FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN ELECTRONICS AND COMMUNICATIONS ENGINEERING

Antennas 521388S:

Design Assignment 2024
Group 24

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CONTENTS

LIST OF SYMBOLS AND APPREVIATIONS

CST	Computer Simulation Technology
f_r	Resonance frequency of the antenna
μ_0	Permeability of free space
ϵ_0	Permittivity of free space
ϵ_r	Dielectric constant of the substrate
ϵ_{reff}	Effective Dielectric Constant
e_{cd}	Conduction and dielectric efficiency of the antenna
G	Gain as a function
D	Directivity as a function

1 DESIGN TASK IN BRIEF

The task assigned was to design a single micro-strip rectangular antenna with linear polarization as the first step and then make an array of antennas of the same type as second part. The specifications of the given design task is summarized in Table 1.1.

Table 1.1. Design Specifications for the task

Group Number	Antenna Type	Polarization	Freq ($/GHz$)
24	Patch antenna array - Square/rectangular	Linear	5.20

Chapter 2 of this report contains report on design of single element and Chapter 3 of this report contains design report of the antenna array. The design of antenna is done using the Student Licensed Computer Simulation Technology (CST) Studio software programme. Each chapter will discuss a holistic view of the required theoretical calculations for the design, the steps taken to design in the simulation tool, the results produced after the simulation and a discussion of the results observed.

2 PART 1: SINGLE ANTENNA

2.1 A Background on Rectangular Patch Antennae

A patch antenna is designed such that the maximum radiation pattern is normal to the patch plane. Numerous sustrates can be used to design patch antennae. Usually it is best practice to select substrate materials that have lower dielectric constants since they provide better efficiencies. The thickness of the substrate are desired to be thin in designing of patch antennae since they bring the advantage of minimizing undesired radiation and coupling between antennae [1].

A rectangular patch is the most widely used type of patch antenna. It is easier to analyze rectangular patches with transmission line model which can be generalized to represent a micro-strip antenna.

Dimensions of the patch, transmission line, thickness of the substrate play vital role in determining the performance of the patch antenna.

The following section discusses the theoretical calculation steps to determine the dimensions of a rectangular patch antenna.

The designing process assumes that we know the following three parameters:

1. The dielectric constant of the substrate (ϵ_r)
2. The desired resonance frequency of the antenna (f_r)
3. The thickness of the substrate (h)

- Step 1: Calculation of a practical width of the patch is found by equation 2.1.

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \tag{2.1}$$

- Step 2 : The micro-strip look wider than the physical dimensions in the context of electric field because some waves travel in the substrate and some in the air. This is called as the Fringing Effect. In order to balance out this effect an Effective Dielectric Constant (ϵ_{reff}) is introduced before using the direct value to impact the height of the design. Equation 2.2 shows the calculation of ϵ_r.

$$\epsilon_{\text{reff}} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2.2}$$

- Step 3: Using the above calculated W and ϵ_{reff} values the transmission line Fringing effect compensation length (ΔL) can be calculated as shown in equation 2.3.

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{W}{h}+0.8)} \tag{2.3}$$

- Step 4: The actual length of the patch can be calculated using equation 2.4.

$$L = \frac{\lambda}{2} - 2\Delta L \tag{2.4}$$

2.2 Actual calculation for the design

It was understood during this theoretical calculation that to design a square patch it requires an iterative method of solving for other parameters once the length and width of the patch shall be fixed to be equal or in a more strict manner, they shall be fixed to a value (ex : 15cm).

Nevertheless the theoretical calculations for the given tasks with initial values as shown in Table 2.1 provided the results as shown in Table 2.2. The Matlab Code used for the calculation is attached in 2.2.

Table 2.1. Initial values for patch dimension calculation

Parameter	Value	Remarks
ϵ_r	3.55	Rogers RO4003C (lossy)
h	$1.6mm$	
f_r	$5.2GHz$	
l_{pcb}	$30mm$	Length of the Substrate
w_{pcb}	$30mm$	Width of the Substrate
w_{thLine}	$1.5mm$	Width of transmission line

Table 2.2. Calculated values for patch dimension calculation

Parameter	Value	Remarks
L	$27.4331mm$	Length of the patch
W	$19.1248mm$	Width of the patch
ΔL	$0.7065mm$	

Table 2.3. Optimized values for patch dimension calculation

Parameter	Value	Remarks
L	$14mm$	Length of the patch
W	$13mm$	Width of the patch
ΔL	$8mm$	
w_{thLine}	$1.2mm$	Width of transmission line

