DESIGN OF MICROSTRIP PATCH ANTENNA ARRAY

ECE 541 Final Project for Spring 2023

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TASK 1

Single Element Design:

Design Process:

1. Initially I started my design by making a few patch antenna calculations and backing my math with an online calculator by EM talk.
2. The antenna is then constructed using boxes in HFSS. The values provided for the antenna length and width are set in this stage.
3. The inset box is created and placed at one of the edges of the antenna. This box is then subtracted from the main antenna.
4. Finally, a feed is included in the antenna design. The feed used here is calculated using the formulas given in the textbook and the same is checked using an online calculator by EM talk.
5. The antenna substrate used in this design is FR4-Epoxy with a thickness of 1mm. This is a very commonly found design board for PCB prototyping. From the HFSS software, it was found that the relative dielectric constant is 4.4.
6. It was observed that the antenna resonated at a lower frequency due to fringing effects. This resonance pattern in S11 was corrected by reducing the length of the patch.
7. Similarly, the impedance of the transmission line was corrected by changing the inset length and width. The feed line length and width are also tuned to get the impedace4 as close to 50 ohms as possible.

Isolated Antenna Specifications:

Given Specifications	Obtained Specifications	Met?
Bandwidth 9.8-10.2, fc=10GHz	9.8048 -10.2100GHz	Yes
|Reflection coefficient|<-10dB across the entire bandwidth with 50ohms system impedance.	-40dB at 10GHz	Yes
Feed type1. Microstrip 2. coaxial port	Microstrip	Yes
Directivity peak at broadside >5dBi	5.966dBi	Yes
Linear polarization	Linear polarization	Yes
Radiation efficiency >55%	63.2%	Yes
Broadside polarization Ratio <-20dB	50.3805dB	Yes
Fits within a 14 x14 x2 mm		Yes

Table 1: Isolated Antenna Specifications.

Documentation:

1. **Sketch of the geometry with final dimensions labelled.**

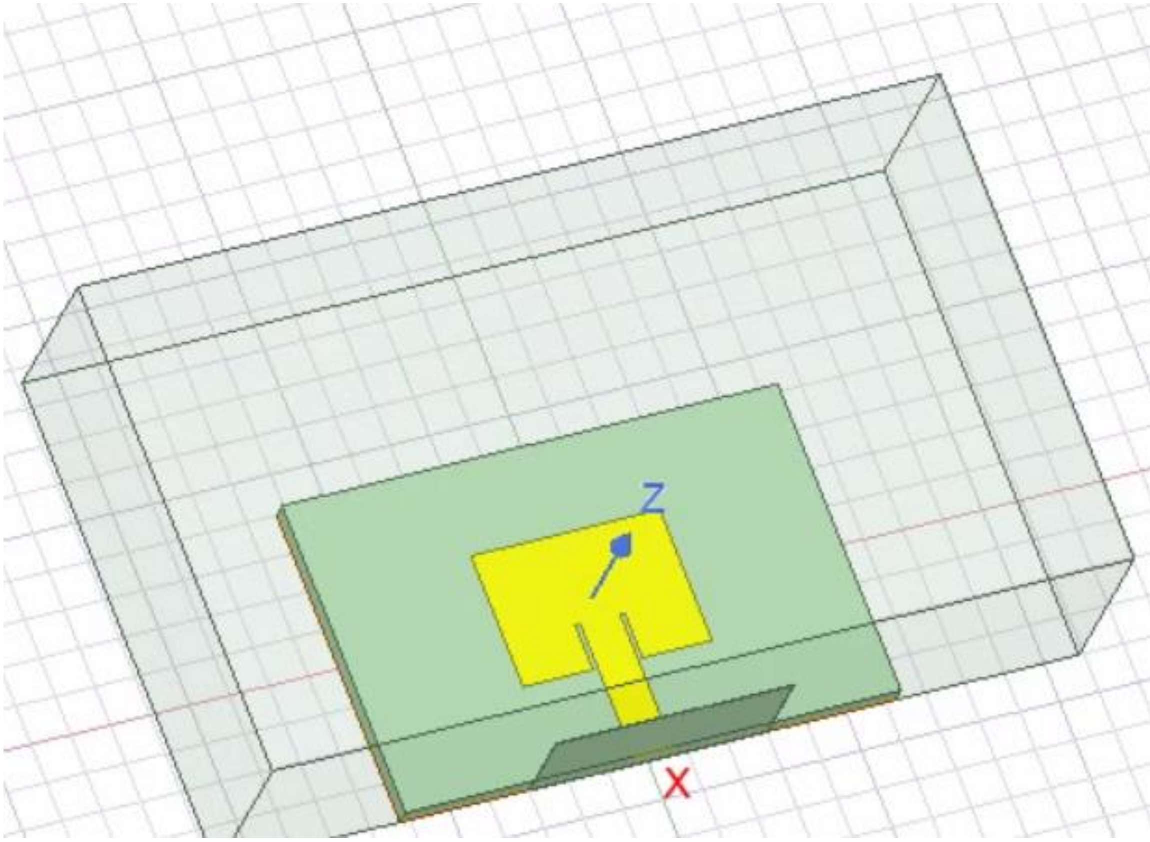

Fig 1. Isolated patch antenna design.

Name	Value	Unit	Evaluated Value	Type
sub_L	16	mm	16mm	Design
sub_W	25	mm	25mm	Design
length_patch	6.8235	mm	6.8235mm	Design
width_patch	9.517	mm	9.517mm	Design
width_feed	2	mm	2mm	Design
length_feed	-9.75	mm	-9.75mm	Design

Fig 2. Patch length and width.

The length and width of the antenna are shown in the above table from HFSS. The substrate thickness used is 1mm. Therefore, the patch fits in the 14mm X14 mm X2 mm volume given in the specification.

