RF PROJECT 2

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6/28/2020

Assigned Parameters:			
Dielectric	Frequency (GHz)	Array	Polarization
Taconic HT-30	3.5	4 elements Y axis , 0.9λ	$E(\theta = 0°, \varphi) = E_0\hat{x}$

I was assigned a dielectric Taconic HT-30. I was unable to find this dielectric in CST, or in the manufacturer's catalog. I therefore used Taconic RF-30, which has a dielectric constant of 3, with permission.

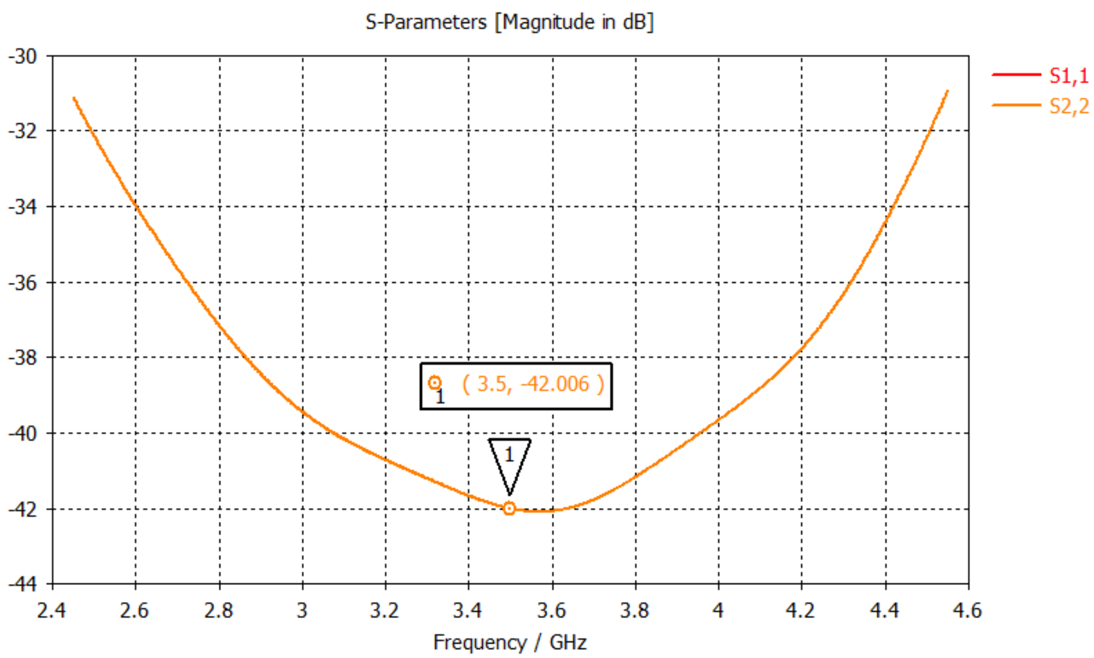
Throughout this project I sometimes used a ground plane/substrate that was very large. I know that the rule of thumb is dimensions of the patch +6mm on every side, but I decided to make the ground plane huge, to make CAD modeling easier, especially when working with microstrips & changing their dimensions. If making the designs "for real life" – I would simply trim the substrate to the appropriate dimensions after the work was done.

1) (5 points) Build a CST model of a 50Ω coaxial line with an inner pin diameter of 1mm, and with a dielectric medium (in between the inner pin and the external shield) of a material named Teflon. The length of the coax cable should be two wavelengths (according to the frequency given in the table below). Place ports at the input and at the output of the coax line, with characteristic impedance (of the ports) according to that of the coax cable (as specified in the table) and simulate the 2ports S-Parameters over the frequency band of 0.7f -1.3f.

a. Optimize for $S_{ii} < -25dB$
b. What is the insertion loss of the cable at frequency f?
c. Present the S-parameter results of the optimized cable over the given frequency band

$$Z_0 = \frac{138}{\sqrt{\epsilon_r}}\log_{10}\left(\frac{D}{d}\right) = \frac{138}{\sqrt{2.1}}\log_{10}\left(\frac{D}{1}\right) = 50\,[\Omega] \rightarrow D = 3.35$$

S parameters:



Well below -25dB from the beginning – no optimization necessary.

Insertion Loss: Insertion loss at 3.5GHz is an immensely small number – essentially 0.

2) (15 points) Build a CST model of the patch antenna, according to the above guidelines and your patch antenna parameters in the table below. Use the designed coax cable in a length of a quarter wavelength in order to feed the patch antenna, without using a microstrip line: create a hole in the ground plane in a diameter which is identical to that of the shield of the coax cable, insert the edge of the coax cable into this hole, and extend the inner core of the coax above the ground plane so that it will touch the metal plate that implements the patch. Now, fine-tune the (allowed) parameters of the antenna in order to achieve a matching (Return Loss, or S11 in dB scale) of better than -10dB over the frequency band 0.98f -1.02f. Note that the impedance of the coax cable must remain 50⍰!

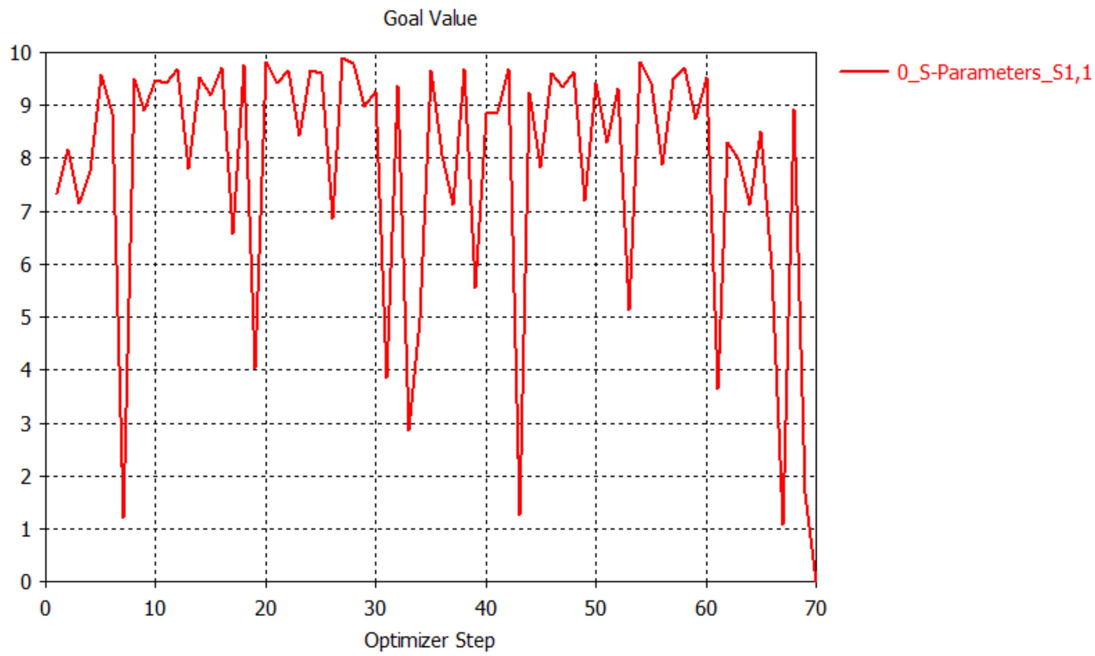
a. Present the input matching over the bandwidth 0.7f -1.3f. Use markers on the plot in order to demonstrate the achieved design goals.
b. Compare the optimized size of the patch to the theoretical one. If there is any difference, what is the reason for that
c. Present the 3D far field radiation pattern of the patch antenna at the frequency f, and the radiation pattern over the 2 main planes: the Y-Z plane ("Elevation") as a function of ⍰ , and the X-Z plane ("Azimuth") as a function of θ
d. . What is the direction of the peak gain of the patch antenna, and what is the peak gain and directivity values? – The ideal patch can have a gain of above 7.5dBi. Compare it to the gain of your patch and explain the differences. What is the antenna efficiency
e. Present the surface currents on the patch antenna and on the ground plane at the time points t=0, t=T/4, t=T/2 and t=3T/4. Compare it to the expected results according to the theory and explain the differences, if those exist

I use a MATLAB script (found online) to calculate the theoretically optimal dimensions of the patch:

```
Enter known parameters:
Enter the permitivity3
Enter height of substrate (mm)4
Enter target frequency (GHz)3.5
Enter input impedence (ohms)50
Calculating...
Rectangle Patch
Patch Width:30.3046 mm
Patch Length:22.7813 mm
Substrate Width:54.3046 mm
Substrate Length:46.7813 mm
Inset:8.7349 mm
Inset Gap:0.17405 mm
Radiation Width:71.949 mm
Radiation Length:64.4257 mm
Radiation Height:21.6444 mm
Feed Width:6.6167 mm
Feed Length:13.2333 mm
```

I use the above parameters as a jumping-off point. When simulating for them – I obtain bad S-parameters regardless of the location of the feed port.

I then run an optimizer using particle swarm optimization, with the goal $S_{11} < -10dB$; $0.98f \leq f \leq 1.02f$, operating on parameters W,S (dimensions of patch) and M,N (input port offset). The optimizer's goal function graph:



The final trial obtains goal function=0, i.e the goal is met.

The trial corresponding to this result has:

Patch Width: 53.99mm

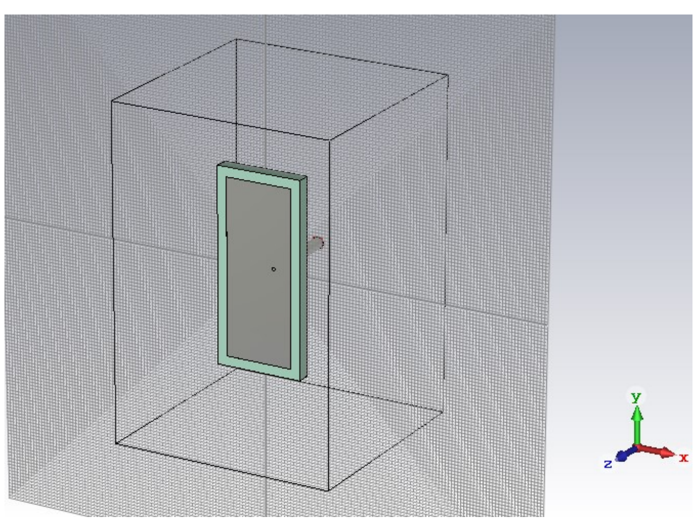
Patch Length: 20.83mm

Feed Port X Offset: 4.83mm

Feed Port Y Offset: 2.21mm

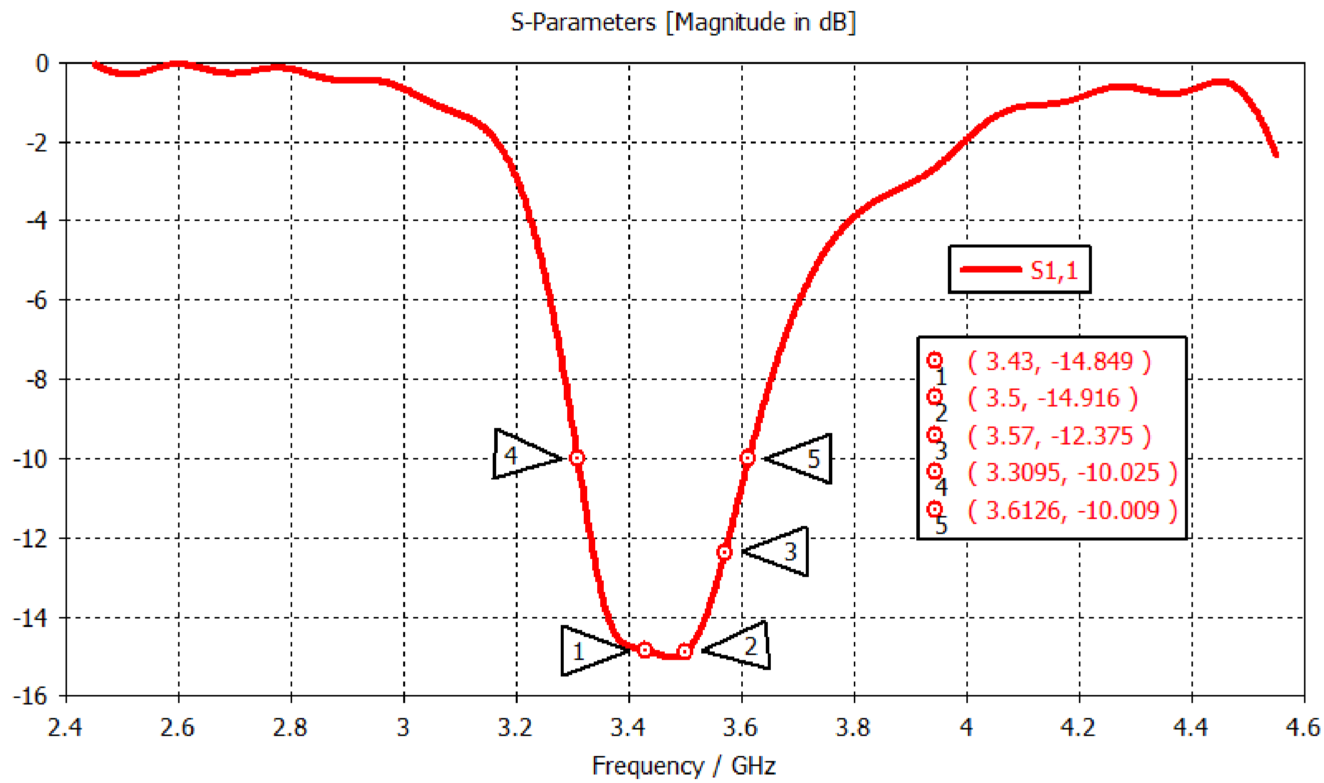
The optimized size of the patch is not the same as the theoretical one. Theoretical size: 30x22 and got 54x21 in practice. This is likely because I did not consider ϵ_{eff}, and used the dielectric's ϵ instead. Also, the MATLAB seems to be programmed for a microstrip fed inset-matched patch, and we are feeding with a coax, so that could play a role too.