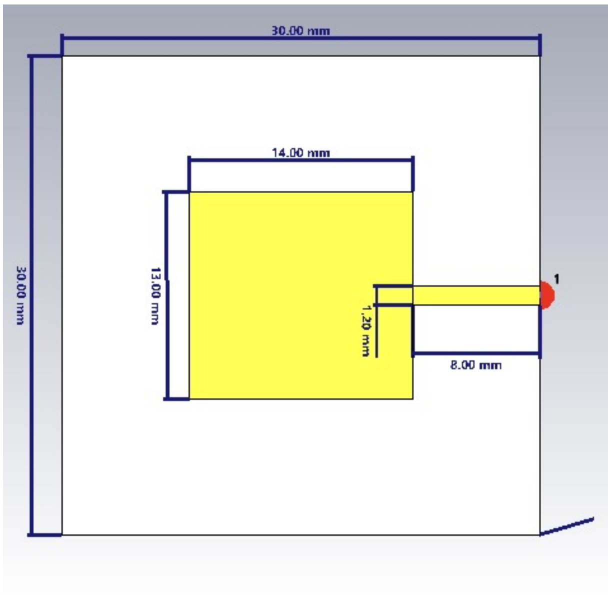

Figure 2.1. Design Dimensions 1

MATLAB Code for calculation of dimensions of the design

```
Er = 3.55;
h_pcb = 1.5e-3;
Fr = 5.2e9;
v0 = 3e8;

% Calculation of W
W = (v0/(2*Fr)) * sqrt(2/(Er+1));
sqrtBrac = (1 + 12*h_pcb/W)^-0.5;
Ermin1 = 0.5*(Er -1);
Erplus1 = 0.5*(Er +1);

% Calculation of Dielectric Constants Eff
E_reff = Erplus1 + Ermin1*sqrtBrac;

% Calculation of delta L
deltaL_num = (E_reff +0.3)*((W/h_pcb) +0.264);
deltaL_dennum = (E_reff - 0.258)*((W/h_pcb) +0.8);
deltaL = 0.412*h_pcb*deltaL_num/deltaL_dennum;

% calculation of L
lambda = v0/Fr;
L = 0.5*lambda - 2*deltaL;
```

However these values had to be optimized for the desired design with a lot of experimental trials. Table 2.3 summarizing the final optimized dimensions of the patch antenna.

Figure 2.1 show the dimensions of the patch antenna from CST.

2.3 Results and Discussion

The section contains the required results after the simulation from CST.

2.3.1 S Parameters - S_{11}

Figure 2.2 shows the variation of the magnitude of S Parameter as seen on the same port as transmitted. S_{11} in general would be the reflected power transmitted from port 1 and is observed in port 1. To develop an efficient antenna this S_{11} value should be to an acceptable minimum in the working range of the antenna. In this design the resonance frequency of the antenna is $5.2GHz$. It can be seen in Figure 2.2 that marker 1 shows the exact minimum is occuring at $5.201GHz$ with $-9.42dB$ attenuation of the reflected power. This acceptable operating range which is less than $-6dB$ is from $5.079GHz$ to $5.3372GHz$ leaving an S_{11} bandwidth of $258.15MHz$ for the designed antenna.

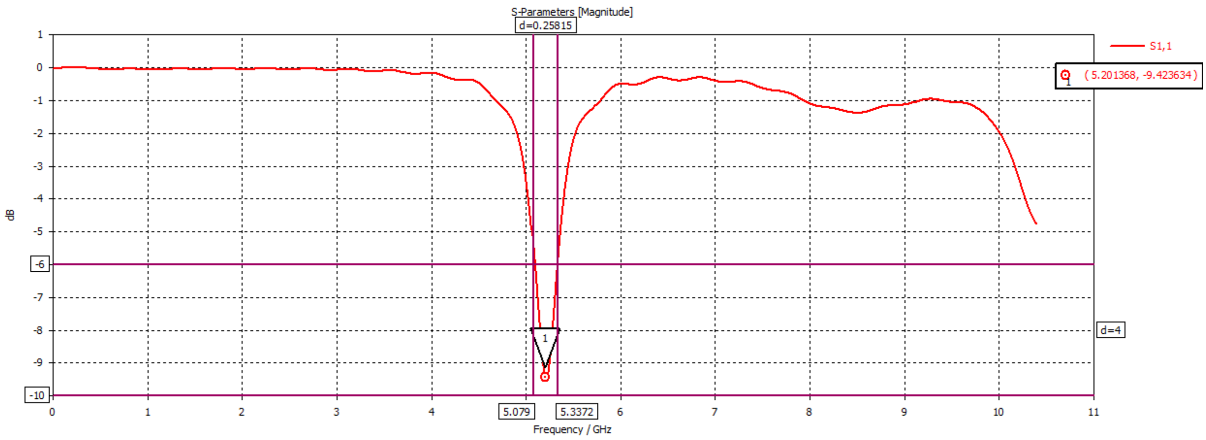

Figure 2.2. Magnitude variation of S Parameter of the antenna

2.3.2 Major Dimensions Affecting S Parameters Bandwidth and Resonance Frequency

While attempting to optimize the performance of the antenna and bring the resonance frequency to an acceptable value, it was observed that the length and width of the patch played a major role. In theory, it can also be seen, as per Equations 2.1 and 2.4, that W and f_r have an inversely proportional relationship. Similarly, ΔL and subsequently L also impact the performance of the antenna significantly.

Additionally, it was observed that h played another role which is quite chaotic to understand its impact on the performance. Therefore, after several attempts to manipulate h, it was decided to leave h fixed, mainly due to the chaotic results it produced, especially for larger values.

2.3.3 Radiation and Total Antenna Efficiencies

Antenna radiation efficiency means the fraction of the power radiated from the antenna relative to the power delivered to the antenna. However due to mismatches of impedance between the antenna and the transmission line or the generator, the total efficiency will always be lower than the antenna efficiency. This effect can be seen in Figure 2.3 where the red line shows the Radiated Antenna Efficiency and the green line shows the Total efficiency which is always lower due to aforementioned impedance mismatches [2].

