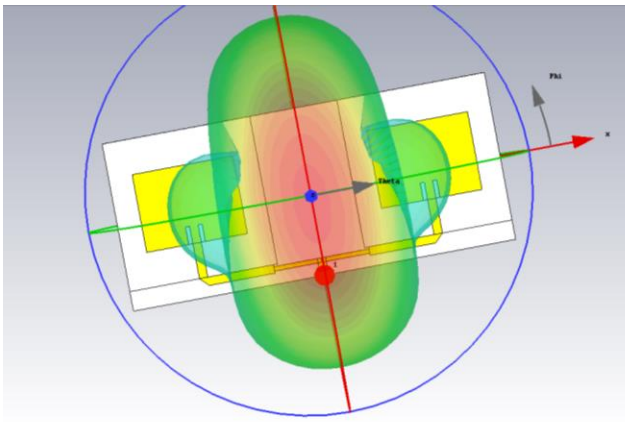

Figure 5. Simulated Far Field Top View

Measured Results

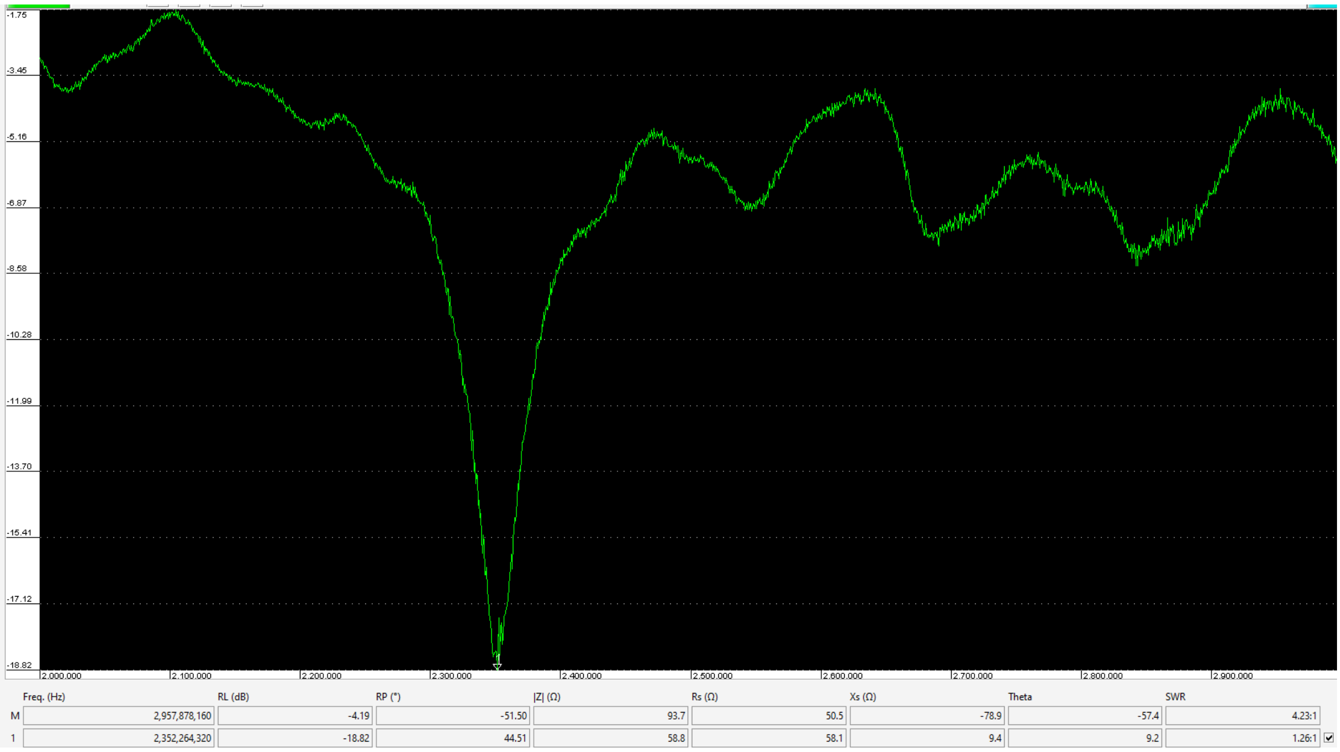

Figure 6. S11 of Fabricated Antenna

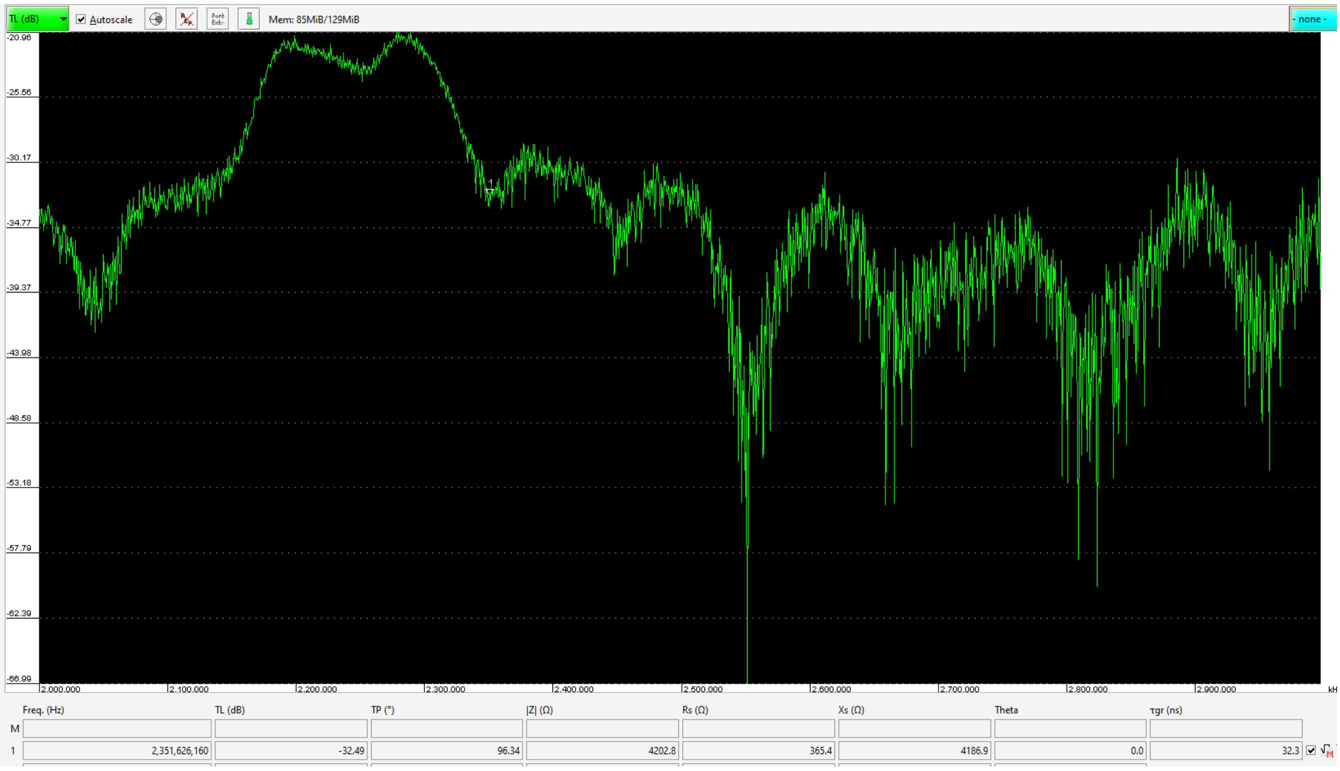

Figure 7. S21 of Fabricated Antenna at Resonance Frequency

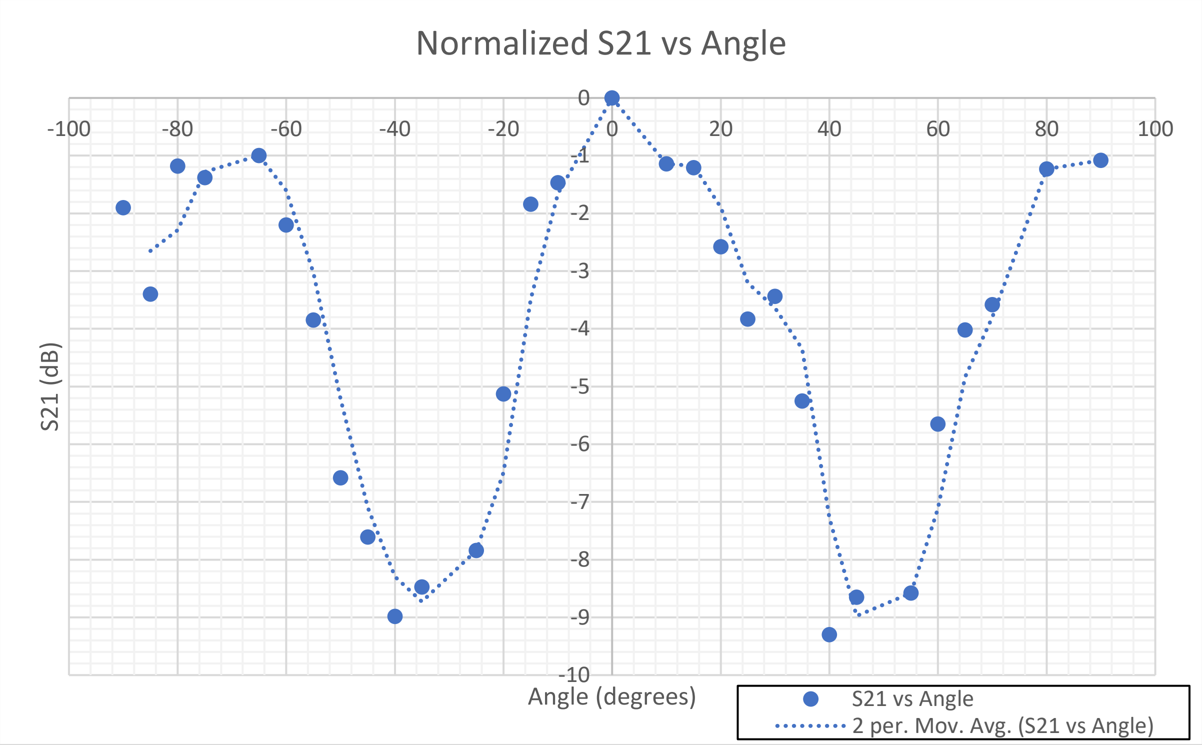

Figure 8. Normalized Radiation Pattern of Fabricated Antenna

10dB Antenna Bandwidth

$$f_0 = 2.3516\ GHz$$
$$f_L = 2.3197\ GHz$$
$$f_H = 2.3873\ GHz$$
$$\%BW = \frac{f_H - f_L}{f_0} * 100 = 2.877\%$$

Gain measurement using Friis Transmission Equation

$$Gain(db) = \frac{1}{2}\big(32.45 + 20\log(2.352) + 20\log(0.2) + (-32.49)\big)$$
$$= -3.295\ dB$$

3dB beamwidth

$$\theta_L = -14°$$
$$\theta_U = 24$$
$$= 38°$$

Side Lobe Level

$$SLL_{Left} = -1dB$$
$$SLL_{Right} = -1dB$$

Discussion

From Figure 3, the simulation calculated the resonance frequency of the antenna to be at 2.3983GHz (0.07% error) with an S11 of -48.055 dB. From Figure 4, the realized gain was calculated to be 5.437 dB. Thus, the modelled design met all design specifications (greater than 5dB gain, resonance frequency within 10% of 2.4GHz, S11 less than -10dB) according to the simulations.

The fabricated antenna had worse S-parameters from the simulated model. The antenna had a S11 at -18.82dB (39% of simulated result) at a resonance frequency of 2.352GHz, giving an approximate 2% error to the assigned frequency of 2.4GHz. This is still within the minimum design specification however. The gain was calculated to be 3.295 dB, which is less than the simulated gain, and less than the minimum design specification of 5 dB. From Figure 8, we can see the radiation pattern of the antenna. It is not as directional as the simulated far field plot as dictated by the 3dB beamwidth, and the side lobes are large, almost at the same power level as the main lobe.