The model:



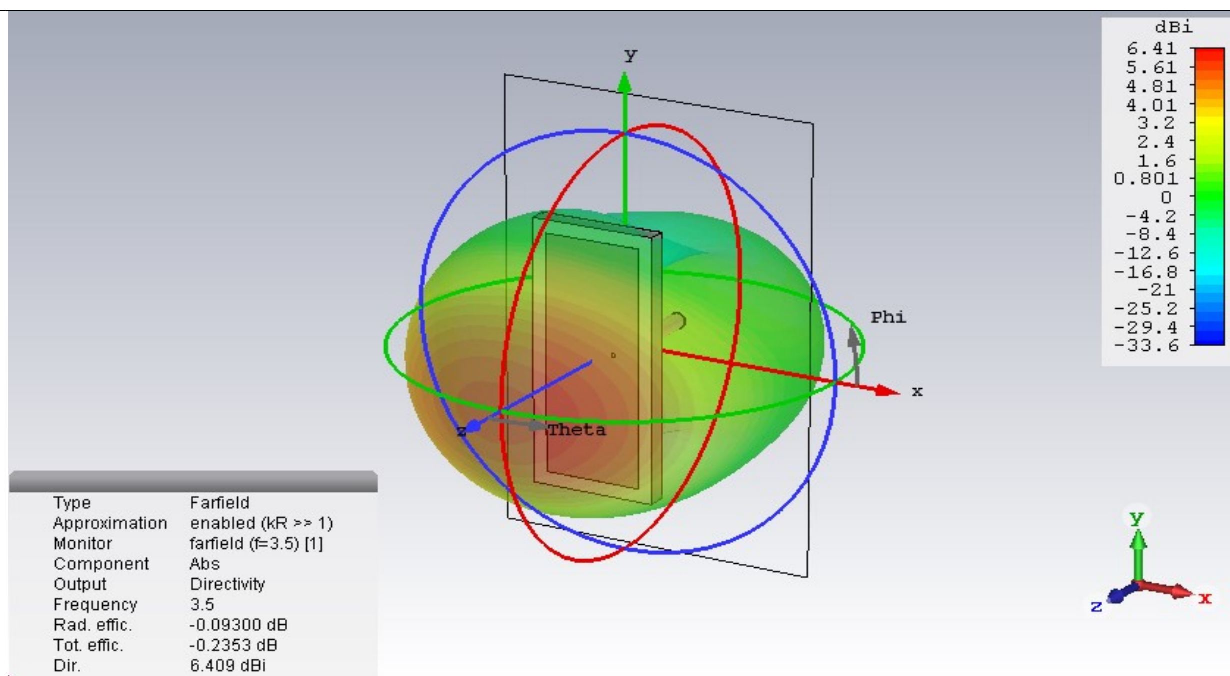
My line impedance is $Z = 49.4\Omega \approx 50\Omega$ as required.

S11 parameters:

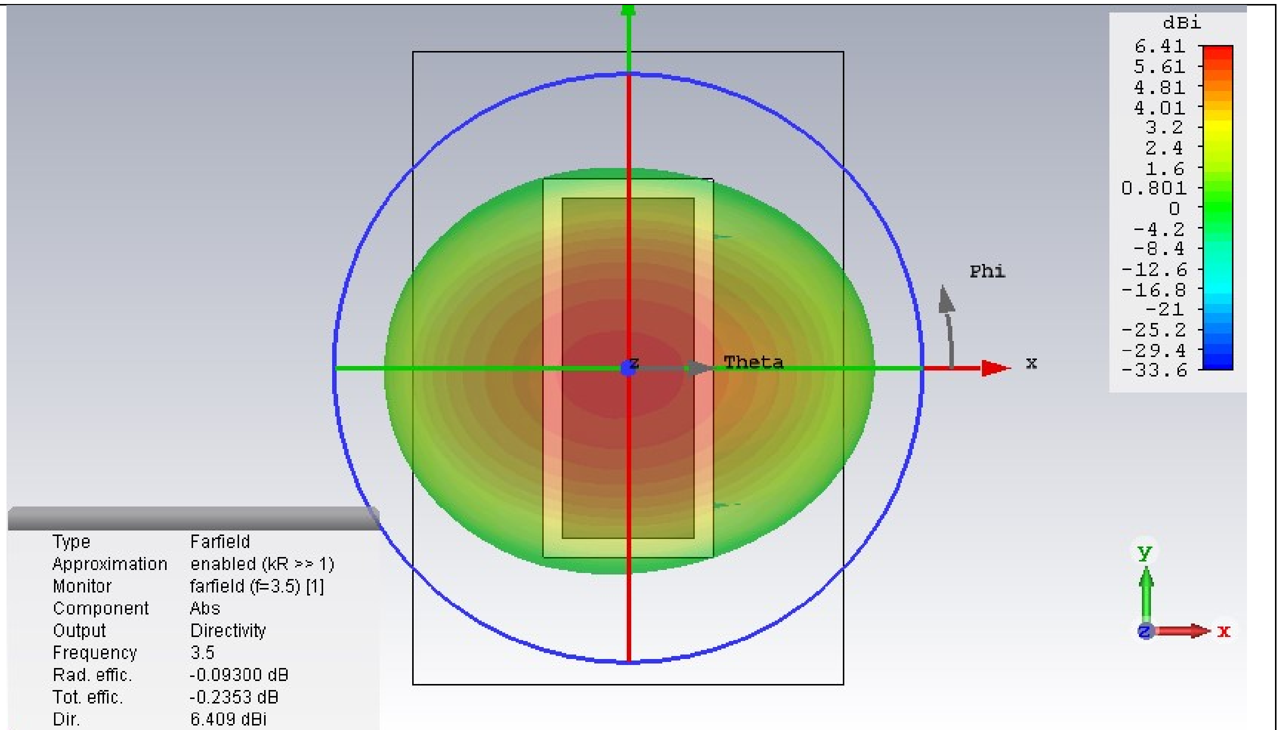


Markers 1,3 are placed at the edges of the region for which we require $S_{11} < -10dB$. Both of them satisfy the requirement, and everything in between satisfies it too. Marker 2 is placed at the operating frequency 3.5GHz, and has a value -13.916dB, which is also good. In fact – we ended up with a result that is better than the requirement. Markers 4,5 are placed at the edges of the region where we satisfy $S_{11} < -10dB$, and this region is $[3.31G, 3.61G] \rightarrow 0.94f - 1.03f$.

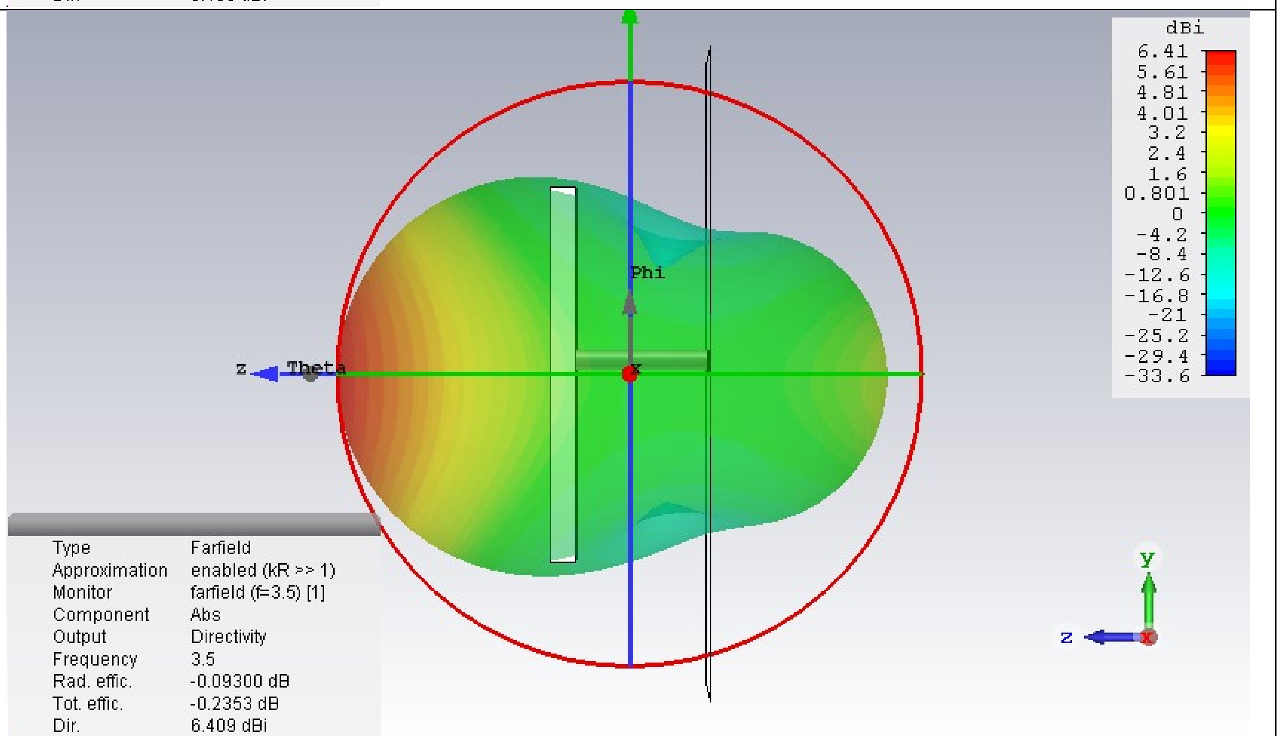
Farfield:

Perspective	

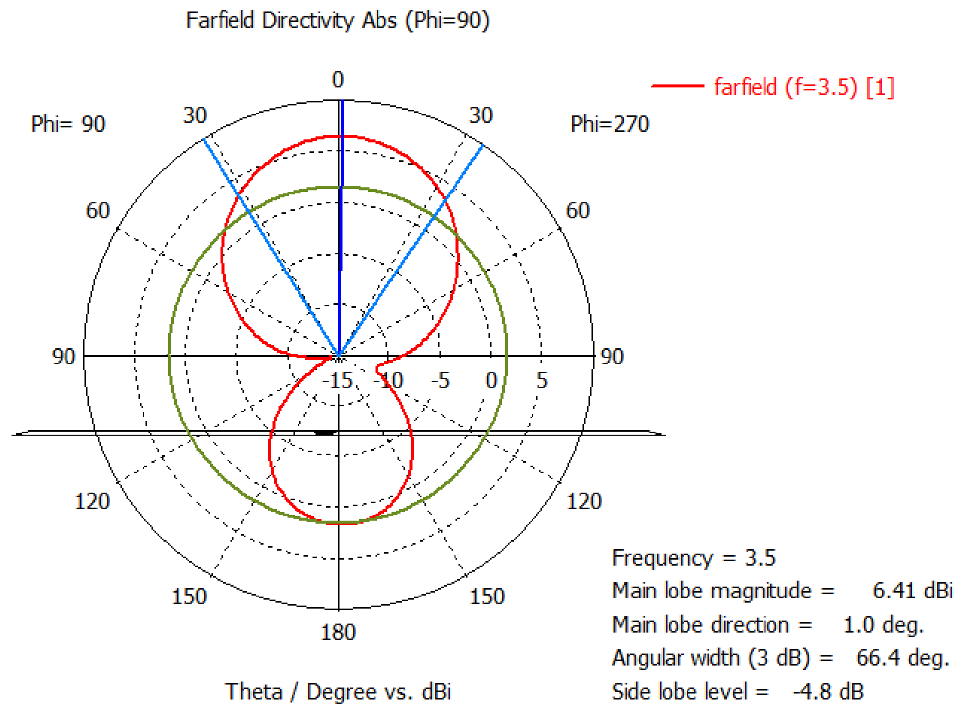
Front


dBi
6.41
5.61
4.81
4.01
3.2
2.4
1.6
0.801
0
-4.2
-8.4
-12.6
-16.8
-21
-25.2
-29.4
-33.6
Phi
Theta
x
z
y
x
z
Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=3.5) [1]
Component Abs
Output Directivity
Frequency 3.5
Rad. effic. -0.09300 dB
Tot. effic. -0.2353 dB
Dir. 6.409 dBi