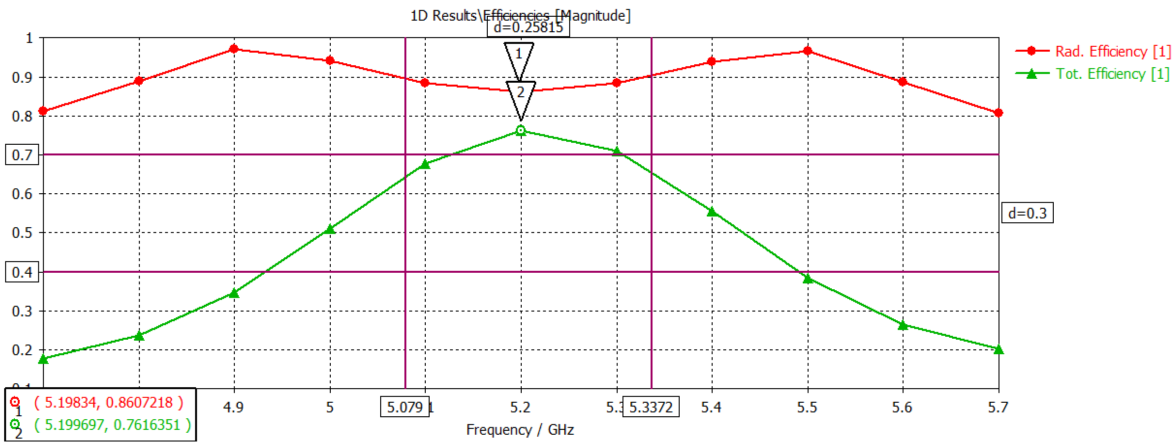

Figure 2.3. Variation of Radiation and Total Antenna Efficiency with Frequency

2.3.4 Axial Ratio

For antennas with linear polarization the axial ratio is not an interesting parameter. The axial ratio of pure linear polarization is infinite due to the orthogonal components of the fields being always zero. Therefore this was left out as not applicable in this scenario. However for the sake of completeness Figure 2.4 shows the distribution of axial ratio in 3D.