2. Figures and other data that is representing the specifications met.

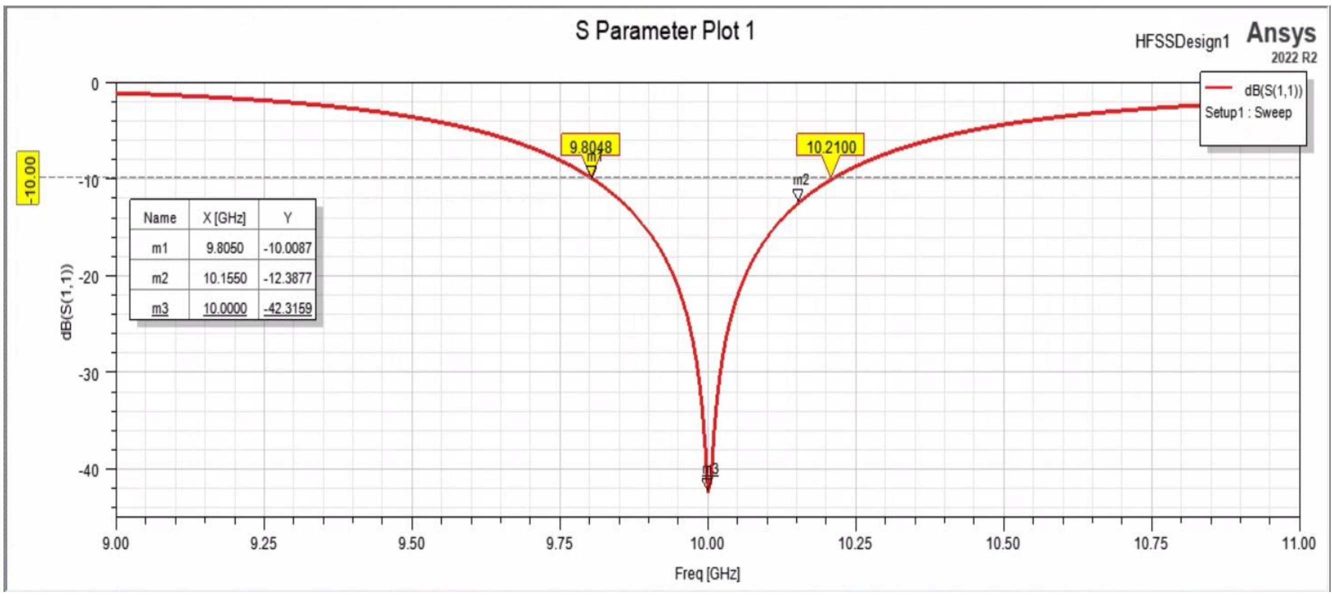

Fig 3. The S11 parameter plot for the isolated antenna model.

The plot above represents the S parameter plot of the isolated antenna. From the plot, it can be observed that the antenna resonates at 10GHZ which is our center frequency. The antenna also has a bandwidth from 9.804GHz to 10.21GHz at -10dB. From the above plot, we can say that the bandwidth requirements are met by the antenna.

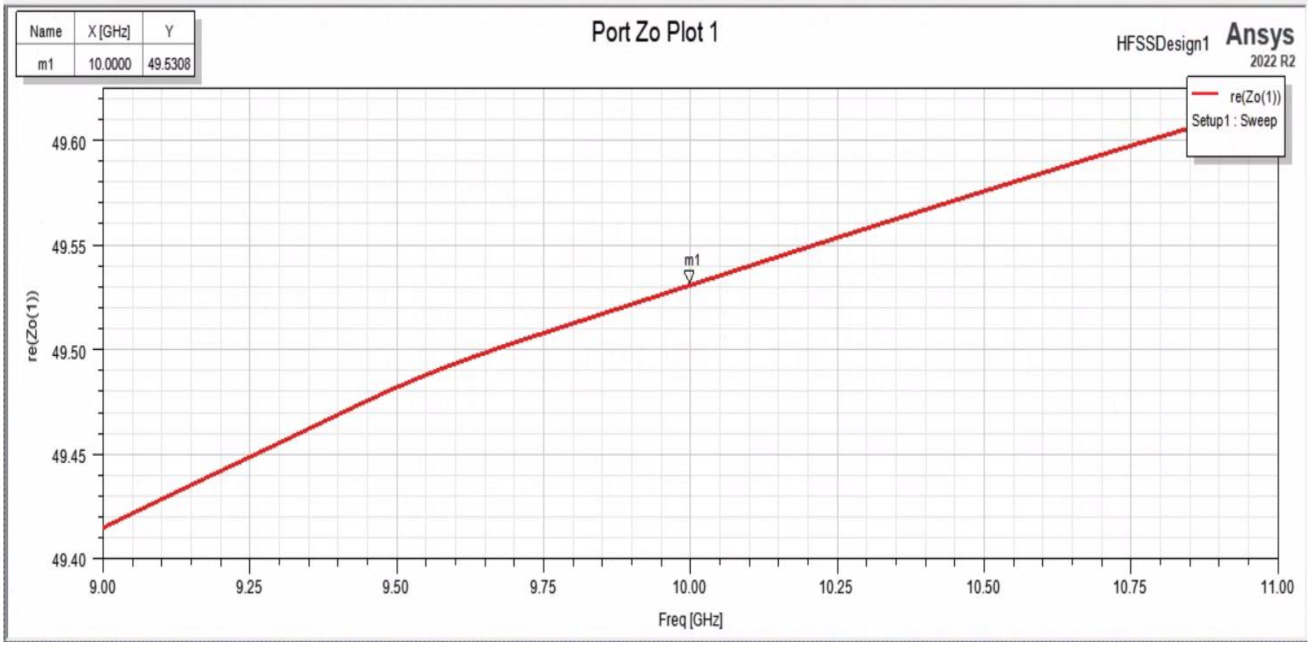

Fig 4. The isolated port impedance Z0 for the patch antenna

The above graph represents the port impedance at 49.53 ohms which is close to the 50 ohms impedance specified in the specifications sheet. The port impedance was tuned by changing the inset length and width value to get the optimum port impedance of 50 ohms.