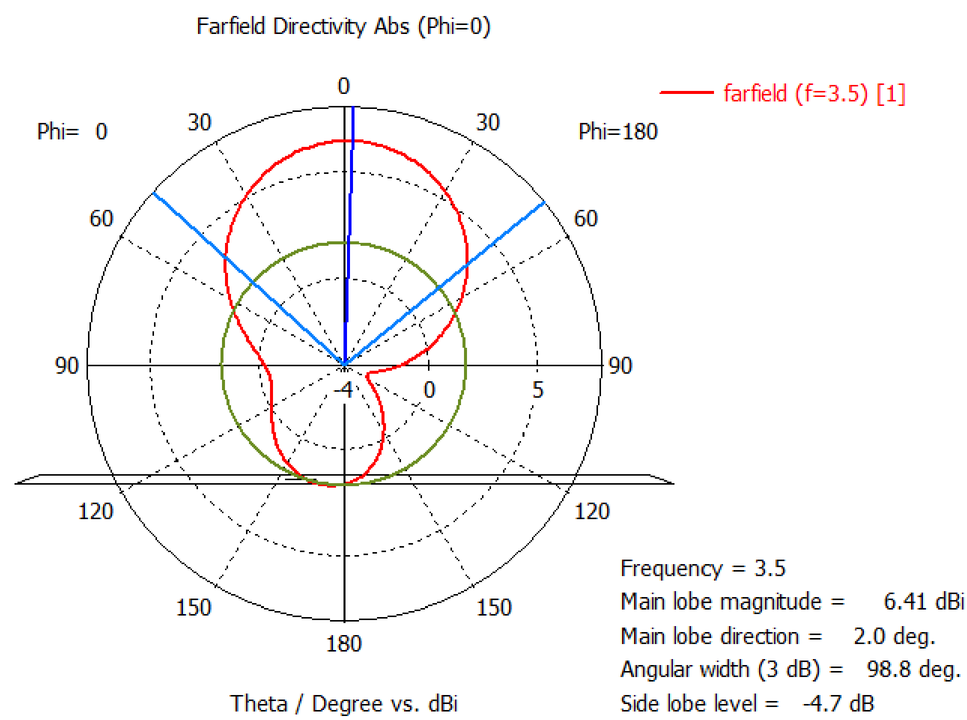
Side:


dBi
6.41
5.61
4.81
4.01
3.2
2.4
1.6
0.801
0
-4.2
-8.4
-12.6
-16.8
-21
-25.2
-29.4
-33.6
Phi
Theta
z
x
y
z
Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=3.5) [1]
Component Abs
Output Directivity
Frequency 3.5
Rad. effic. -0.09300 dB
Tot. effic. -0.2353 dB
Dir. 6.409 dBi

Y-Z Plane



X-Z Plane



Direction of Peak Gain (main lobe): $\theta_{\varphi=90^\circ}^{\text{peak}} = 1^\circ$, $\theta_{\varphi=0^\circ}^{\text{peak}} = 2°$, both angles give the same gain. Essentially – the main lobe is in the $\hat{z}$ direction, except for a tiny tilt.

Peak Gain (Realized Gain):6.174dB

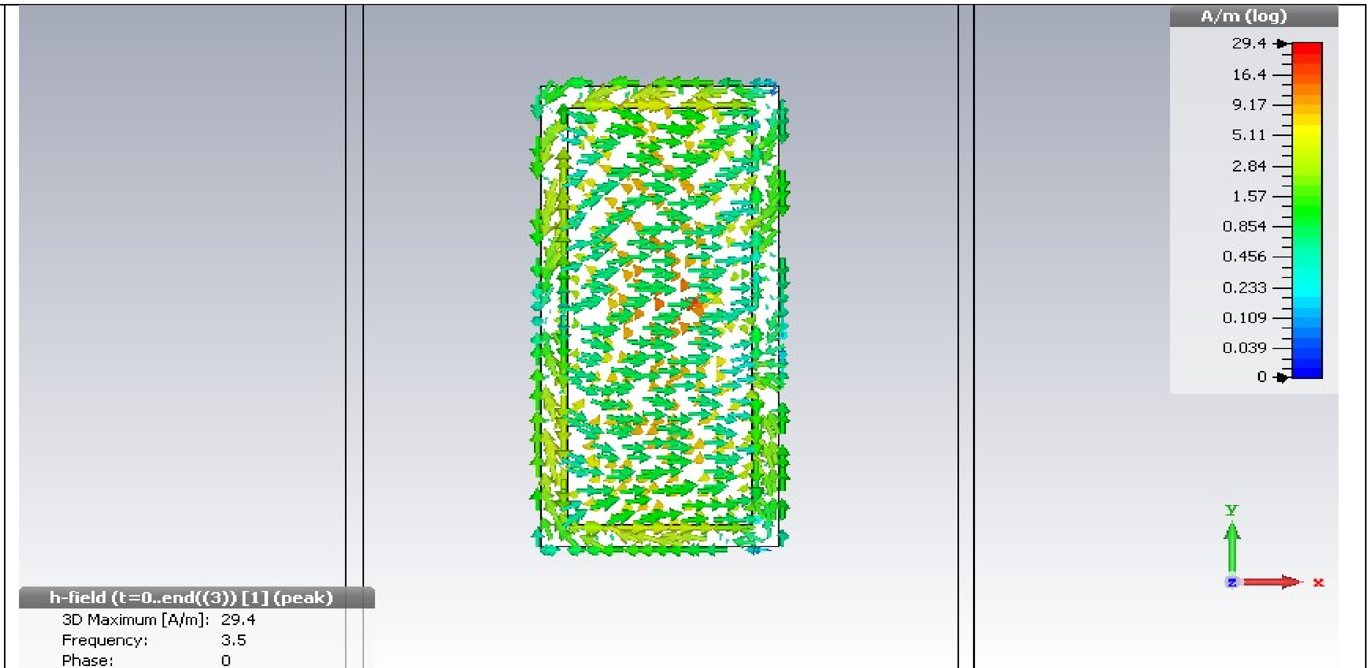
Directivity: 6.409dBi; 4.371 abs units

Radiation Efficiency: 0.9788

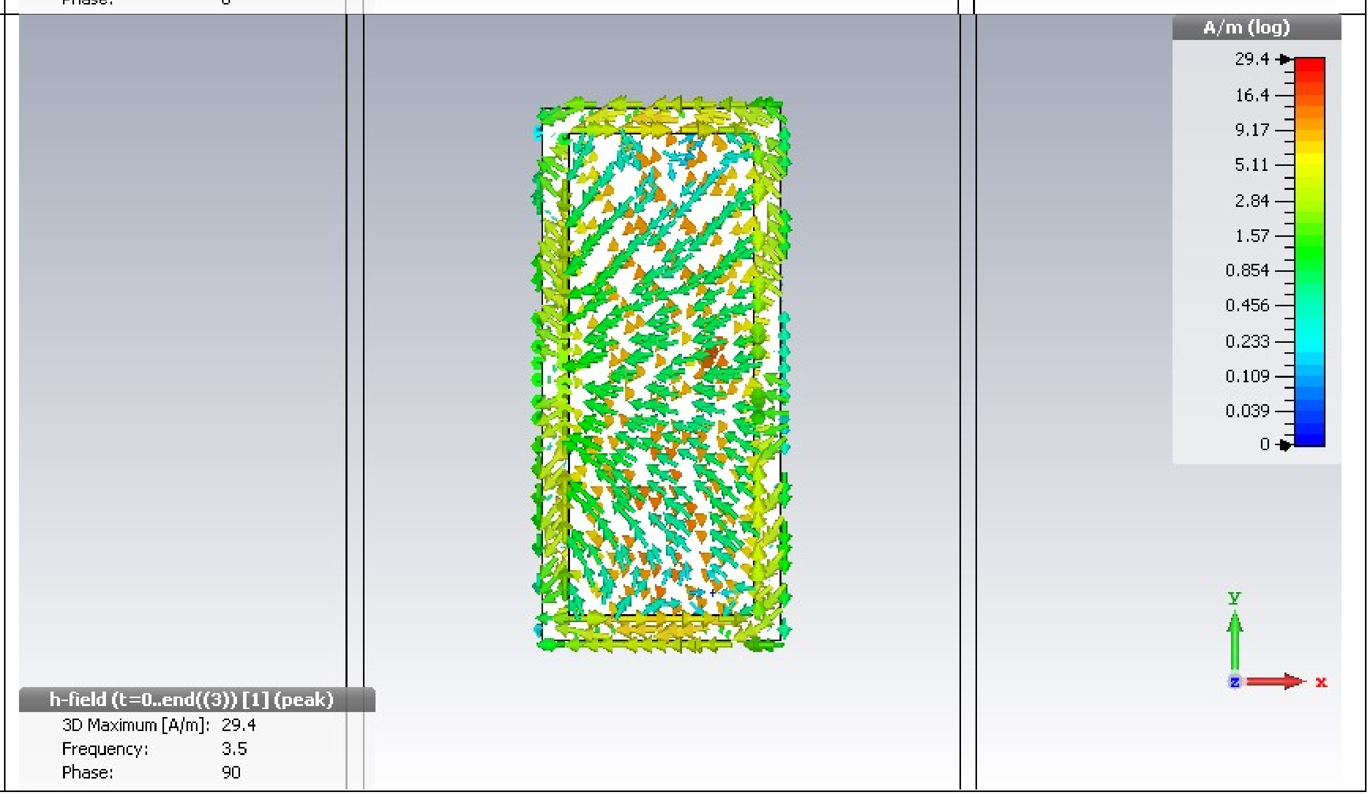
An ideal patch antenna can have a gain above 7.5dBi. We have a smaller gain. In practical terms – this is a result of my choice of parameters. I had a gain of 7.5dBi throughout the intermediary optimization stages, but as the optimizer reached the required S parameter bounds, the gain dropped. In terms of theory – I think I have a lower gain because of the dimensions of the patch. The “theoretical” patch parameters result in a more “square” patch, with a smaller beam width. Before optimization, I had (in linear view) a strong peak at $\hat{z}$ direction, and small grating lobes near it. After optimization of patch dimensions to satisfy S11 requirements, the patch became wide and short, so the beam width is increased. Because the beam width is increased, there is less radiated energy “concentrated” in the direction of the main lobe, and the average radiated power is increased, dropping the directivity. Therefore, the maximum gain (which is measured as the gain at the main lobe, and is proportional to directivity) is reduced.

Surface Currents:

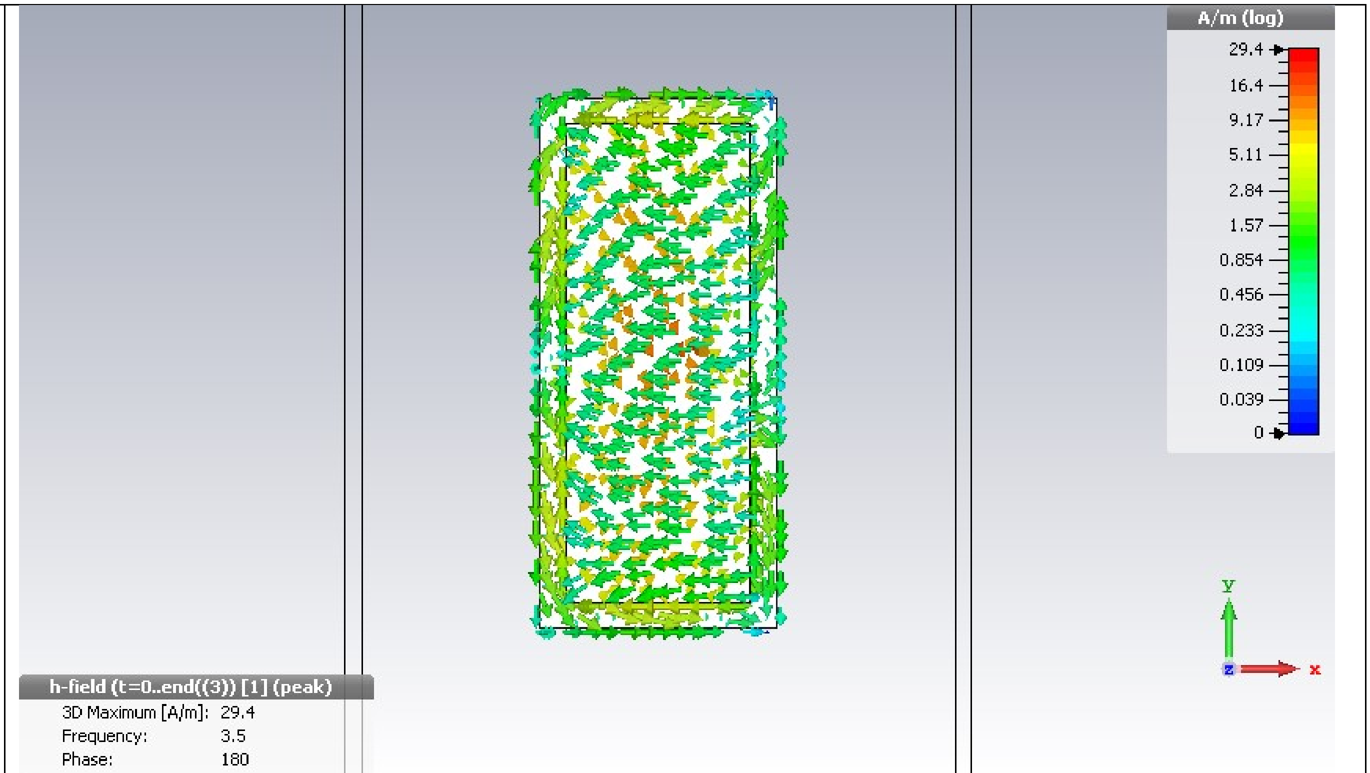
0



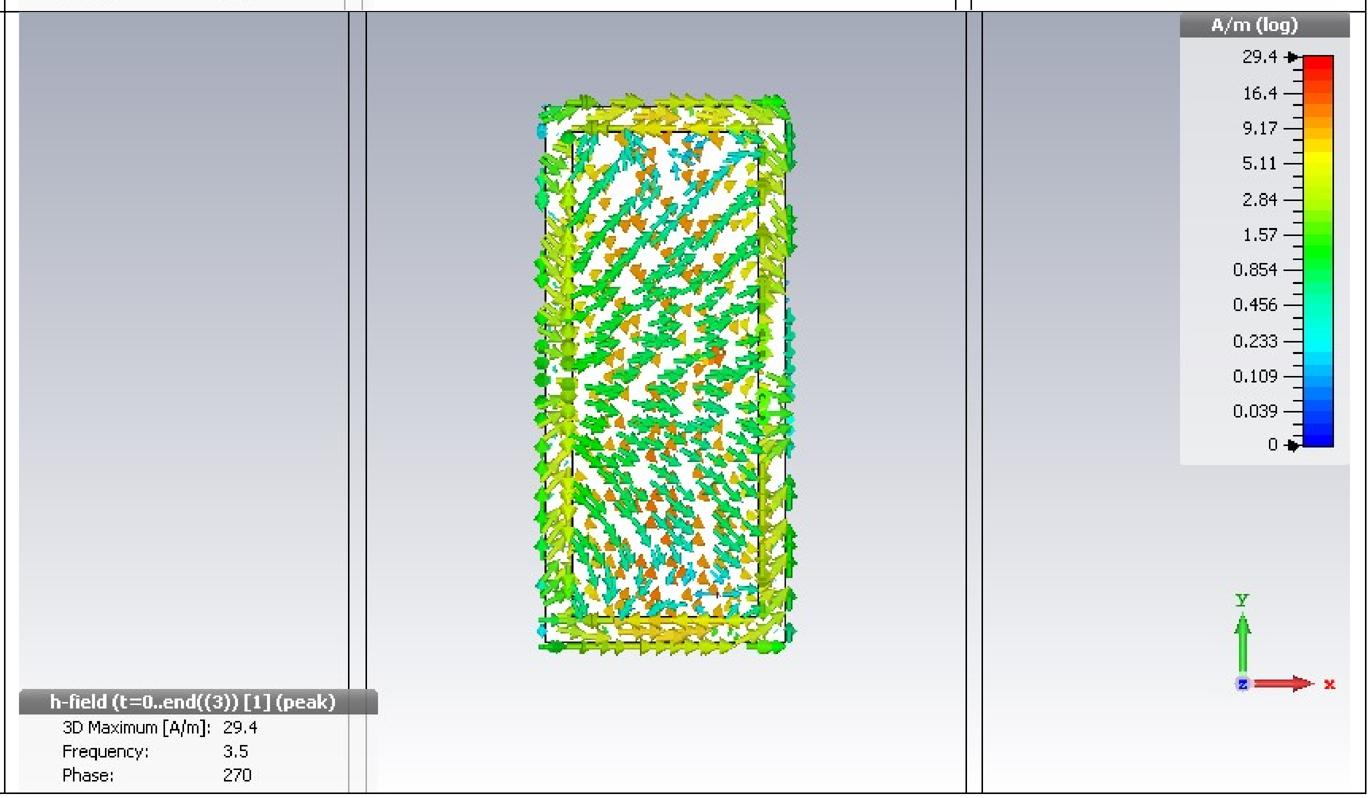
T/4



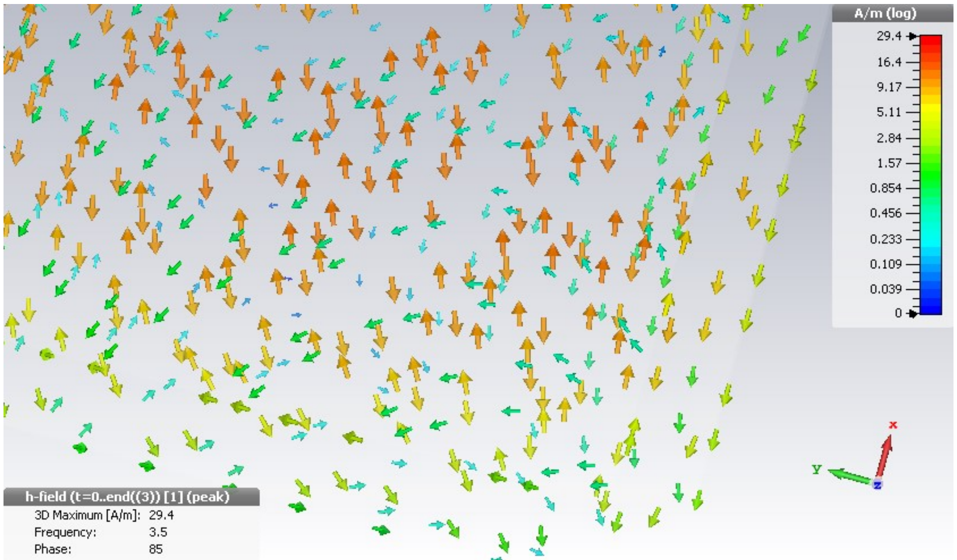
T/2



3T/4



One thing we would expect is that the edge currents on the ground plane and the patch are in opposite directions. This is the case in my simulation. The same holds true for the surface currents, though it is hard to discuss their direction as they "swirl". In general, I can observe that for each specific "current arrow" pair – they always point in opposite directions. I tried to zoom into the output to demonstrate this:



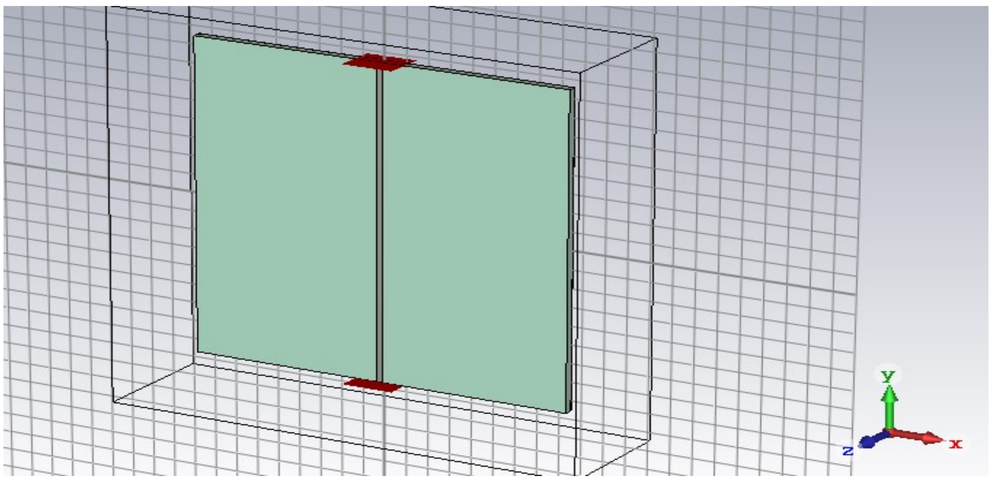
It is hard to see, because there is no indication of which surface current belongs to which plane (disabling transparency occludes the ground plane entirely), but in animation it is evident that the ground plane surface currents are in opposite direction to the patch currents.

This makes complete sense. The patch antenna is a voltage radiator, i.e. the voltages add up in phase. The currents on the patch add up in phase too, but their radiation capabilities are nulled by equal and directionally opposite currents in the ground plane.

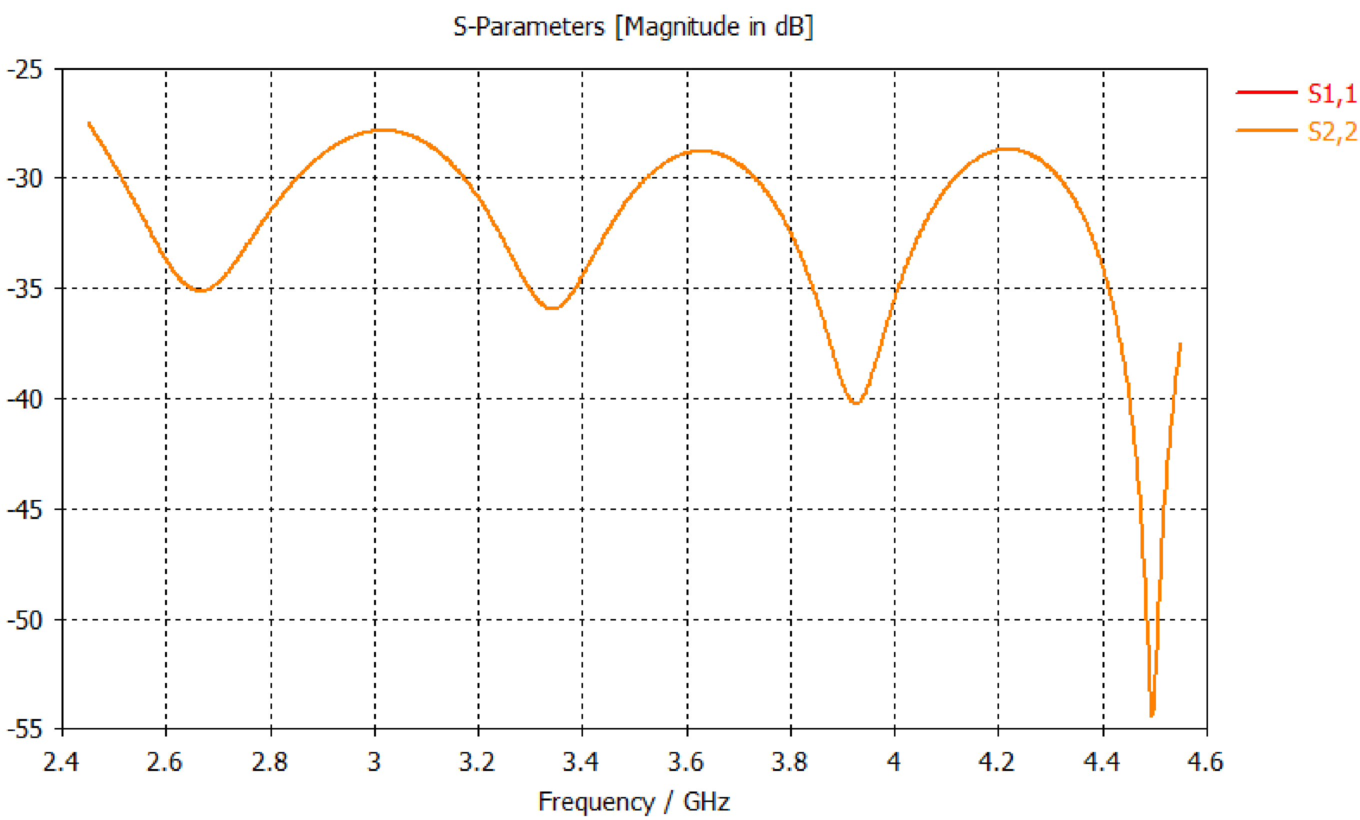
3) (5 points) Build a CST model of a 100Ω microstrip line that it is implemented on the same dielectric substrate as your optimized patch antenna. The length of the microstrip should be two wavelengths (according to the frequency given in the table below). Place wave ports at the input and at the output of the microstrip line and simulate the 2ports S-Parameters over the frequency band of 0.7f -1.3f.

   a. Optimize the parameters of the microstrip line so that Sii (S11 and S22) will be below 25dB
   b. What is the insertion loss of the microstrip at the frequency f? – compare it to that of the coax cable at the same length and explain the differences.
   c. Present the S-Parameters results of the optimized microstrip line at the given frequency band.