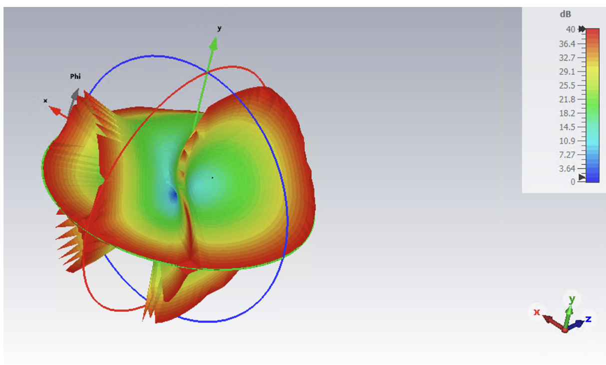

Figure 2.4. Axial Ratio Result

2.3.5 Radiation Patterns - Directivity

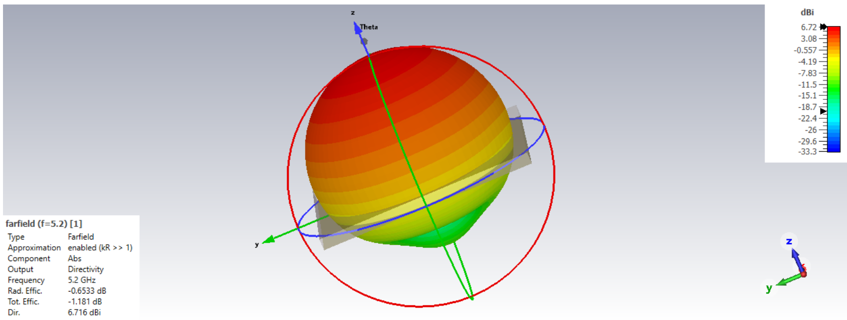

Figure 2.5. Absolute Directivity in 3D

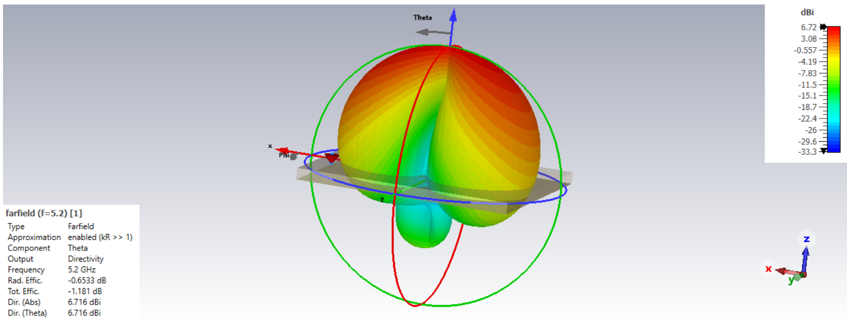

Figure 2.6. Directivity along Theta Component in 3D

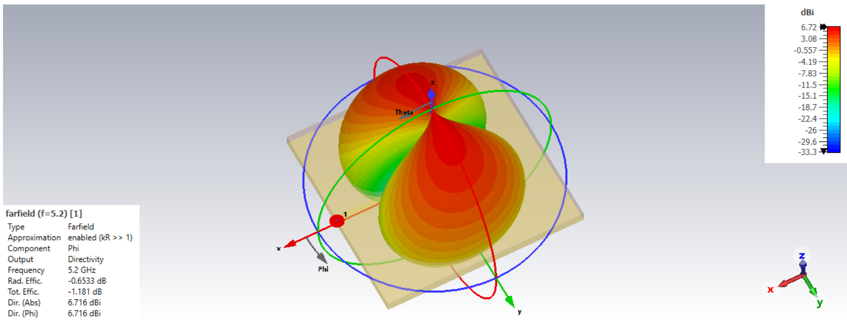

Figure 2.7. Directivity along Phi Component in 3D

2.3.6 Radiation Patterns - Gain

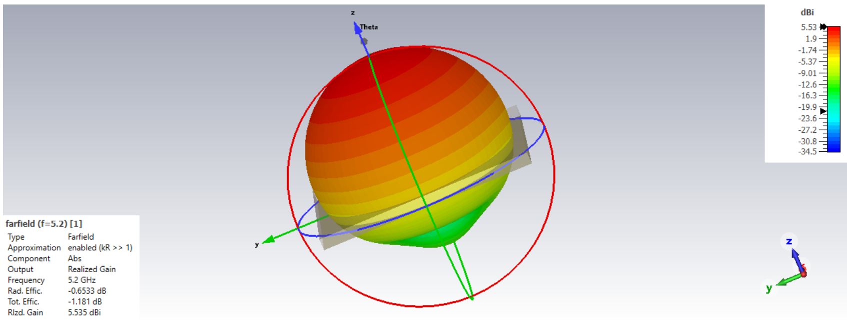

Figure 2.8. Absolute Gain in 3D

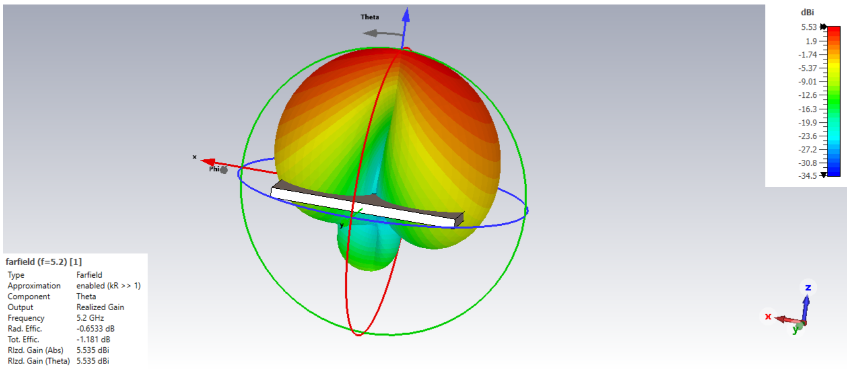

Figure 2.9. Gain along Theta Component in 3D

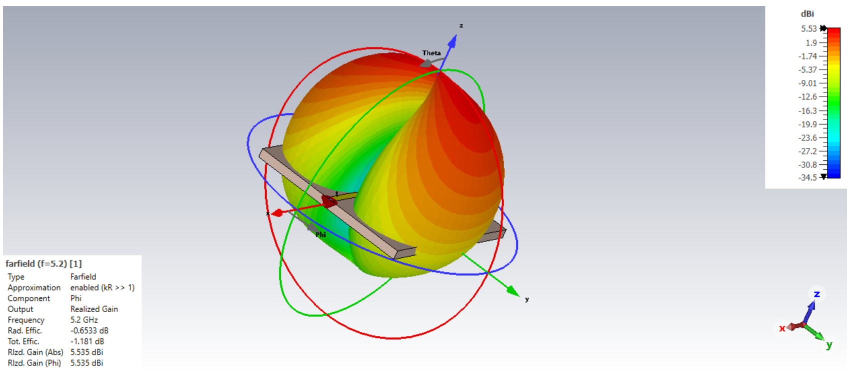

Figure 2.10. Gain along Phi Component in 3D

2.3.7 Correlation between gain and directivity

Based on the 3D plots shown in Sections 2.3.5 and 2.3.6 is can be seen the patterns of the Gain and Directivity distribution are almost identical. Therefore one can come to a conclusion there shall be a correlation between gain and directivity.

2.3.8 Correlation between gain and efficiency

Any explicit relation between gain and efficiency cannot be seen using the plots. However based on the equation 2.5 is can be obviously seen there exists a correlation between Gain and Efficiency where G stands for Gain and e_{cd} stands for conduction and dielectric efficiency of the antenna and D stands for the directivity of the antenna.

$$G(\theta, \phi) = e_{cd} \times D(\theta, \phi) \tag{2.5}$$

2.3.9 3D Plot Vs Polar Plot

Figures 2.11, 2.11, 2.13 and 2.14 show 2D Polar plots of the Gain variation across fixed planes. It is obvious compared to 3D plots presented in the previous sections that 2D Polar plots are easier to analyze. For example the plot explicitly shows the maximum direction of the parameter in question. The patterns are clearly understandable.