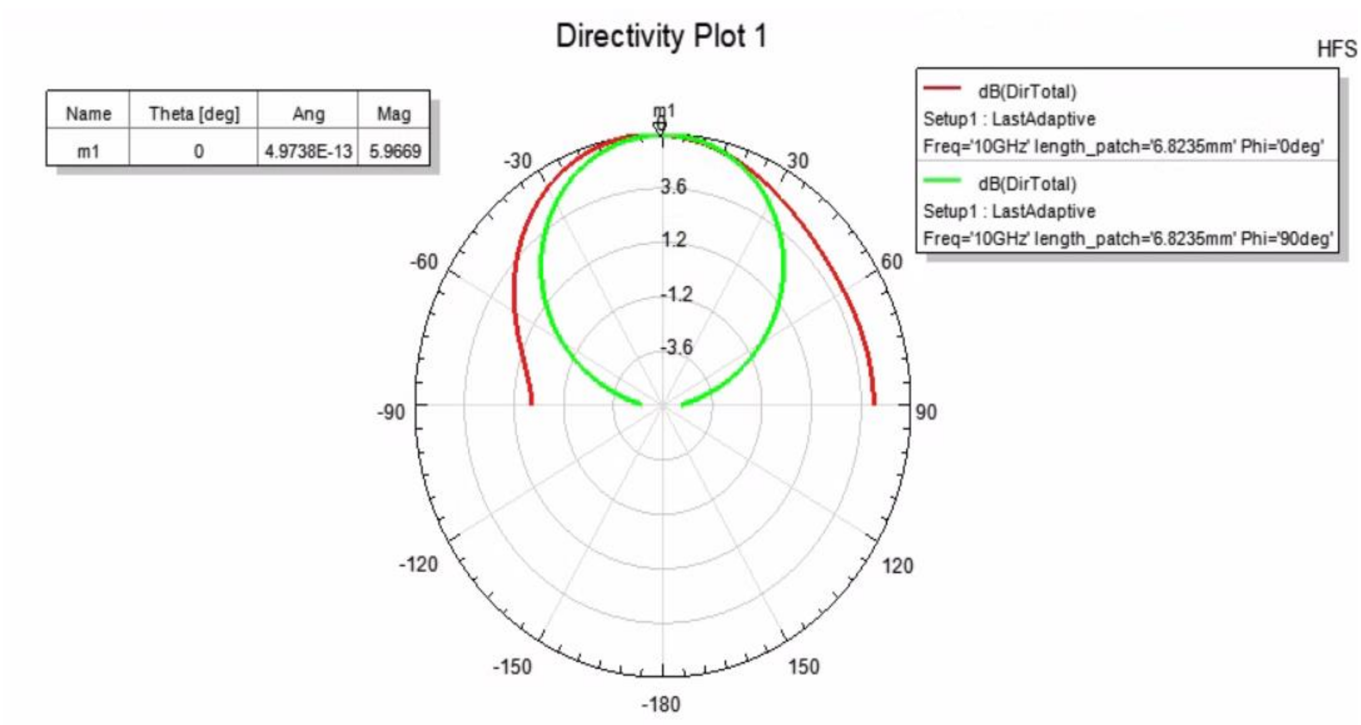

Fig 5. Isolated microstrip antenna Directivity plot.

The above plot represents the isolated microstrip antenna’s directivity plot. The plot shows that the antenna can achieve 5.966dBi(green lobe) of directivity peak at the broadside.

	Freq [GHz]	RadiationEfficiency Setup1 : LastAdaptive length_patch='6.8235mm'
1	10.000000	0.632107

Fig 6. The radiation efficiency of the isolated antenna.

From the above table, we can see that the radiation efficiency is 0.632 which when multiplied by 100 will give 63.2%.

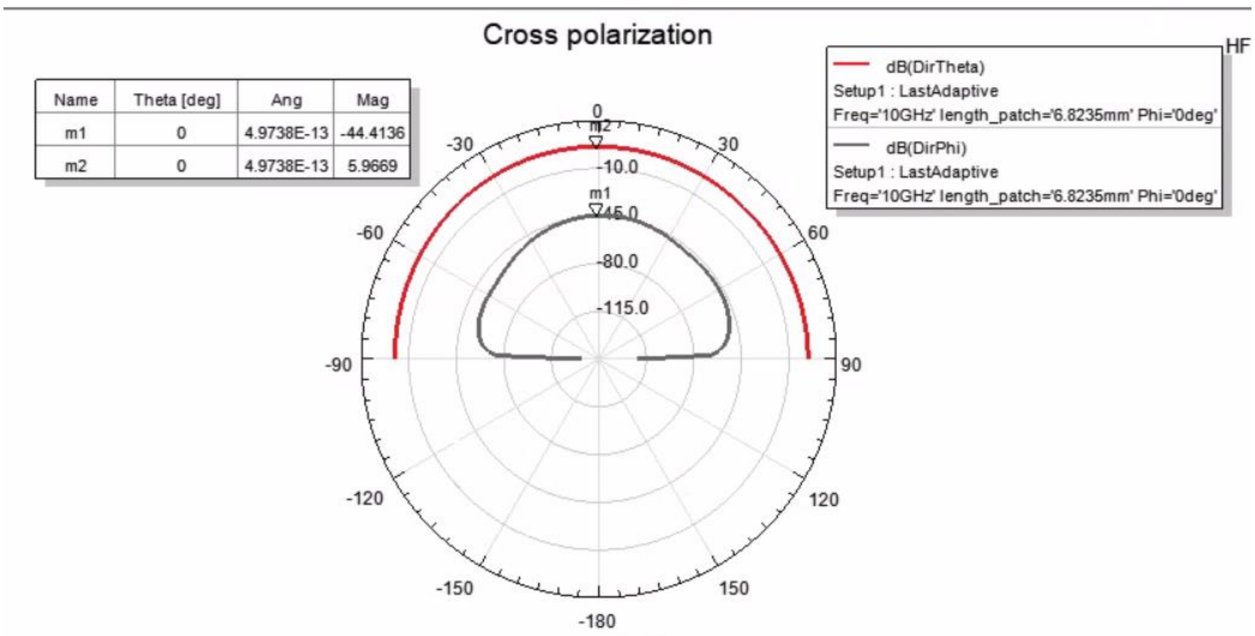

Fig 7. Cross polarization plot for the isolated microstrip antenna.

From the above graph, we can see that the cross-polarization can be obtained by taking the difference between the marker point m1 (black line) and the marker point m2(red line). The difference is 50.3805, this satisfies the specification of <-20dB.

3. **Discussion explaining all of the design choices.**

The design of the microstrip antenna began by calculating the length and width of the patch antenna.

for Length calculations,

$$(f_r)_{010} = \frac{v_0}{2L\sqrt{\varepsilon_r}}$$

$$10\times10^9 = \frac{30\times10^9}{2(\sqrt{4.4})L}$$

$$\frac{10\times10^9}{30\times10^9}\cdot2(\sqrt{4.4}) = \frac{1}{L}$$

$$0.66(\sqrt{4.4}) = \frac{1}{L}$$

$$1.39 = \frac{1}{L}$$

$$L = \frac{1}{1.39} = 0.714\ cm$$

$$0.714\times10 \Rightarrow 7.14\ mm$$

$$\boxed{L = 7.14\ mm}$$

The image above represents the length of the patch. This is the initial calculation used to start with the design procedure.

for width calculations.

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

$$= \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (14-6)$$

$$= \frac{30\times10^9}{2(10\times10^9)}\sqrt{\frac{2}{4.4+1}}$$

$$= \frac{3}{2}\sqrt{\frac{2}{5.4}}$$

$$= 0.912\ \text{cm}$$

$$\Rightarrow 0.912\ \text{cm}\times10$$

$$\boxed{W \Rightarrow 9.12\ \text{mm}}$$

Support the answers with online calculator.

The image above is used to represent the width of the patch. We can see that the width is 9.12mm.