The model:



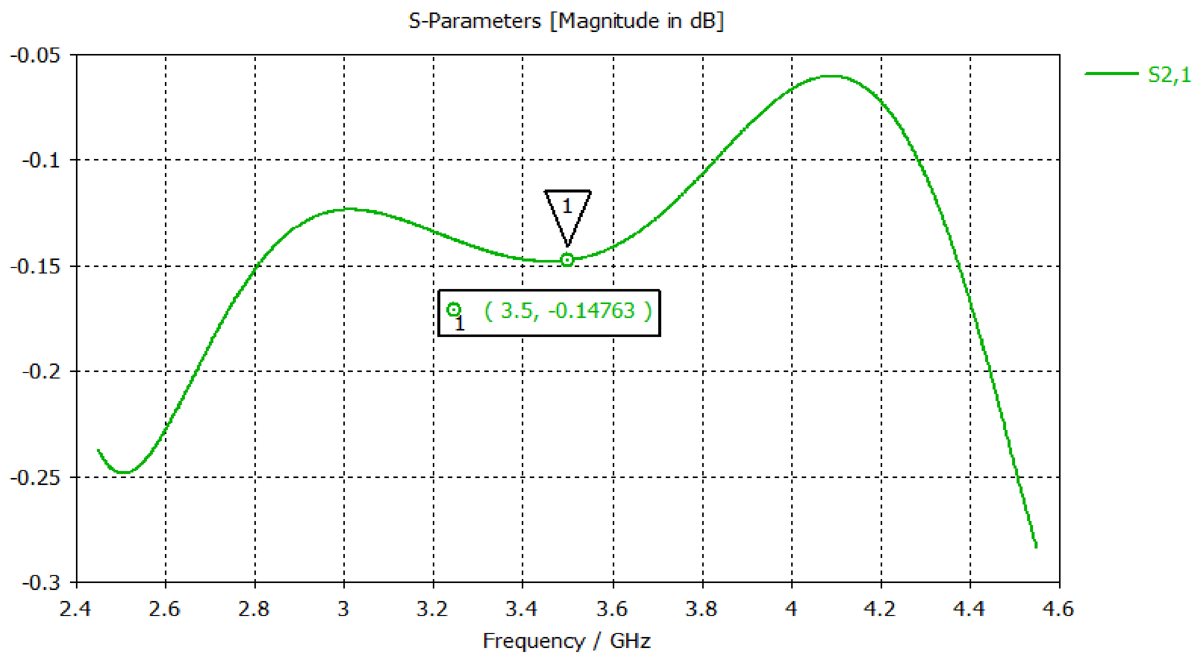
Optimized S-parameters:



In the design of the microstrip I defined the width as $W_{strip} = a \cdot Z$ where Z =thickness of the substrate, and a is a parameter that I optimize.

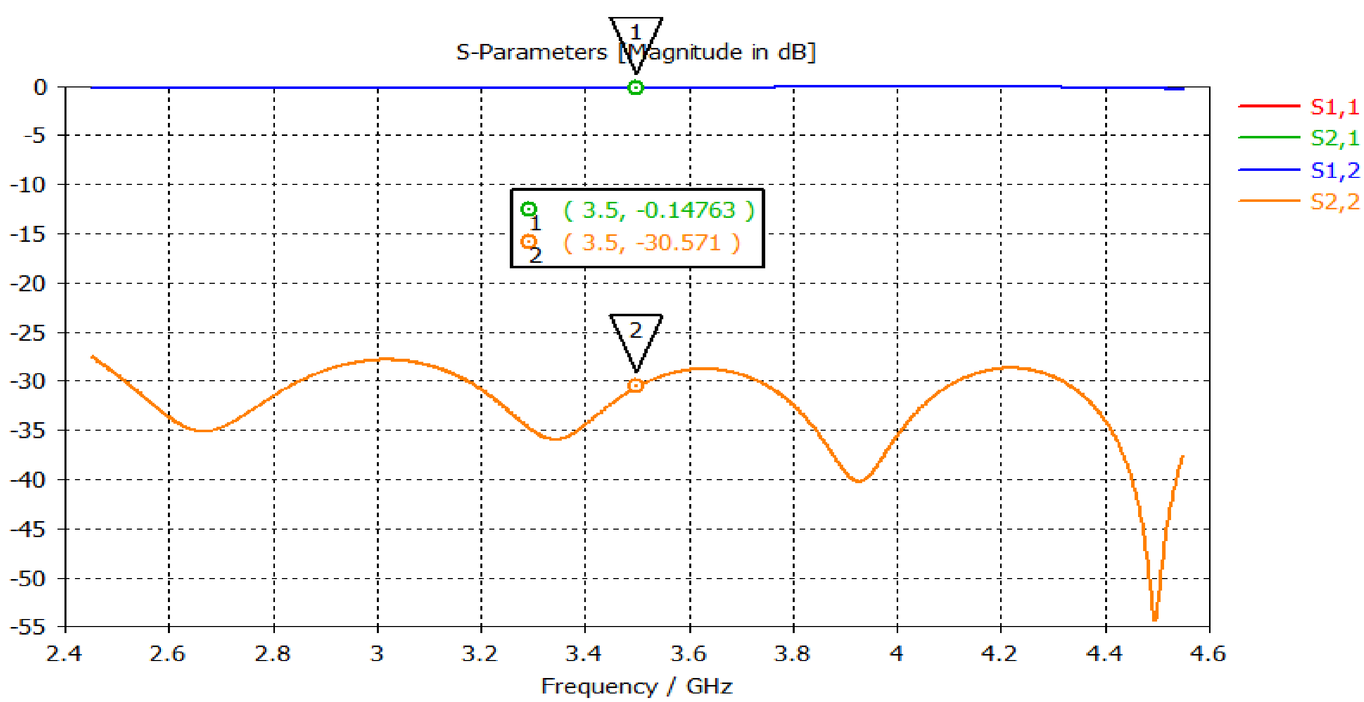
When doing theoretical calculations for this question, I found $a = 0.66$ gives 100Ω impedance exactly. However, at this value the Sii parameters exceeded -25dB by a small margin at low frequency. To fix this, I made $a = 0.67$, which gave a resultant impedance 101.7Ω, which is close enough to 100, but fixed S11.

Insertion Loss:



This insertion loss is higher than for the Coaxial cable. This is to be expected. – microstrip losses are (rule of thumb) 10X worse than coax. This could be because the microstrip has more loss mechanisms than the coax, such as leakage. The coax can't leak because it is shielded, unlike the strip.

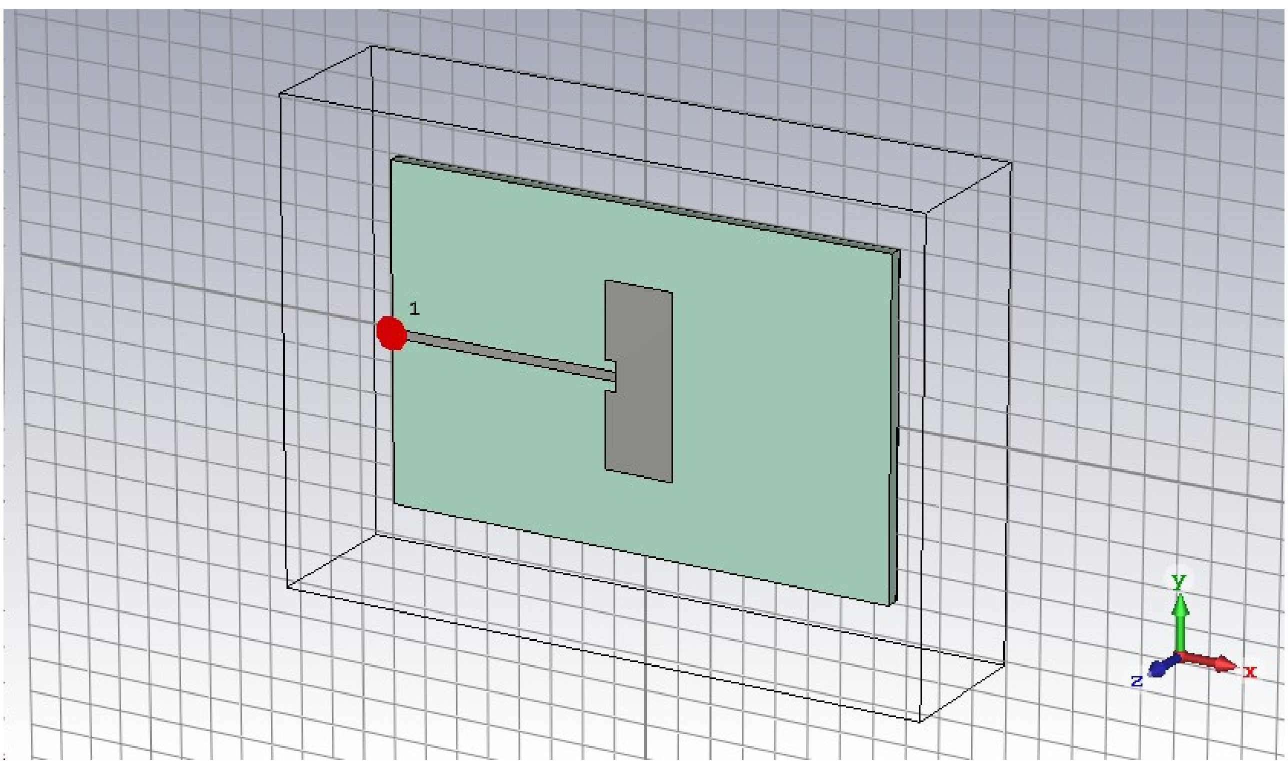
All S-parameters:



4) (15 points) In this section you are required to replace the coax feed with a microstrip feed for the patch antenna: feed the patch antenna that you designed in Section 2 using the microstrip line that you designed in Section 3. In this case, the microstrip line should have a length of a half wavelength. Place a lumped port on the far edge of the microstrip line in order to feed it. The impedance of the line must remain 100Ω and all the patch parameters (width, length, height of the substrate) must remain the same as in Section 2 above! If needed, a quarter wavelength transmission line can be designed in order to match the patch antenna to the 100Ω microstrip line. Other matching options of the patch antenna to the line can be used instead. Now, fine-tune the (allowed) parameters in order to achieve a matching (Return Loss, or S11 in dB scale) of better than 10dB over the frequency band 0.98f -1.02f.

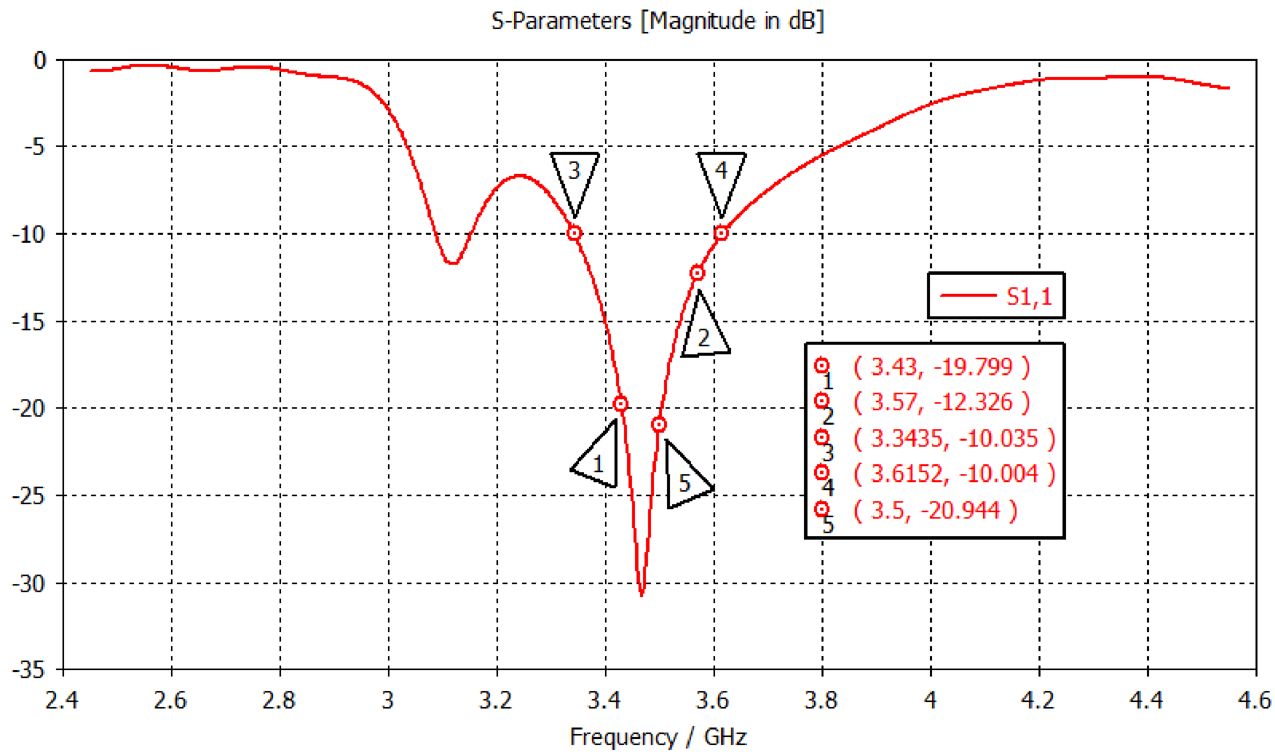
a. Present the input matching over the bandwidth 0.7f -1.3f. Use markers on the plot in order to demonstrate the achieved design goals.
b. Present the 3D far field radiation pattern of the patch antenna at the frequency f, and the radiation pattern over the 2 main planes: the Y-Z plane (“Elevation”) as a function of θ, and the X-Z plane (“Azimuth”) as a function of φ. Is there any difference comparing the radiation patterns that you got in Section 3? – if there are, explain the differences

The optimized model:



I used the inset matching method to maintain the required impedance across the specified bandwidth, and to satisfy the S11 requirement. I did not use stub matching or quarter wavelength matching because they are narrow bandwidth techniques, whereas the inset can potentially give a better bandwidth.