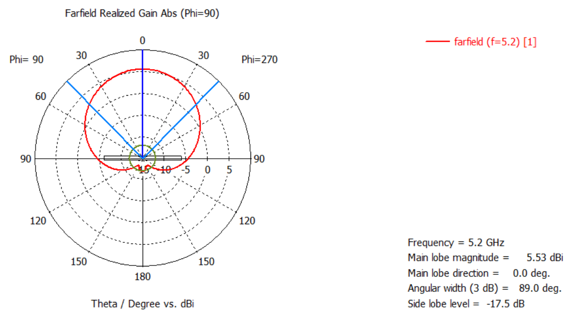

Figure 2.11. Far-field Realized Gain through ϕ = 90 plane

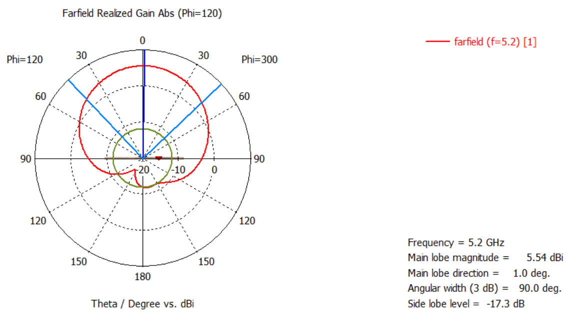

Figure 2.12. Far-field Realized Gain through ϕ = 120 plane

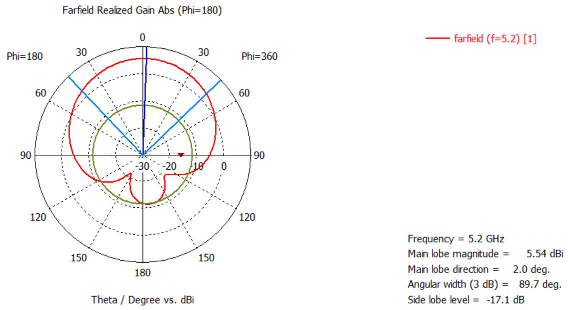

Figure 2.13. Far-field Realized Gain through ϕ = 180 plane

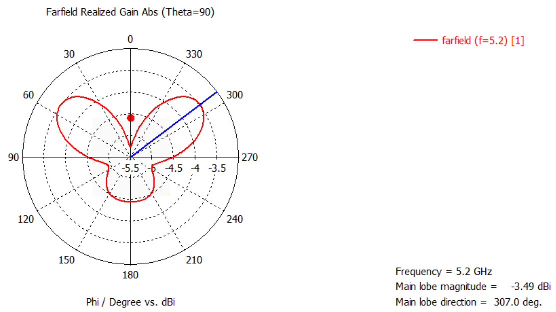

Figure 2.14. Far-field Realized Gain through θ = 90 plane

3 PART 2: ANTENNA ARRAY

3.1 Design Procedure

Linear patch antenna array was created using 4 identical copies of the single antenna designed in Chapter 2. The design procedure was to select the components and ports together and translate them along an axis linearly with equal amount of distance between them.

In the design of the linear array, in addition to the important parameters discussed in Chapter 2, the major dependency here is the distance between the individual antenna elements. However the design was done to minimize the overlap and the possible gap between each elements therefore the elements were shifted the exact amount equal to the width of the substrate used.

After the array is created the simulations were done separately for each element the results were obtained using the post processing tool in CST combining the elements in different combinations of amplitude and phase of the voltage feed for each element. The 3D design schematic is shows in Figure 3.1.

3.2 Results

Results have been produced as images in this section. Section 3.3 has the discussion answers for the questions asked in the task sheet based on the observed results in this section.