The approximate Z_{in} value used is calculated using:-

$$R_{in} = 90 \frac{(\varepsilon_r)^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right) \qquad (14\text{-}18\text{b})$$

$$= 90 \frac{(4.4)^2}{4.4-1}\left(\frac{7.14}{9.12}\right)$$

$$\boxed{R_{in} = 401.21}$$

The point where the feed should be placed on the patch to get 50 Ω impedance is given by

$\cancel{R_{in}(y=y_0)\cos}$

$$R_{in}(y=y_0) = R_{in}(y=0)\cos^2\left(\frac{\pi}{L}y_0\right) \qquad (14\text{-}20\text{a})$$

$$R_{in}(y_0) = R_{in}\cos^2\left(\frac{\pi}{L}y_0\right)$$

$$50 = (401.21)\cos^2\left(\frac{\pi\, y_0}{7.14}\right)$$

$$0.124 = \cos^2\left(\frac{\pi\, y_0}{7.14}\right)$$

The image above shows the Rin of the patch when fed from the edge of the patch.

$$0.352 = \cos\left(\frac{\pi y_0}{7.14}\right)$$

$$\frac{\cos^{-1}(0.352)(7.14)}{\pi} = y_0$$

$$\frac{(1.21108)(7.14)}{\pi} = y_0$$

$$\boxed{2.75 = y_0}$$

From the above image, we can see that the inset length required is 2.75mm.

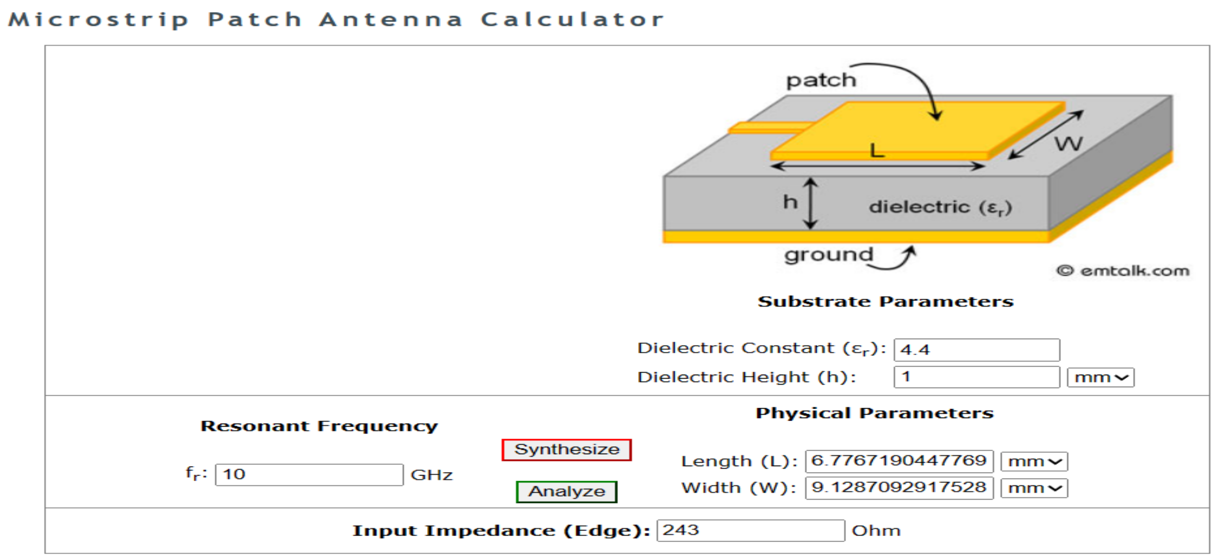

Fig 8. Online calculator calculations of the patch antenna.

From the above images, we can conclude that the length and width of the antenna from hand calculations align with the calculations from the online calculator. The microstrip line impedance calculator by EM talk is used to calculate the dimensions.

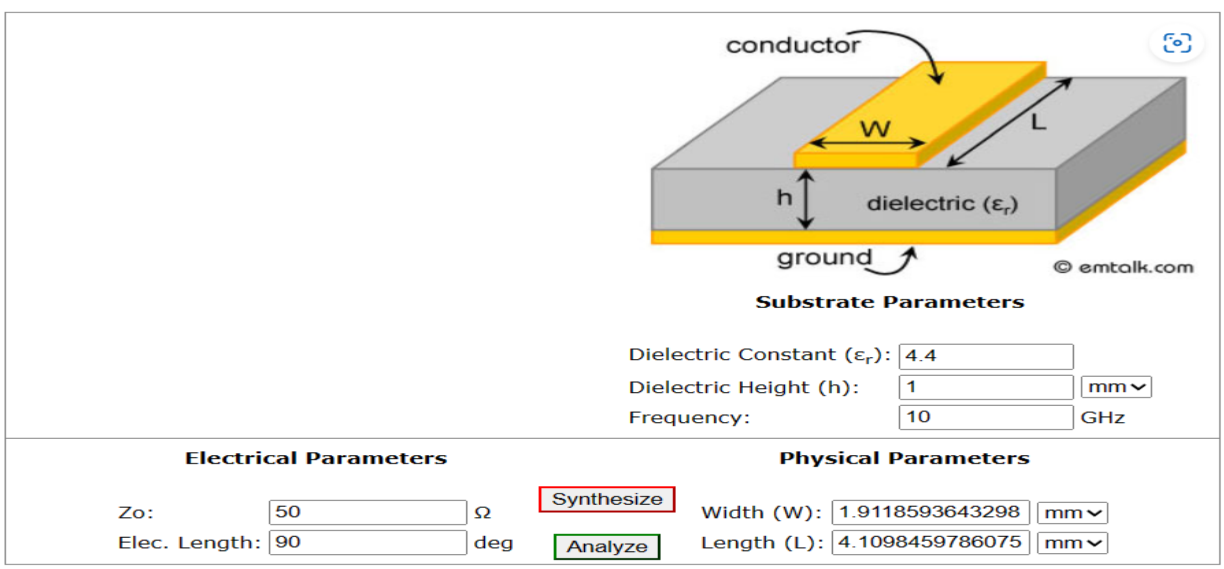

Fig 9. Microstrip line calculated using an online tool. The equations for the design of a microstrip line are also mentioned in Michael Steers's RF design book.

The antenna length and width do not match the calculated values as we need to tune them, this is because of fringing effects the antenna will appear longer than the actual length of the antenna. Due to this the antenna length is reduced and made to resonate at the required frequency. Finally, the width of the microstrip line is chosen in such a way that it does not touch the microstrip line thickness. This parameter is generally chosen by the trial-and-error method.