A possible explanation into the difference in performance between the simulated and fabricated antenna is the impurity of the materials used in manufacturing and the resolution of the dimensions of the manufactured antenna. The simulation assumed that the substrate and conductor were homogenous with no impurities. Impurities in the FR4 and copper can change the permittivity and permeability giving different readings. The machine that manufactured the antenna could have a minimum resolution. The simulated model had a resolution in dimensions of 0.01 mm, however the machine could have a resolution of 1mm, rounding up and changing the dimensions of the antenna. From the parametric sweep, small changes in dimension gave large changes in the S-parameters. The small directivity and large lobes could be a result of this manufacturing discrepancy. If the distance between antenna in the array is changed, then the electromagnetic waves would constructively and destructively interfere with each other in a non-desired way. Thus, the antenna would behave as two separate antennae, with the large side lobes being the maximum directivity of each antenna and the main lobe being a constructive superposition of the two antenna adjacent side lobes. Different variables such as incorrectly calibrated network analyser and outside radiation interference could also be a factor in the discrepancy of results.

ECE4122 Brainstorming

What parameters changes the S parameters result?

Changing patch length predominately changes the resonance frequency while changing the inset length changes the amplitude of the S11 parameter at resonance. It was discovered that changing the patch length also slightly changed the amplitude at resonance, at one point reducing it to below minimum design requirements, however changing the patch width as well increased the resonance amplitude. Thus, it was a balancing act between patch length, patch width and inset length to get desired performance out of the antenna.

How does a microstrip patch antenna radiate? What is a fringing field? Does the substrate size change the S parameters? is there min subs size that does not change the S-param?

The patch antenna radiates using fringing fields (explained in Background. Microstrip Patch Antennas and Arrays). These fields extend perpendicularly past the patch. The fringing field is the electric field outside of the electric field directly under the patch. Changing the substrate size would not have a large effect on the S-parameters. However, if the height of the substrate is less than the length of the fringing fields, then this would interfere with the operation of the antenna as it wouldn't be able to correctly produce fringing fields, thus the S-parameters would change.

Why when incorporating the power divider to the patches, the performance is different to the single patch?

With the single patch, power is supplied to the antenna through a specifically designed microstrip power line with a 50-ohm impedance. When the power divider is incorporated into the patch, this changes the impedance of the power line. Even though a quarter-length impedance transformer is used, the impedance is still different from the original 50-ohm feed line (slightly) resulting in a different impedance mismatch and hence different performance.

What happens if the inter-element distance too close? and too far?

Changing the inter-element distance changes the directivity (gain) of the antenna and the radiation pattern. If the inter-element distance is closer, then the electromagnetic waves interfere destructively and constructively differently than there were at 0.7λ apart. If the antennas are too close, then the antenna would basically behave as one big patch antenna, however the width would be extremely large, giving bad performance and S-parameters. If they were too far apart, then the antennas would basically behave as two separate antennas, thus it wouldn't be as powerful as the array.

What is the reflection coefficient? Why are you asked to ensure the S11 value to be at least less than -10 dB?

The reflection coefficient is a measure of how closely the antenna impedance is matched to the transmission line and thus how much power is transferred from the line to the antenna and not reflected. A S11 value of -10dB ensures that at least 90% of power is transmitted and not reflected.

Any possible reason for why the device performance is not as good as simulated?

Possible reasons include (discussed in Discussion):

- Material impurities
- Manufacturing measurement resolution
- Interference from outside sources when performing S-parameter scan
- Incorrectly calibrated VNA Mini

How do you ensure at least three mesh cells across the substrate or gaps? Why is it important?

The mesh density settings of the antenna in CST Microwave Studio were changed to ensure there were at least three mesh cells across the substrate and gaps. This is important as the mesh cells determine the accuracy of the simulations. Since the patch antenna radiates through the edge of the antenna and the gaps due to fringing fields, and the main electric fields are in the substrate, the density of the cells in these areas were increased to ensure an accurate simulation.