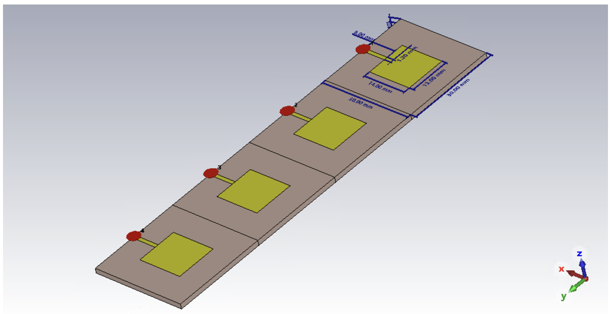

Figure 3.1. Four element linear patch antenna array

3.2.1 S Parameters - S_{xx}

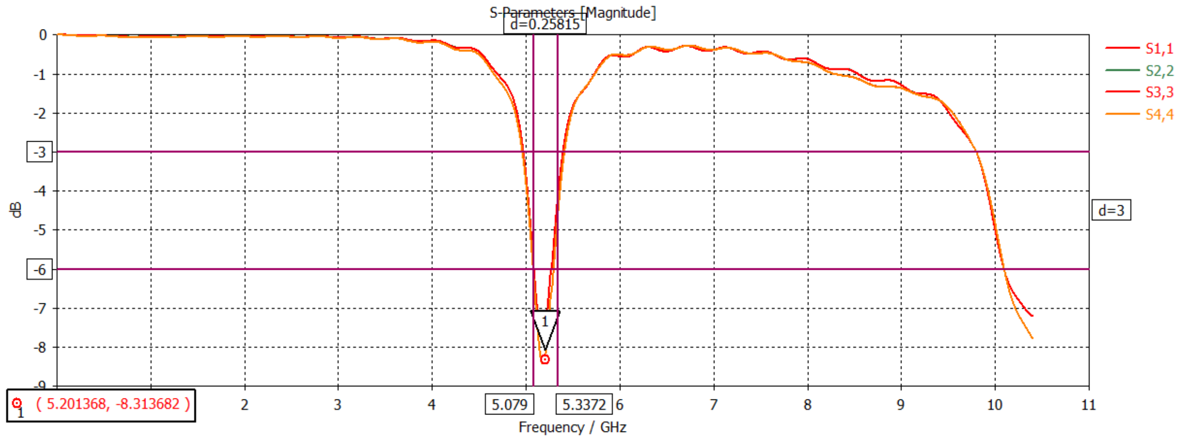

Figure 3.2. Variation of S11 magnitude with frequency for all four elements

3.2.2 S Parameters - S_{xy}

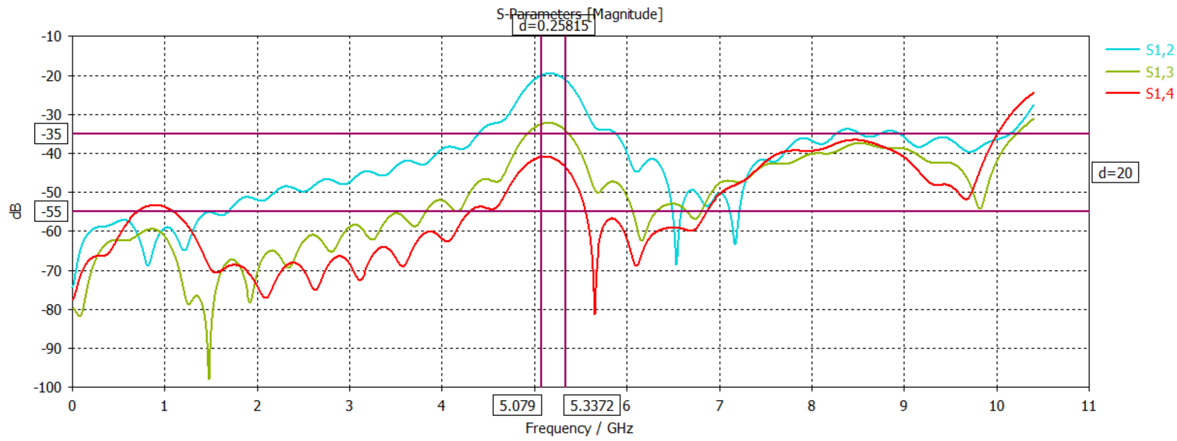

Figure 3.3. Variation of S12,S13 and S14 magnitude with frequency for all four elements

3.2.3 Efficiency

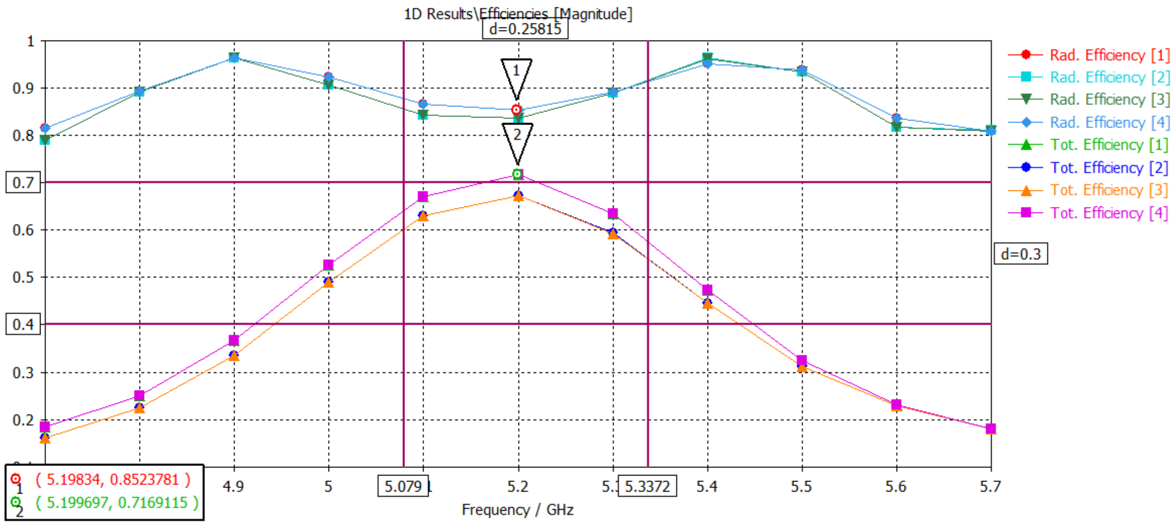

Figure 3.4. Radiation and Total Efficiencies of four elements separately

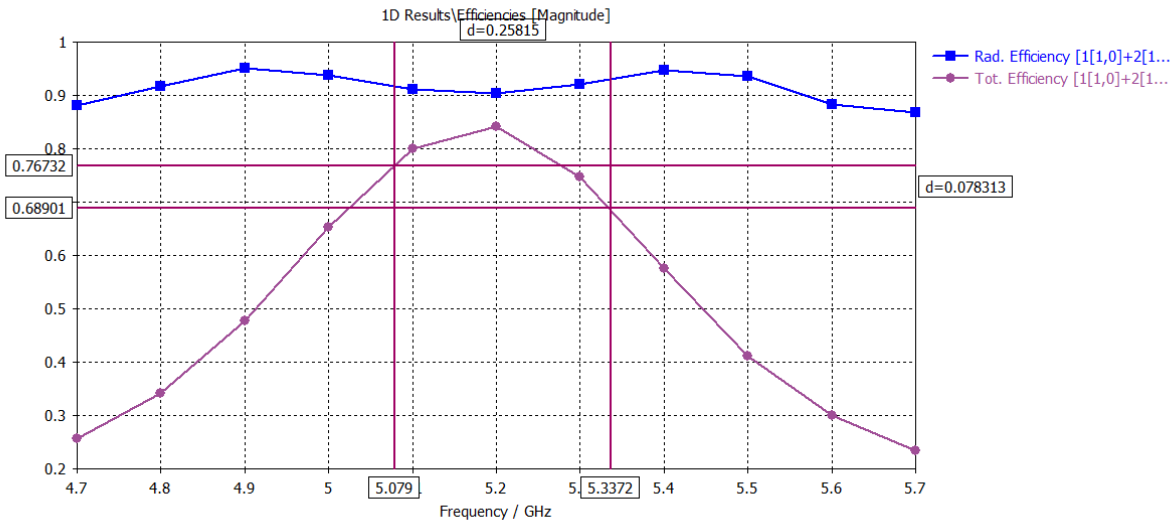

Figure 3.5. Radiation and Total Efficiencies of four elements combined together with $Amplitude = 1$ and $Phase = 0$ for all elements.