TASK 2

Broadside Array Design

Procedure:

1. The microstrip patch design that was used in Task 1 is used in designing the broadside array design.
2. The antenna is imported in a new design file and the elements of the antenna that is the feed and the patch are duplicated along the y-axis.
3. The duplicated elements are then assigned wave ports. The total number of elements used in this design is 4. Therefore N=4 and M=2.
4. The FR4 epoxy plane and the ground plane are each extended in such a way that they cover the whole patch along with as shown in the array design below.
5. During the initial array design, I had a choice of considering either binomial or Dolph-Tschebyscheff array taper. I chose Dolph-Tschebyscheff because it requires less phase angle to steer the beam as compared to binomial. I also observed that when we try to steer the angle of the binomial array, the grading lobes are as large as the main lobe. This is a very unsatisfactory result. The Dolph-Tschebyscheff on the other hand is a compromise between the binomial and the uniform array. The weights of the Dolph-Tschebyscheff are calculated and inserted into the Excitation edit sources. *Further discussion of the design process will be mentioned below along with some calculations and comparisons between binomial and Dolph-Tschebyscheff*
6. Finally, we can run the simulation once and use the active directivity in HFSS to plot the S11 and other plots without running the simulation again.

The specifications given for broadside array design are as shown below.

Given Specifications	Obtained Specifications	Met?
|reflection coefficient|<-15dB at center frequency driven with uniform amplitude and phase.	The maximum observed is -21dB.	Yes
Pattern maximum must be at broadside and directivity is > 10dBi at the center frequency.	10.66 dBi at 10GHz.	Yes
The elements should be fed with 1. Coaxial feeds **or** 2. Microstrip line feeds.	Fed using microstrip line feeds.	Yes
The largest side lobe should be at least 20dB below the main sidelobe.	-22.37dB below the main lobe	Yes.

Table 2. represents the broadside array design specifications.

Antenna Dimensions and the Array model image.

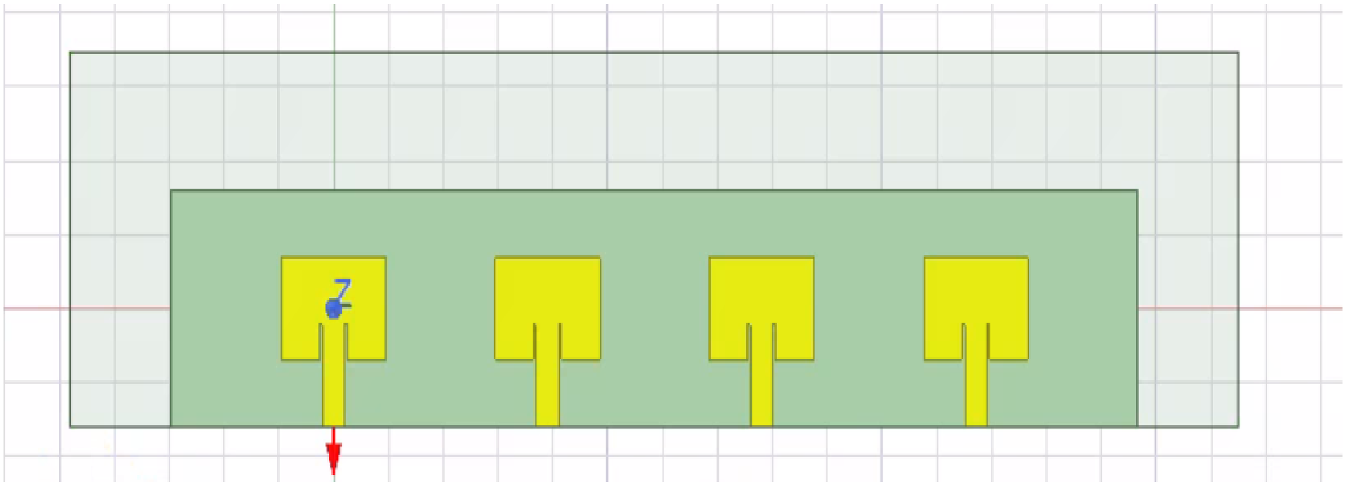

Fig 10. An array antenna is used to get the results in the above table.

From the Design specifications, the length and width of the array are observed to be as follows. The length is 16mm and the width of the whole array containing 4 elements is 88.068mm.

XSize	16	mm	16mm	
YSize	88.068	mm	88.068mm	

Fig 11. The length and width of the array is as shown in the figure above.

As it is required to only show the maximum directivity that can be obtained by a beam, there won't be any phase variables in this task.

	Source	Type	Magnitude	Unit	Phase	Unit
1	1:1	Port	0.18	W	0	deg
2	2:1	Port	1	W	0	deg
3	3:1	Port	1	W	0	deg
4	4:1	Port	0.18	W	0	deg

Fig 12. The figure above represents the weights of the array used.

Model data Proving all the specifications are met.