S11:

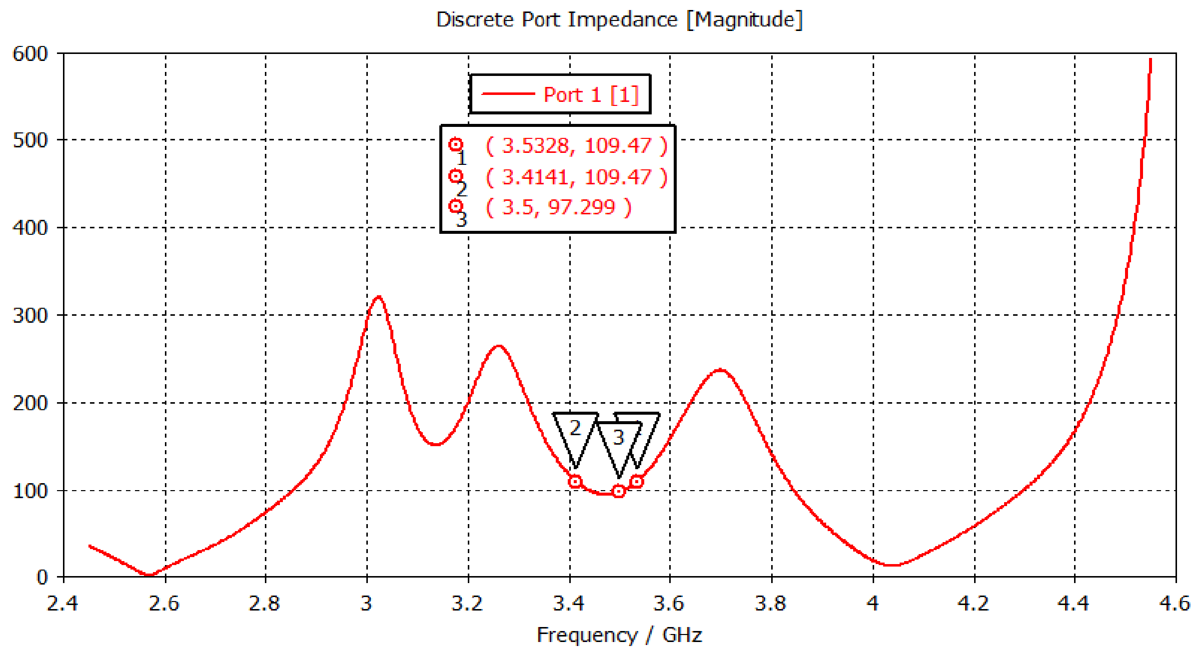


Markers 1,2 denote the $0{,}98f, 1.02f$ points. We can see that we have good matching at these points, below -10dB, and that the interior between these two points only contains even better matching. Marker 5 denotes S11 at our operating frequency, at which we have input matching of -20.944dB, which is good, given that -25dB is the “golden standard”.

The actual bandwidth of this design is given by markers 3,4: $3.3435 - 3.6152 \rightarrow 0.955f - 1.033f$.

The required bandwidth was 4%, I obtained a bandwidth of 7.8%.

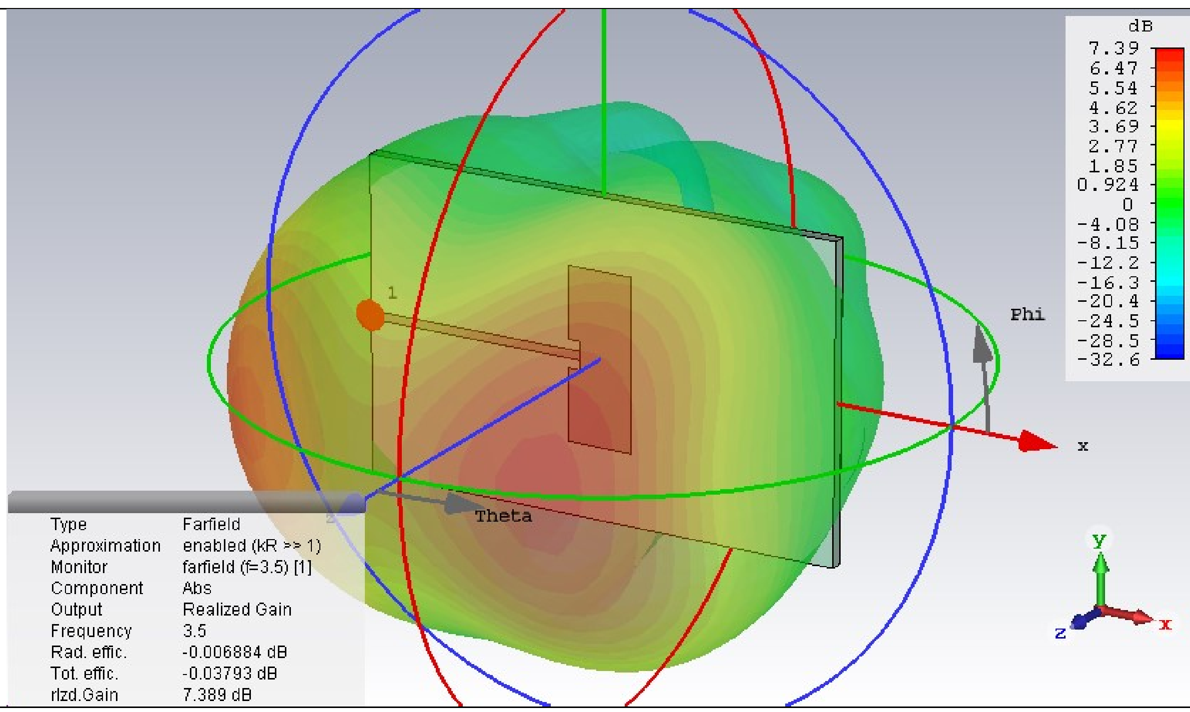
Since we have good matching, it makes sense that the impedance would be 100Ω within the required region, or close to it. To check – I display the impedance port1 sees:

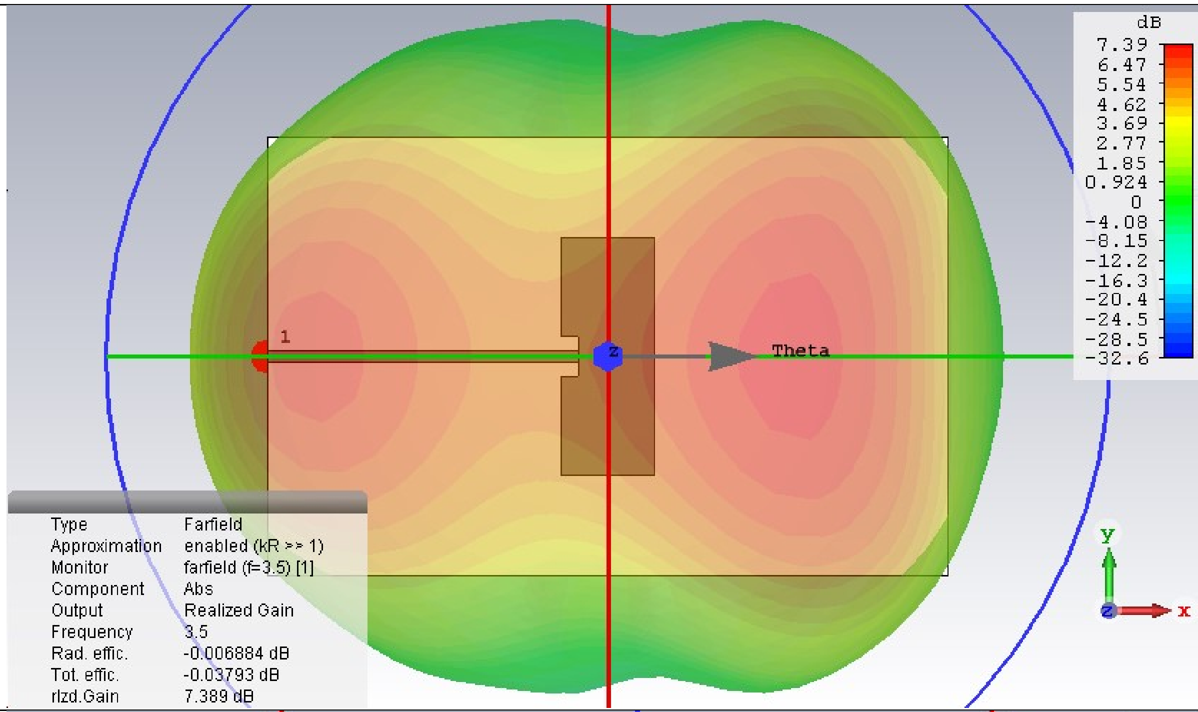
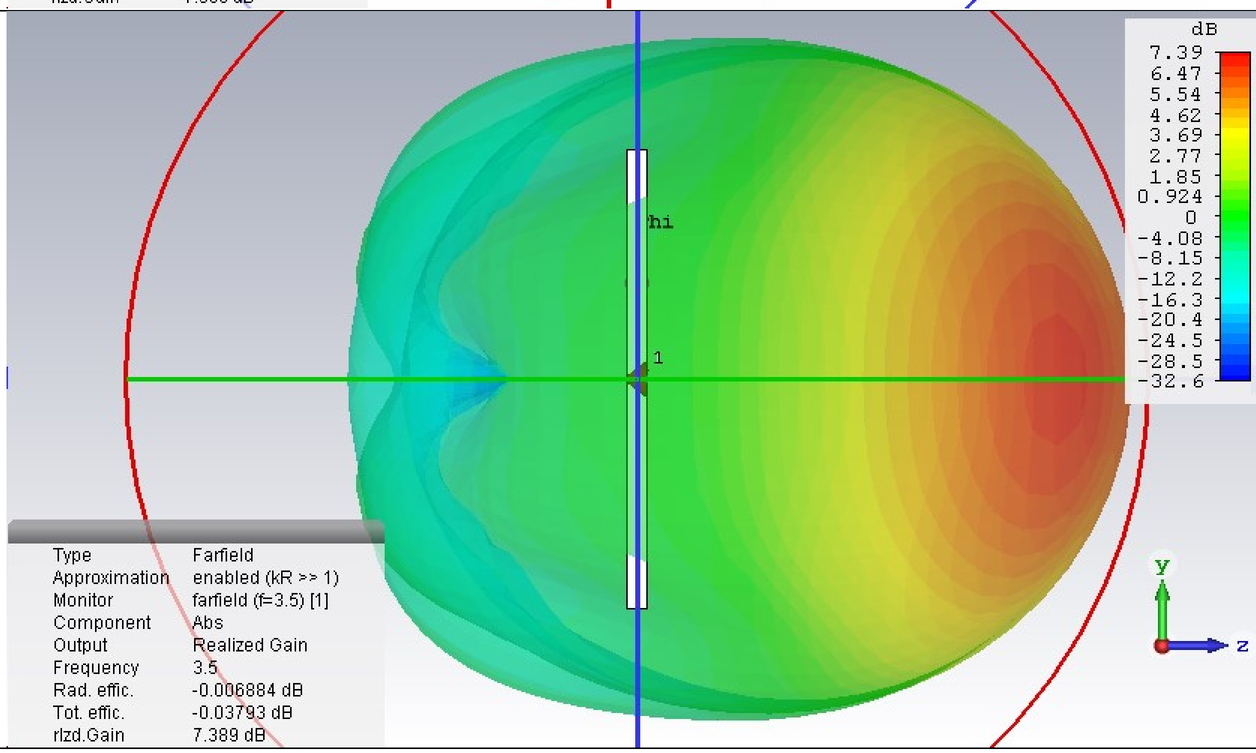