3.2.4 Radiation Patterns

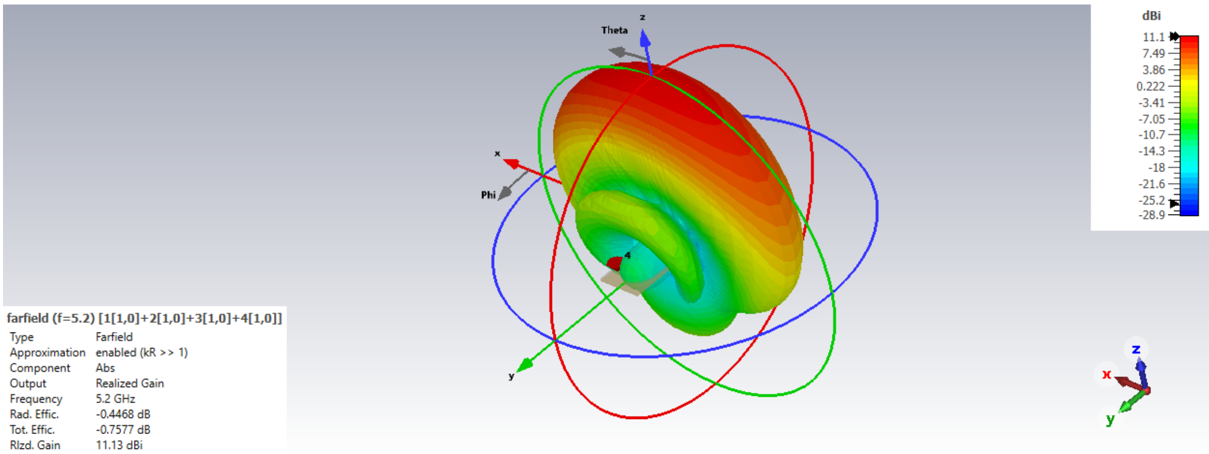

Figure 3.6. Absolute Realized Gain of the array combined together with $Amplitude = 1$ and $Phase = 0$ for all elements.

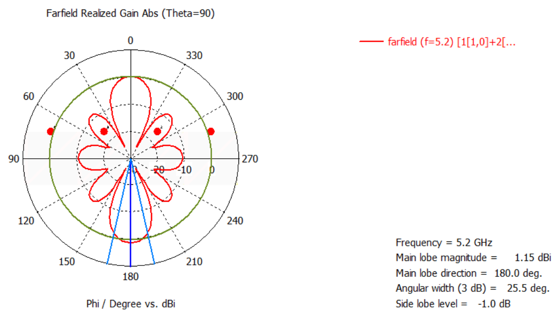

Figure 3.7. Far-field Realized Gain of array through $\theta = 90$ plane of four elements combined together with $Amplitude = 1$ and $Phase = 0$ for all elements.

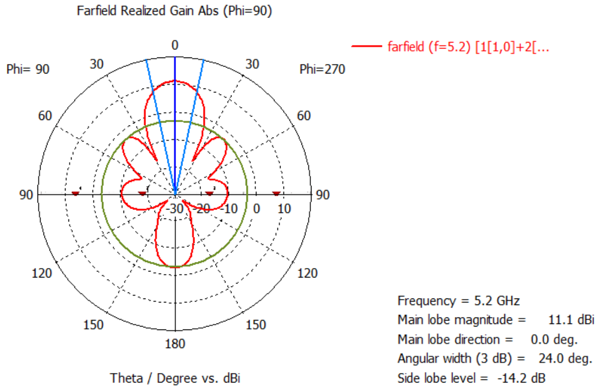

Figure 3.8. Far-field Realized Gain of array through ϕ = 90 plane of four elements combined together with $Amplitude$ = 1 and $Phase$ = 0 for all elements.

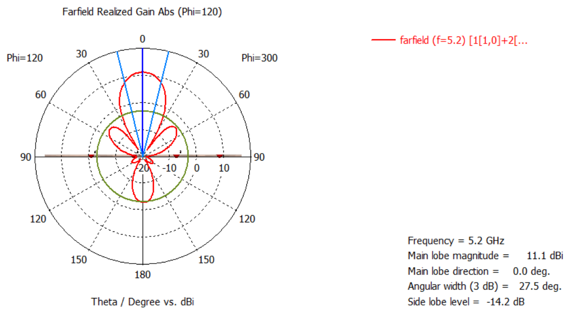

Figure 3.9. Far-field Realized Gain of array through ϕ = 120 plane of four elements combined together with $Amplitude$ = 1 and $Phase$ = 0 for all elements.

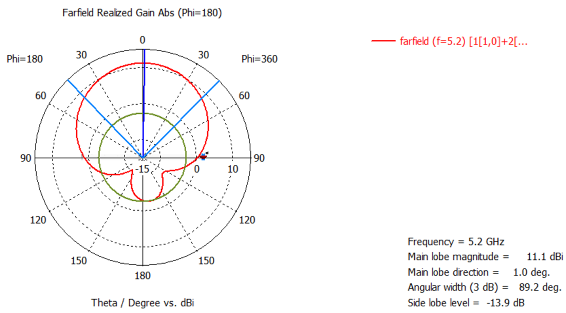

Figure 3.10. Far-field Realized Gain of array through ϕ = 180 plane of four elements combined together with $Amplitude$ = 1 and $Phase$ = 0 for all elements.