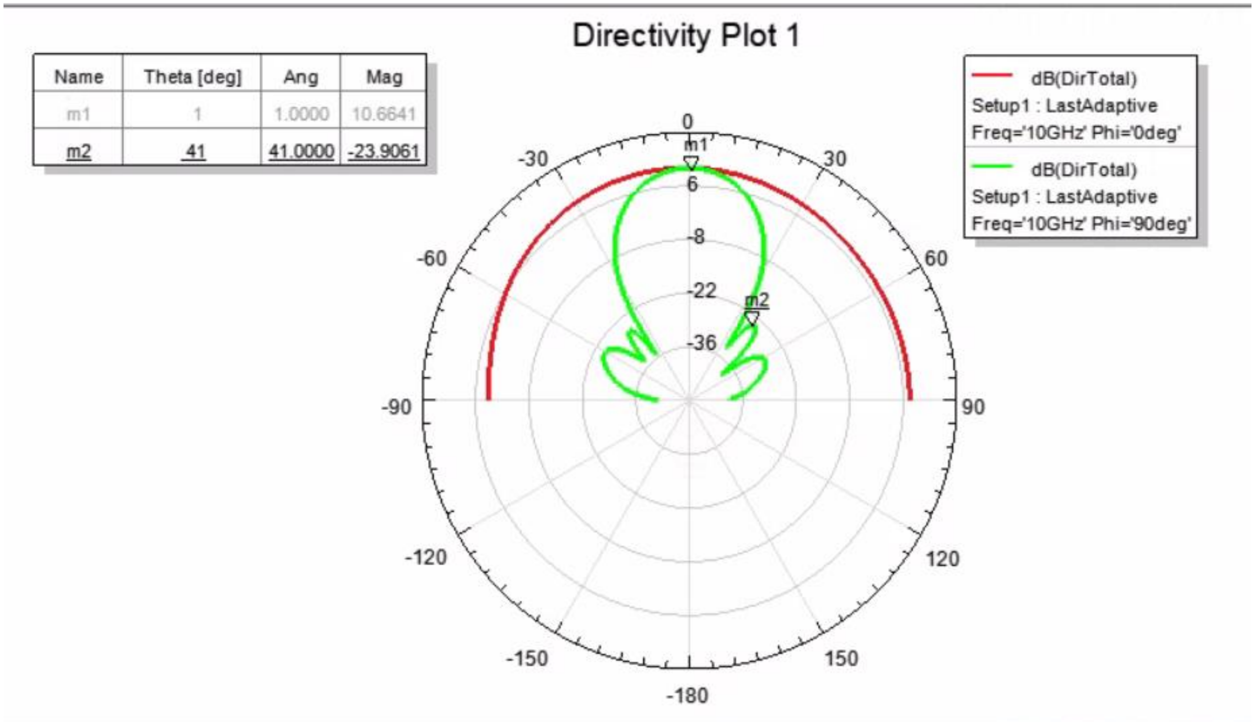

Fig 13. The above plot represents the directivity of the array.

The directivity from the above graph is observed to be 10.9903. the directivity increases by either increasing the weights of the array. Changing the weights of the array also increases the grading lobes level and the side lobes level.

	Freq [GHz]	dB(ActiveS(1:1)) Setup1 : LastAdaptive	dB(ActiveS(2:1)) Setup1 : LastAdaptive	dB(ActiveS(3:1)) Setup1 : LastAdaptive	dB(ActiveS(4:1)) Setup1 : LastAdaptive
1	10.000000	-20.166477	-23.699284	-23.561727	-20.084182

Fig 14. Active S-parameter plot.

From the above table, we can see that the values of the active S parameters range from -22.0575 to - 23.0996dB.

Design choices

For the array mentioned above, the design choices are as follows.

1. Initially I was given the task of choosing between a binomial array or a Dolph-Tschebyscheff array. Some of the design considerations I took into consideration before choosing a type of taper are as follows.

Binomial Taper.	**Dolph-Tschebyscheff Taper.**
1. Binomial taper does not have any sidelobes.	1. Dolph-Tschebyscheff taper has sidelobes compared to binomial but they are minimal compared to uniform taper.
2. Binomial taper requires huge phase values to change the beam in a particular direction.	2. Dolph-Tschebyscheff taper requires relatively small values for beam steering.
3. Binomial taper when steered in a particular direction, the grading lobes will affect the array's main beam and the required criteria of the main lobe to side lobe level cannot be met.	3. Dolph-Tschebyscheff taper on the other hand does not suffer from such a problem. It can steer to a certain angle before grading lobes come into effect and the specifications are not met.

Table 3. Differences considered before choosing the type of taper for Array design.

2. The array distance is calculated from the centre of one patch to the other. For the design shown in the above case, the distance is calculated as the distance between the two patches (dis_u +2(W/2)).
3. Calculations used to get the Dolph-Tschebyscheff taper are as shown in the images below.

we Know that the array factor is given by

$$AF = \sum_{n=1}^{N} w_n \cos\left[(2n-1) u\right]$$

$$u = \frac{n \cos\theta}{2}$$

$$\sum_{n=1}^{2} w_n \cos\left[(2n-1) u\right]$$

$$u = \frac{n \cos\theta}{2}$$

$$w_1 \cos(u) + w_2 \cos(3u).$$

$$w_1 \cos(u) + w_2 \left[4\cos^3(u) - 3\cos(u)\right]$$

$$w_1 \cos(u) + w_2 \left[4\cos^3(u) - 3\cos(u)\right]$$

$$w_1 \cos(u) + w_2 \left[4\cos^3(u) - 3\cos(u)\right]$$

$$\left[w_1 \cos(u) + w_2\, 4\cos^3(u) - w_2\, 3\cos(u)\right]$$

$$\cos(u)\left[w_1 - 3w_2\right] + \cos^3 u \left[4w_2\right]$$

now, considering

$$z_0 = \cosh\left[\frac{\cosh^{-1}(32)}{N-1}\right]$$

$$\cosh\left[\frac{\cosh^{-1}(32)}{3}\right] = 2.12$$

$$\cos(u) = \frac{t}{2.12}$$

$$AF = \left(\frac{t}{2.12}\right)(w_1 - 3w_2) + 4(w_2)\left[\frac{t^3}{9.52}\right]$$

$$-\frac{3w_2 t}{2.12} + \frac{t w_1}{2.12} + \frac{4w_2 t^3}{9.52}$$

equating the array factor to

$4z^3 - 3z$

where, $z = t$

$$4z^3 - 3z = -\frac{3w_2 z}{2.12} + \frac{w_1 z}{2.12} + \frac{4w_2 z^3}{9.52}$$

$$\cancel{4}\cancel{z^3} = \frac{\cancel{4}w_2 \cancel{z^3}}{9.12}$$

$$9.12 = w_2$$

$$-3\cancel{z} = \left(\frac{-3w_2 + w_1}{2.12}\right)\cancel{z}$$

$$-3(2.12) = -3(9.12) + w_1$$

$$6.36 = 27.36 + w_1$$

$\omega_1 = 21$.

normalizing, we get

$$\frac{9.12}{21} = 0.43$$

The value 0.43 is squared and put in the weights of the array. The squared value is 0.18 W.

TASK 3

Scanned Array Design

Procedure

1. In this Task we are not supposed to change any distance or the weights of the taper. We can only change the phases of each taper in the excitation.
2. The values of the phase are calculated using the formula β $=d.\frac{2\pi}{\lambda}\sin(\theta)$ for the Dolph-Tschebyscheff scanning angle.

Specifications Table

<table>
<tr><td>Requires Specifications</td><td>Obtained specifications</td><td>Met?</td></tr>
<tr><td>Array arranged in such a way that the pattern maximum can be scanned along H.</td><td>Array aligned along H</td><td>Yes.</td></tr>
<tr><td>|reflection coefficient| <-15dB</td><td>-20.084dB (minimum) and -23.669dB is the maximum.</td><td>Yes</td></tr>
<tr><td>Maximum directivity >10dBi</td><td>10.52 dBi until 15 degrees.</td><td>No</td></tr>
<tr><td>For all scanning angles, the sidelobe level should be <-16dBi</td><td><-16dBi up to 15 degrees angle.</td><td>No</td></tr>
</table>

Table 4. The table above represents the Specifications for task 3.