Conclusion

The goal of this project was to design a 2-array patch antenna with a resonance frequency of 2.4GHz. CST Microwave studio was used to design and simulate the patch antenna. A parametric sweep was used to find the optimum dimensions for the patch width, patch length and inset length to get desired performance characteristics. The simulations calculated that the antenna would have a resonance frequency of 2.3983GHz, S11 of -48.055 dB and gain of 5.437 dB, which is within design requirements. The fabricated antenna however gave different performance characteristics, with a resonance frequency of 2.352GHz, S11 of 18.82dB and gain of 3.295 dB. Only the gain was below the minimum performance requirements. A possible reason into why performance differed from simulation and reality was due to inaccurate manufacturing and possible subpar materials used. This design project was good in detailing the design process when creating an antenna to meet a specification, the disparity in results between simulation and reality due to many factors outside of your control. When designing another antenna, I would try to make the antenna more robust, factoring manufacturing variables into the design (i.e. offsetting the resonance frequency above the desired frequency so the real antenna would be more accurate) and possible optimizing more to get maximum performance.

References

[1] Monash University Department of Electrical and Computer Systems Engineering, “Design Project: Design of a 2-element Rectangular Microstrip Patch Antenna Array,” *Design Project Manual 2018*, October 2018 [Online]. Available: https://moodle.vle.monash.edu/pluginfile.php/7316015/mod_folder/content/0/Design%20Project%20Manual%202018.pdf?forcedownload=1 [Accessed Oct. 23, 2018]

[2] H. Jang, W. Lee, C. Kim, “Design and fabrication of a microstrip patch antenna with a low radar cross section in the X-band,” IOPScience, Dec. 9, 2010 [Online]. Available: https://cdn.iopscience.com/images/0964-1726/20/1/015007/Full/6133101.jpg [Accessed Oct. 23, 2018]

[3] Monash University Department of Electrical and Computer Systems Engineering, “LAB 6: Antenna and Antenna Array *ECE4122 Lab 6 Manual*, October 2018 [Online]. Available: https://moodle.vle.monash.edu/pluginfile.php/7323044/mod_folder/content/0/ECE4122%20Lab%206%20manual.pdf?forcedownload=1 [Accessed Oct. 23, 2018]

Appendix

Appendix 1. Equations used to determine patch antenna dimensions

$$W = \frac{1}{2f_r\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$e_{effective} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-\frac{1}{2}}$$

$$\Delta L = h * 0.412 * \frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\varepsilon_0\mu_0}} - 2\Delta L$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_{r+1}}{2}} + \frac{\varepsilon_r + 1}{\varepsilon_r - 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

$$Small\ Ratio = \frac{8e^A}{e^{2A} - 2}$$

$$Big\ Ratio = \frac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left(\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right]$$

Since Big ratio is greater than 2, we used that value giving a width:

$$w = h * Big\ Ratio$$

Appendix 2. Data for S21 vs angle

Angle (degrees)	S21	Normalized S21
-90	-35.06	-1.9
-85	-36.56	-3.4
-80	-34.34	-1.18
-75	-34.54	-1.38
-70	-35.29	-2.13
-65	-34.16	-1
-60	-35.36	-2.2
-55	-37.01	-3.85
-50	-39.74	-6.58
-45	-40.77	-7.61
-40	-42.14	-8.98
-35	-41.63	-8.47
-30	-40.17	-7.01
-25	-41	-7.84
-20	-38.29	-5.13
-15	-35	-1.84
-10	-34.63	-1.47
-5	-35.03	-1.87
0	-33.16	0
5	-34.93	-1.77
10	-34.3	-1.14
15	-34.37	-1.21
20	-35.74	-2.58
25	-36.99	-3.83
30	-36.6	-3.44
35	-38.41	-5.25
40	-42.46	-9.3
45	-41.81	-8.65
50	-39.27	-6.11
55	-41.74	-8.58
60	-38.81	-5.65
65	-37.18	-4.02
70	-36.74	-3.58
75	-37.47	-4.31
80	-34.39	-1.23
85	-36.36	-3.2
90	-34.24	-34.24