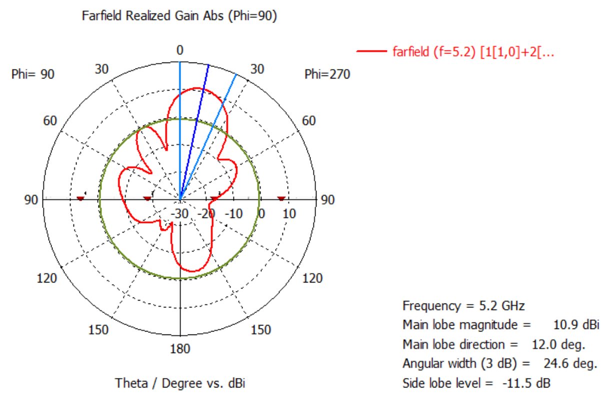

Figure 3.11. Far-field Realized Gain of array through $\phi = 90$ plane of four elements combined together with $Amplitude = 1$ and $Phase = 0, 45, 90 and 120$ respectively for all elements.

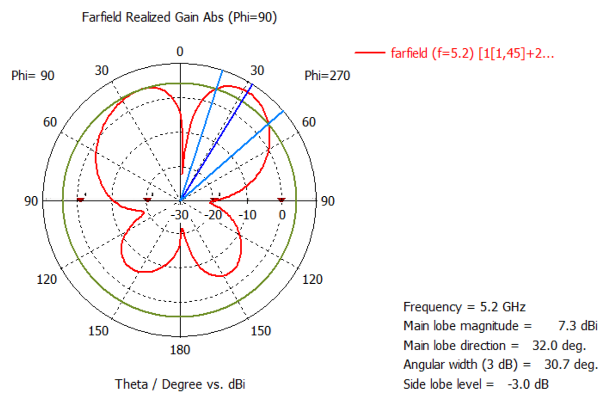

Figure 3.12. Far-field Realized Gain of array through $\phi = 90$ plane of four elements combined together with $Amplitude = 1, 3, 3, 1$ and $Phase = 45, 90, -90 and - 45$ respectively for all elements.

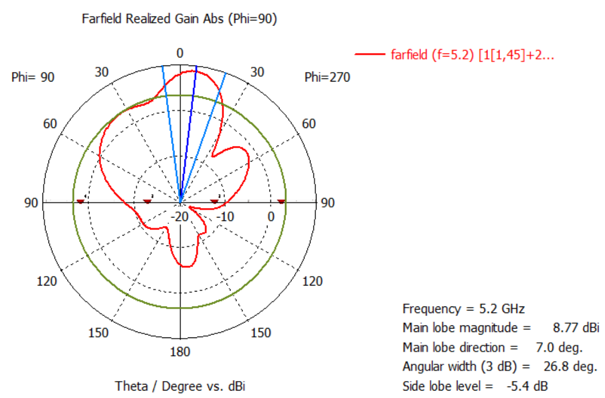

Figure 3.13. Far-field Realized Gain of array through $\phi = 90$ plane of four elements combined together with $Amplitude = 1, 3, 3, 5$ and $Phase = 45, 90, 180, 135$ respectively for all elements.

3.3 Discussion

3.3.1 Comparison between single antenna and array

- Efficiency
  Comparing Figures 2.3 and 3.5, the total efficiency of the antenna array is higher than the single antenna. This is mainly due to the diversity obtained by using multiple antenna elements in the array.

- S11 Parameter
  Comparing figures 2.2 and 3.2 it can be seen that S parameter behaviour has not much impacted when it comes to antenna array from single antenna. However the most attenuation of the reflected power observed in the antenna array has been degraded to $-8.313dB$ from $-9.423dB$. This could be mainly due to the mutual coupling between the individual elements that the reflections have become more than in the single antenna case.

- Radiation Pattern
  As compared to the single antenna case, the radiation pattern has become more directed towards the XZ plane. Therefore one of the main benefits of having antenna arrays has been observed here to have a directed beam for longer distance transmissions.

3.3.2 Difference Between S Parameter Curves

It can be seen from Figure 3.2 that S11 parameter curves for all individual elements are the same. This is due to the fact that all four elements are independently fed by each of there ports without any feeder networks. They behave identically same.

However S_{12}, S_{13}, S_{14} have different behaviours as observed in Figure 3.3. This is due the magnetic coupling between each of the elements. This mutual coupling is the electromagnetic interaction between the antenna elements in an array even though they are not connected with a feeder network.

3.3.3 Steering the antenna array beam

Visualization of steering of beams can be seen in Figures 3.11, 3.12, and 3.13. This beam steering can be achieved by manipulating the amplitude and phase of the feed ot each of the elements in the array when combining the results. In constrast to the simulator in real world this can be achieved by a microwave circuitry which will control the amplitude and the phase of the signal that is fed to each of the elements.

4 REFERENCES

[1] Balanis C.A. (2016) Antenna theory: analysis and design. John wiley & sons.

[2] Bevelacqua P., The Antenna Theory Website — antenna-theory.com. https://www.antenna-theory.com/, [Accessed 28-04-2024].