	Source	Type	Magnitude	Unit	Phase	Unit
1	1:1	Port	0.18	W	-60	deg
2	2:1	Port	1	W	-2*60	deg
3	3:1	Port	1	W	-3*60	deg
4	4:1	Port	0.18	W	-4*60	deg

Fig 14. The above figure shows the phase shift of the antenna which is used to steer the beam by 15 degrees.

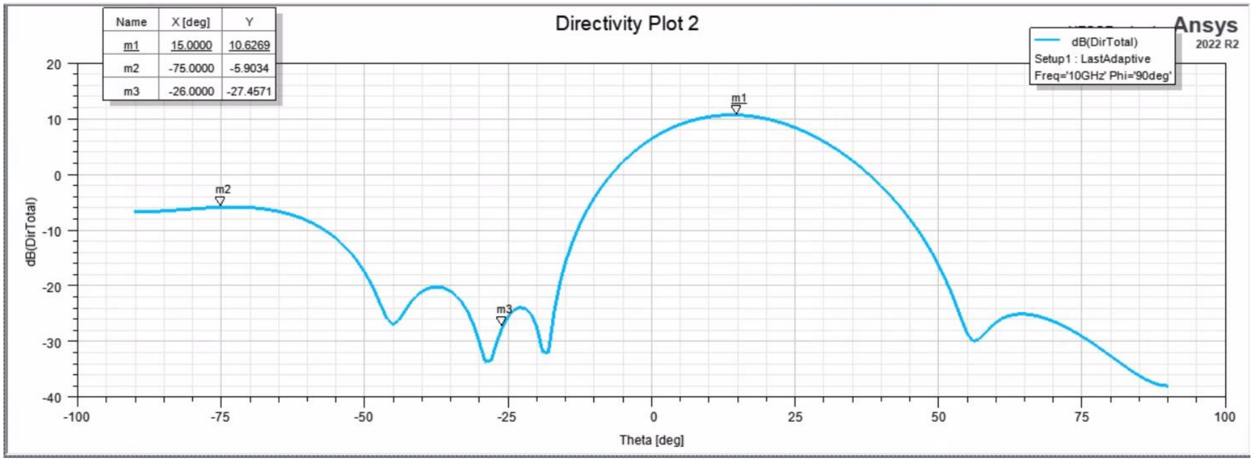

Fig 15. Directivity of the steered angle of 15 degrees.

This is the maximum angle the array presented in this report can steer. If the angle is further increased, the minimum sidelobe level <-16db is not achieved.

The active S-parameters achieved after beam steering is shown below.

	Freq [GHz]	dB(ActiveS(1:1)) Setup1 : LastAdaptive	dB(ActiveS(2:1)) Setup1 : LastAdaptive	dB(ActiveS(3:1)) Setup1 : LastAdaptive	dB(ActiveS(4:1)) Setup1 : LastAdaptive
1	10.000000	-18.850420	-26.286510	-28.560311	-21.267859

Fig 16. The above figure represents the active s parameters for the array for 15 degrees.

	Source	Type	Magnitude	Unit	Phase	Unit
1	1:1	Port	0.18	W	-126	deg
2	2:1	Port	1	W	-2*126	deg
3	3:1	Port	1	W	-3*126	deg
4	4:1	Port	0.18	W	-4*126	deg

Fig 17. The above figure shows the phase shift of the antenna which is used to steer the beam by 30 degrees.

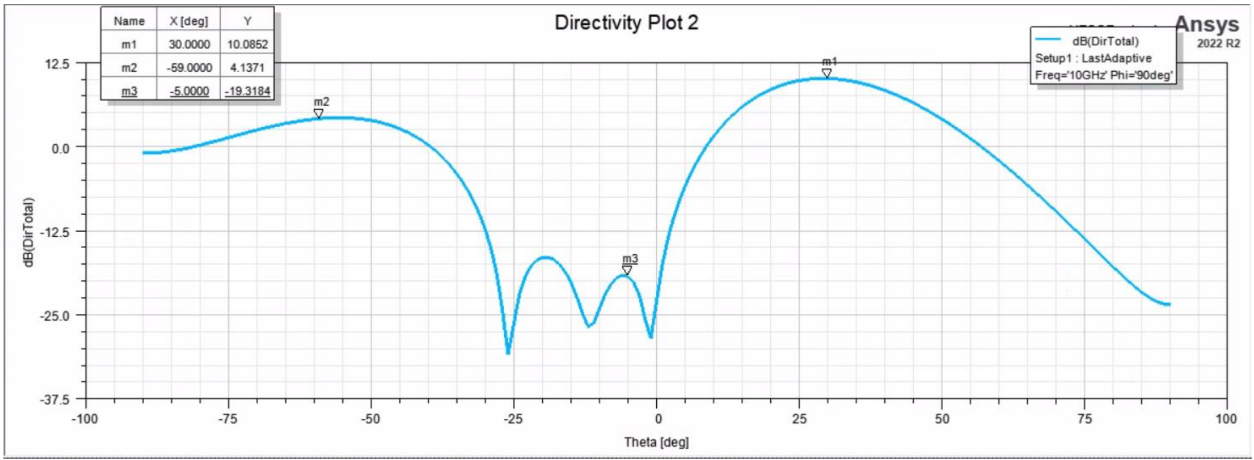

Fig 18. Directivity plot for 30 degrees shift in beam

	Freq [GHz]	dB(ActiveS(1:1)) Setup1 : LastAdaptive	dB(ActiveS(2:1)) Setup1 : LastAdaptive	dB(ActiveS(3:1)) Setup1 : LastAdaptive	dB(ActiveS(4:1)) Setup1 : LastAdaptive
1	10.000000	-19.110322	-28.722441	-32.920218	-22.009863

Fig 19. Active S parameters for 30 degrees.

	Source	Type	Magnitude	Unit	Phase	Unit
1	1:1	Port	0.18	W	-186	deg
2	2:1	Port	1	W	-2*186	deg
3	3:1	Port	1	W	-3*186	deg
4	4:1	Port	0.18	W	-4*186	deg

Fig 20. The above figure shows the phase shift of the antenna which is used to steer the beam by 45 degrees.