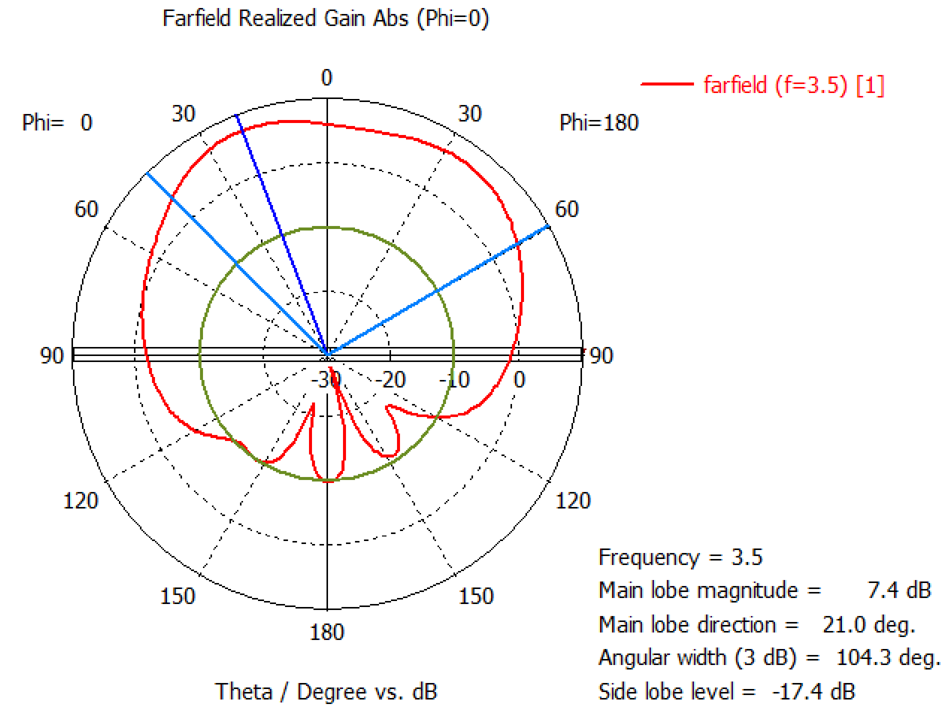
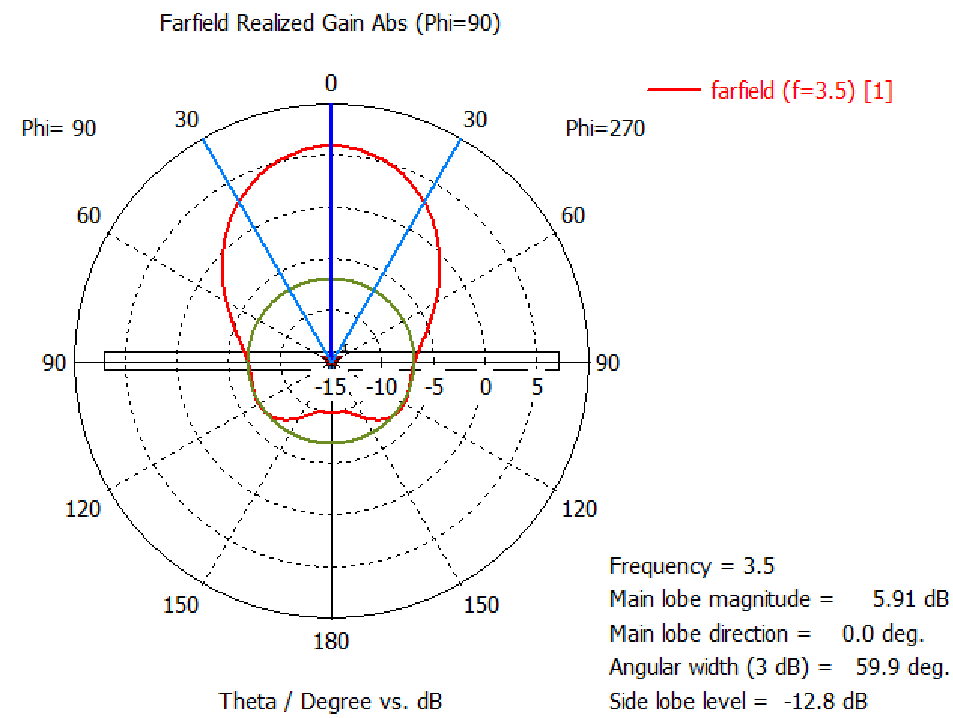
We can see that we meet the impedance requirement at our operating frequency (marker 3), and in a small neighborhood around it (markers 1,2). However, we do not meet the impedance requirement for all of $0.98f - 1.02f$. If we say that 110Ω is "good enough" then we have impedance matching for $3.414G - 3.533G \rightarrow 0.975f - 1.01f$. So our impedance is good for most of the bandwidth, except at the higher frequency edge.

Radiation Pattern:

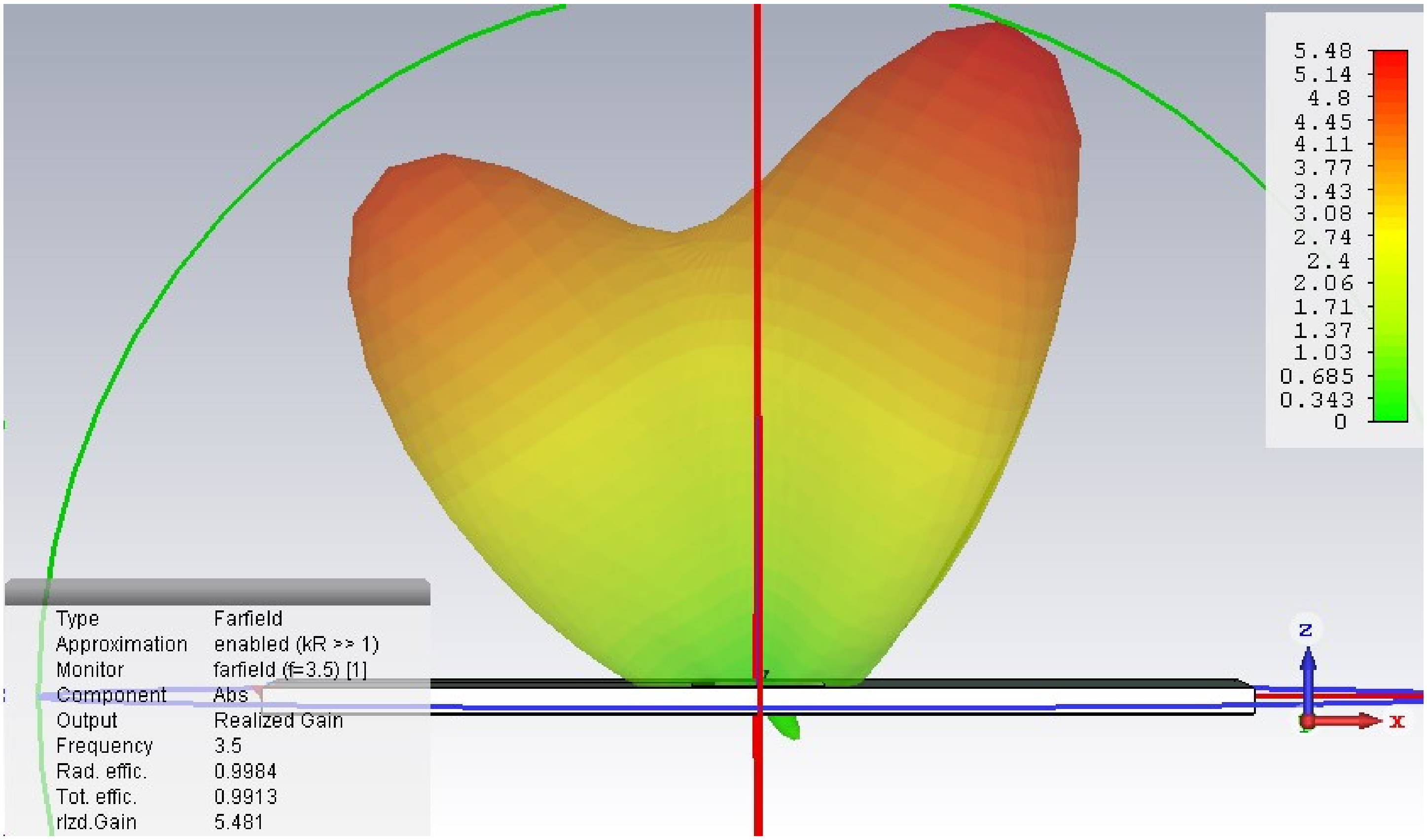
Perspective



Front	dB
7.39
6.47
5.54
4.62
3.69
2.77
1.85
0.924
0
-4.08
-8.15
-12.2
-16.3
-20.4
-24.5
-28.5
-32.6
Theta
Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=3.5) [1]
Component Abs
Output Realized Gain
Frequency 3.5
Rad. effic. -0.006884 dB
Tot. effic. -0.03793 dB
rlzd.Gain 7.389 dB
Side:	dB
7.39
6.47
5.54
4.62
3.69
2.77
1.85
0.924
0
-4.08
-8.15
-12.2
-16.3
-20.4
-24.5
-28.5
-32.6
Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=3.5) [1]
Component Abs
Output Realized Gain
Frequency 3.5
Rad. effic. -0.006884 dB
Tot. effic. -0.03793 dB
rlzd.Gain 7.389 dB

Y-Z Plane	
X-Z Plane	

This radiation pattern is different from one obtained earlier. We observe two lobes, which are especially evident in linear view:



We see that there is a grating lobe in the direction of the feed line, and a main lobe in the direction of the patch. We also have a much better directivity of 7.427dBi (as opposed to 6.4dBi), and a much better gain. Our efficiency is also significantly improved, from 97.88% to 99.84%. It seems that the reason for the presence of this second lobe is that the patch itself is radiating. This could be because my patch is too wide.

5) (60 points) In this section you are requested to use again the antenna that was optimized in Section 4 in order to implement an array as described in the table below. Follow the sections below:

a) Write down the expression for the normalized Array Factor of the array that you should implement. For your convenience, you can change the axis along which the array is implemented, as long as your final conclusion in the sections below remain correct. For example – it might be easier to set the array elements along the Z-axis.

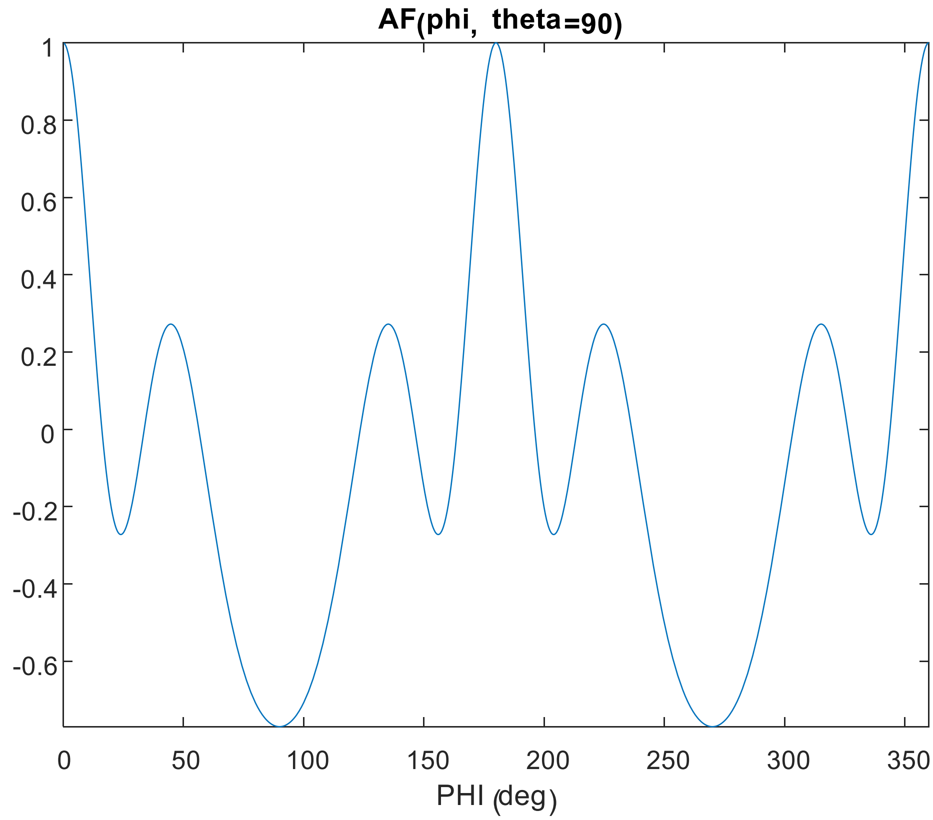
I am building an array along the Y axis, therefore $\psi = kdsin(\theta)\sin(\varphi)$

$$\text{So } (AF)_n = \frac{\sin\left(\frac{N}{2}kdsin(\theta)\sin(\varphi)\right)}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)} \quad ; N = 4,\ k = \frac{2\pi}{\lambda}\ ,\ d = 0.9\lambda$$

$$\epsilon_{eff} = 2.234 \rightarrow \lambda_{eff} = 0.0573[m]$$

b) (5 points) Plot in Matlab the normalized array factor as a function of the observation angle for which the beam-width is set by the array size. Attach your code file to the solution.