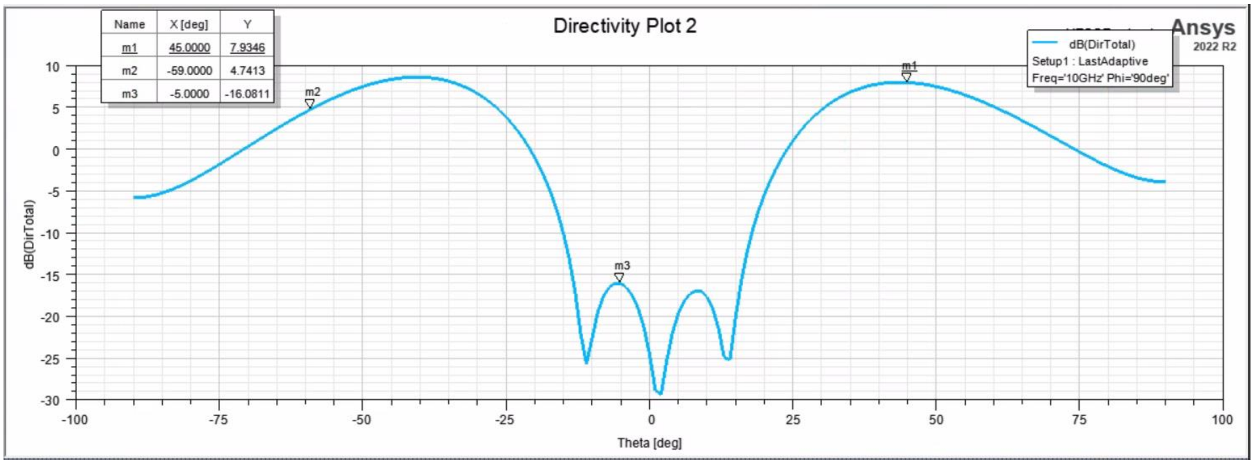

Fig 21. Directivity plot for 45 degrees shift in the beam.

	Freq [GHz]	dB(ActiveS(1:1)) Setup1 : LastAdaptive	dB(ActiveS(2:1)) Setup1 : LastAdaptive	dB(ActiveS(3:1)) Setup1 : LastAdaptive	dB(ActiveS(4:1)) Setup1 : LastAdaptive
1	10.000000	-21.341587	-26.280066	-25.680326	-20.829104

Fig 22. Active S parameters for 45 degrees.

	Source	Type	Magnitude	Unit	Phase	Unit
1	1:1	Port	0.18	W	-240	deg
2	2:1	Port	1	W	-2*240	deg
3	3:1	Port	1	W	-3*240	deg
4	4:1	Port	0.18	W	-4*240	deg

Fig 23. The above figure shows the phase shift of the antenna which is used to steer the beam by 60 degrees.

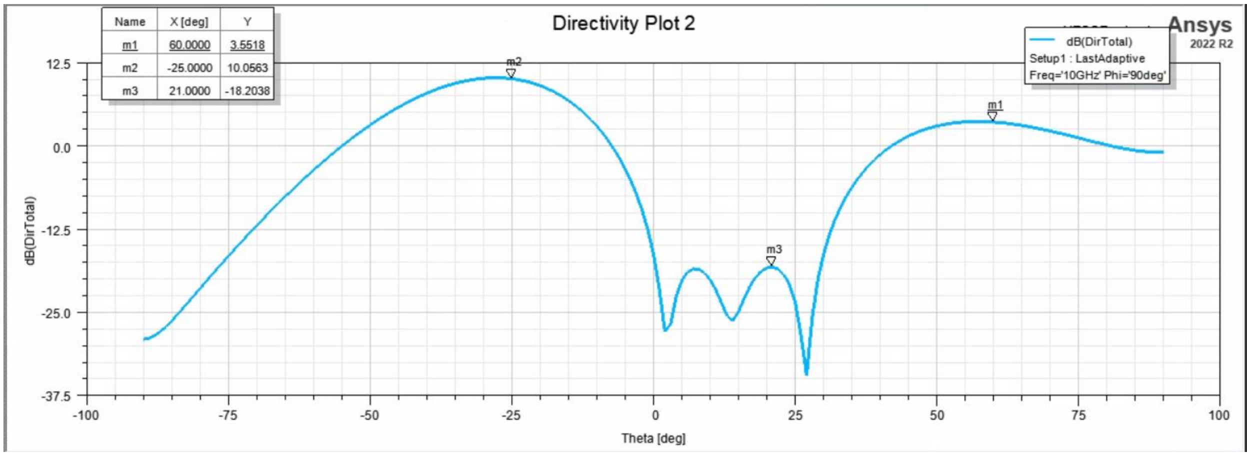

Fig 24. Directivity plot for 60 degrees shift in the beam.

	Freq [GHz]	dB(ActiveS(1:1)) Setup1 : LastAdaptive	dB(ActiveS(2:1)) Setup1 : LastAdaptive	dB(ActiveS(3:1)) Setup1 : LastAdaptive	dB(ActiveS(4:1)) Setup1 : LastAdaptive
1	10.000000	-22.602339	-32.830046	-27.440053	-19.272454

Fig 25. Active S parameters for 60 degrees.

Design choices

1. The design choices considered during task 3 are to scan the angle without losing all the required specifications. Unfortunately, not all the specifications could be met. The main reasons for this are as follows.
    - The Designed array elements' distance is too large. But we cannot go below a certain value as the elements may overlap also less distance between patches leads to lower directivity.
    - The Dolph-Tschebyscheff taper used in this array has a taper value of 0.18 and 1 as shown in task 2. Increasing the taper value increases the value of the main lobe but it also increases the side lobe and the grading lobe levels. So, we cannot compensate for this problem using such an approach.
    - Using the formula from the design procedure in task 3, the angle obtained is 126 degrees. This is not a multiple of 15 degrees. When 120 degrees is inserted in the phase value, the sidelobe level is not met. After a decrement of 15 degrees. The highest value where all the specifications are met is -60 degrees. This phase angle created a phase shift to 15 degrees in my array.
    - Similarly, using a phase shift of 60 degrees created a phase shift of -15 degrees. Therefore, the total beam steering possible with the antenna presented in this report is 30 degrees.

- Using advanced array tapering techniques and phase technique’s, it is probably possible to achieve all the parameters.

CONCLUSIONS

1. We can change the number of elements to increase the directivity, we can probably increase the scanning angle. As we want to present the problem at a lower cost, we should probably avoid such a change in our system.
2. We can also change the distance between the elements by choosing a different type of taper which will give us the flexibility to achieve the full angle.
3. We can send more power to achieve this but we will be using more than the required element power and the trace widths might need to be increased.

REFERENCES

1. Dr Jacob Adams, ECE 541 class notes and recordings, Spring 2023.
2. Constantine A. Balanis, Antenna Theory: Analysis and Design, 4th Edition, Wiley publications.
3. Microstrip patch antenna online calculator:- em: talk - Microstrip Patch Antenna Calculator (emtalk.com)
4. Microstrip line calculator:- Microstrip Line Calculator | em: talk (emtalk.com)
5. Online reference used to design the project:- Antenna-Theory.com - Dolph-Chebyshev Weights