Plot Result:



c) (5 points) Find the directivity of the array, assuming that it is implemented by isotropic elements. If an analytical solution is not trivial, a numerical integration is allowed, conditioned that you attach your code file to the solution

Our array factor:

$$(AF)_n = \frac{\sin\left(\frac{N}{2}kdsin(\theta)\sin(\varphi)\right)}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)} \quad ; N = 4, \qquad k = \frac{2\pi}{\lambda}, \qquad d = 0.9\lambda \ \lambda_{eff} = 0.053m$$

$$U_0 = \frac{P_{\text{rad}}}{4\pi} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} U(\theta,\varphi)\sin(\theta)\,d\theta d\varphi = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left(\frac{\sin(\frac{N}{2}kdsin(\theta)\sin(\varphi))}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)}\right)^2 \sin(\theta)\,d\theta d\varphi$$

$$D = \frac{U_{\max}}{U_0} = \frac{1}{U_0}$$

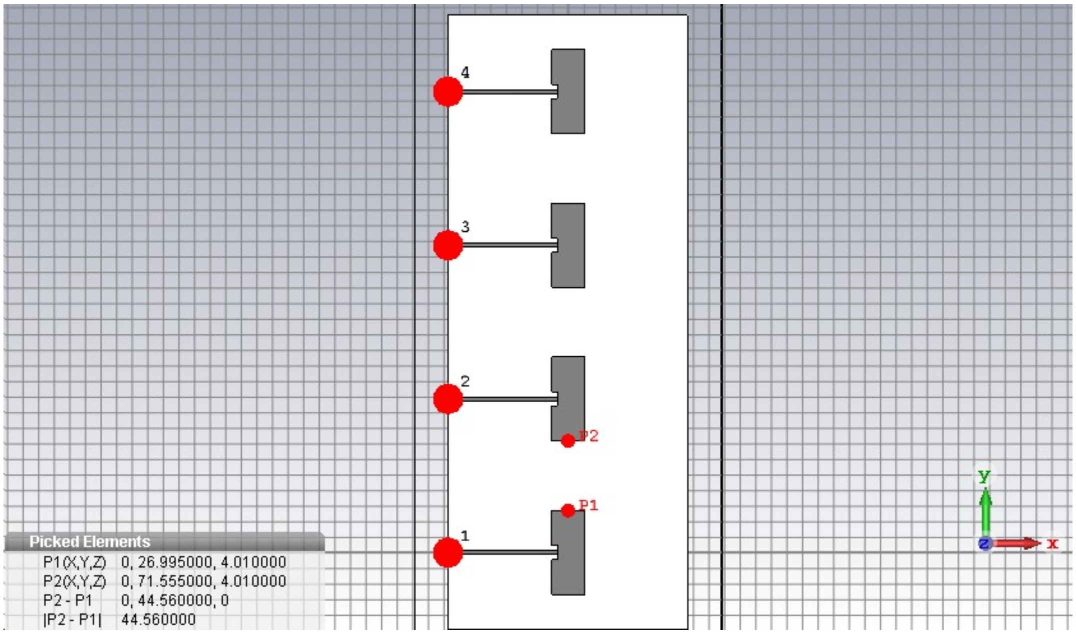
The reason we can say $U_{Max} = 1$ is because we are dealing with normalized quantities. The solution for U_0 was found numerically, with the Matlab code attached to this project. The result was: $U_0 = 0.183 \rightarrow D = \frac{1}{0.183} = 5.46$

d) (5 points) Calculate the required electrical phase $\Delta\varphi$ that is required in order to steer the beam to an angle of 20° along the array's axis. Note the configuration of your array (along the Z-axis or the Y-axis)!

Calculating required phase shift: We want the array to point to $\theta = 20°$, so: $\Delta\varphi = \frac{180}{\pi} \cdot 0.9 \cdot 2\pi \cdot \sin(20) = 110.82°$

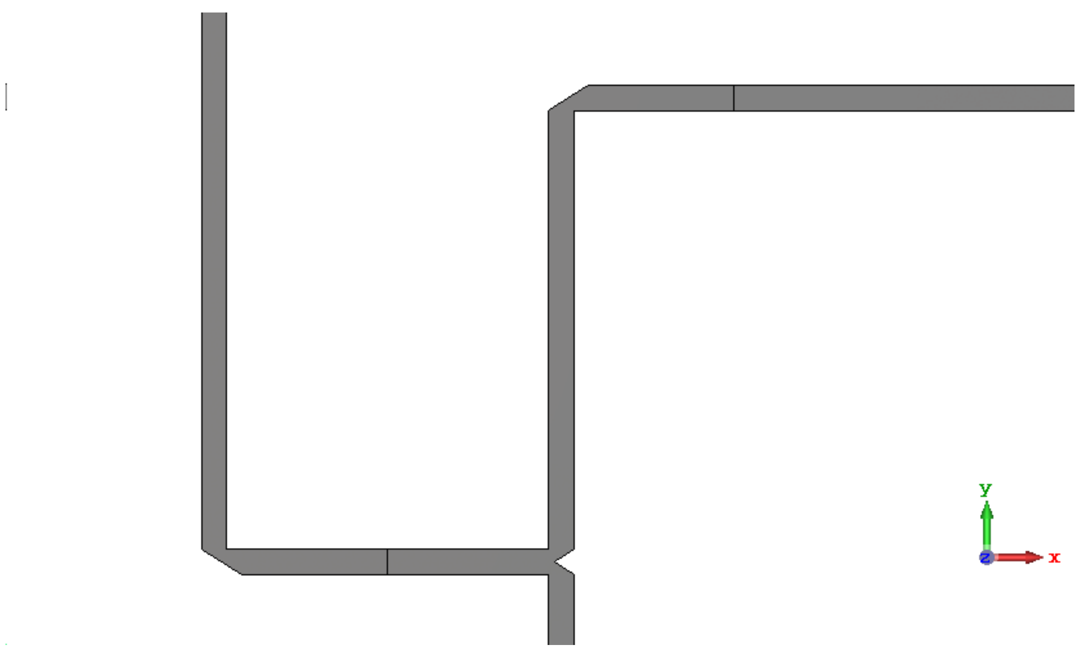
e) (15 points) Implement the array in CST by duplicating the single patch and its microstrip feed, according to the configuration of your array (elements number and polarization). If the substrate + metal ground planes of the patches are not overlapping, fill the entire gap with the same substrate + ground plane. Design the microstrip network so that all the patches will be fed by microstrip lines and the microstrip network will have a single feeding point that will be connected to a quarter wavelength 50Ω coax line that you designed in Section 1. Simulate this structure while feeding all of the patches with the same electrical phase and plot the 3D radiation pattern, as well as 2D the radiation pattern in the azimuth and in the elevation.

To create a baseline model, I use the Array Wizard macro. It's output is presented below:



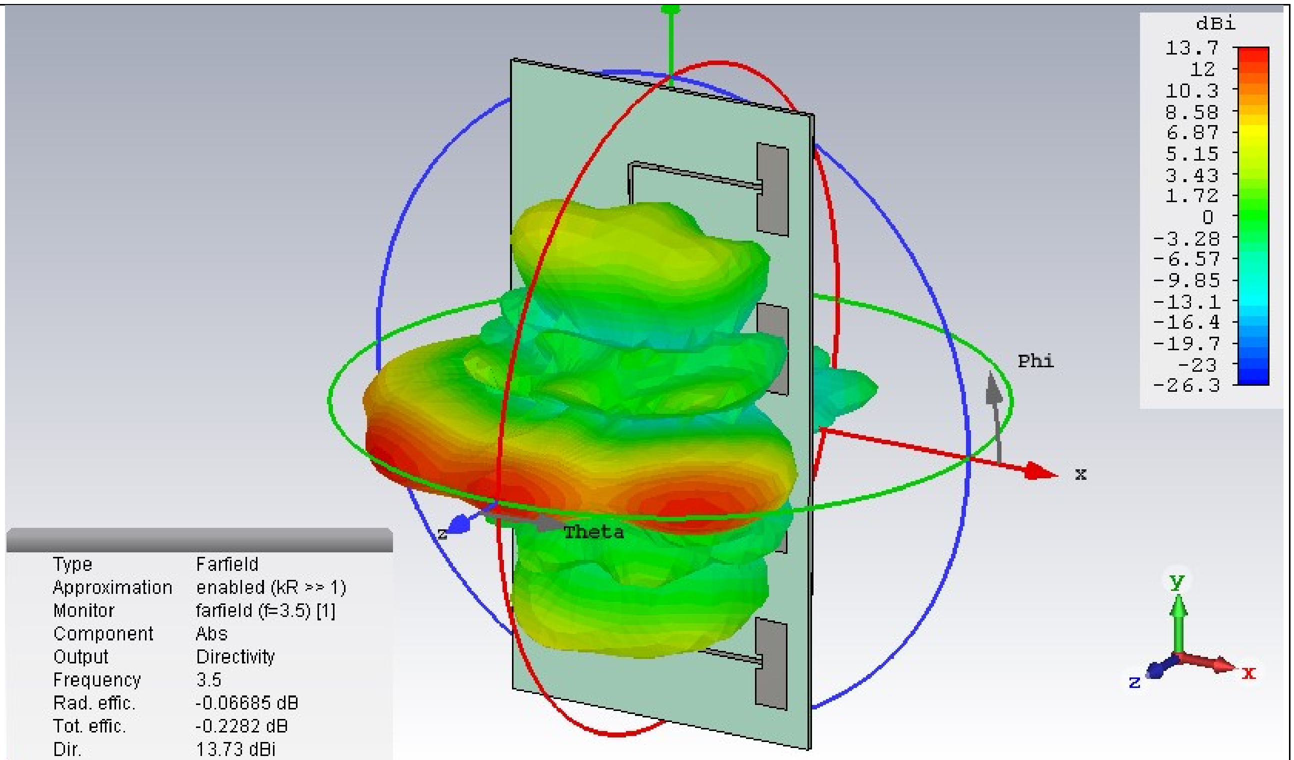
I am applying a 0.9λ spacing edge-to-edge, not center-to-center, because I think that makes more sense, as the patches would be very close otherwise. In fact, doing edge-to-edge allows for the patches to overlap, which wouldn't make sense.

I used mitered bends for 90° turns, and notch cutouts for T-junctions, where the angle of the cutout on either side of approach is equal to the angle of the mitered bend. The parameters of the bend were calculated in accordance with available theory.

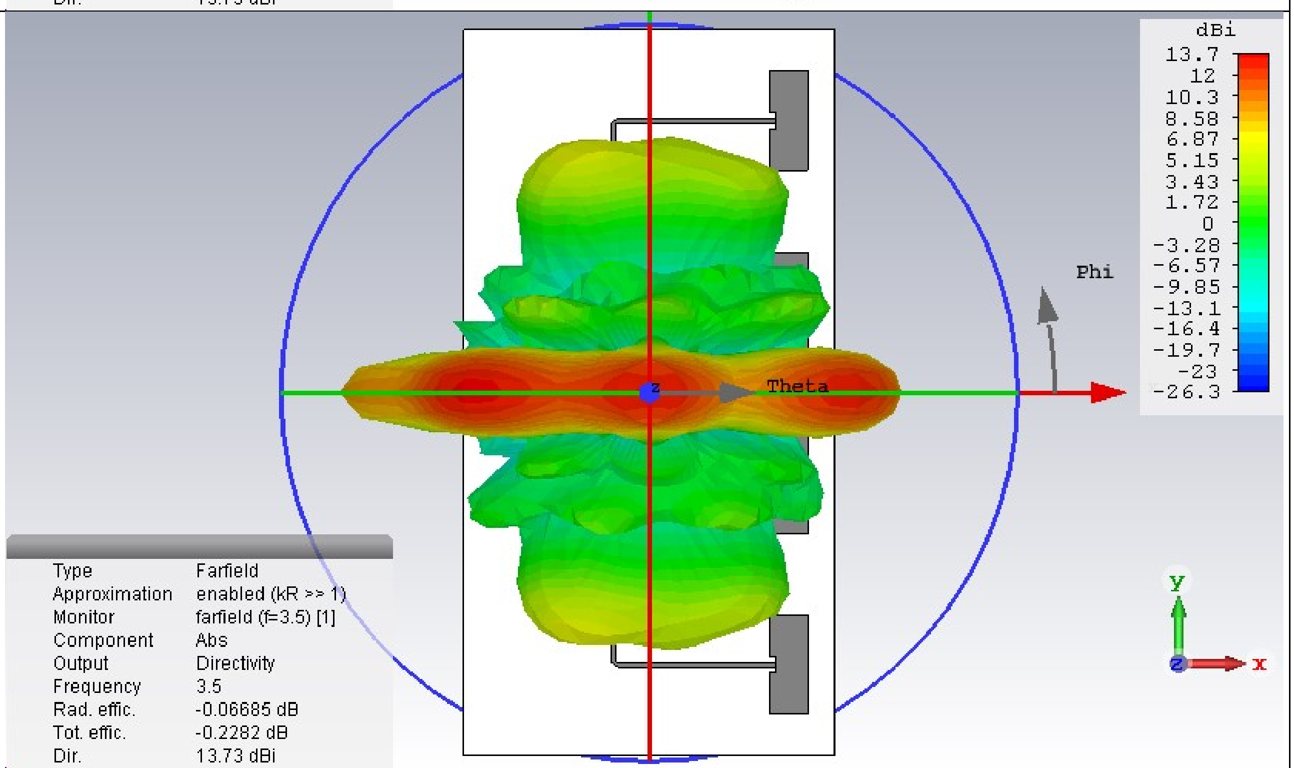


The radiation pattern:

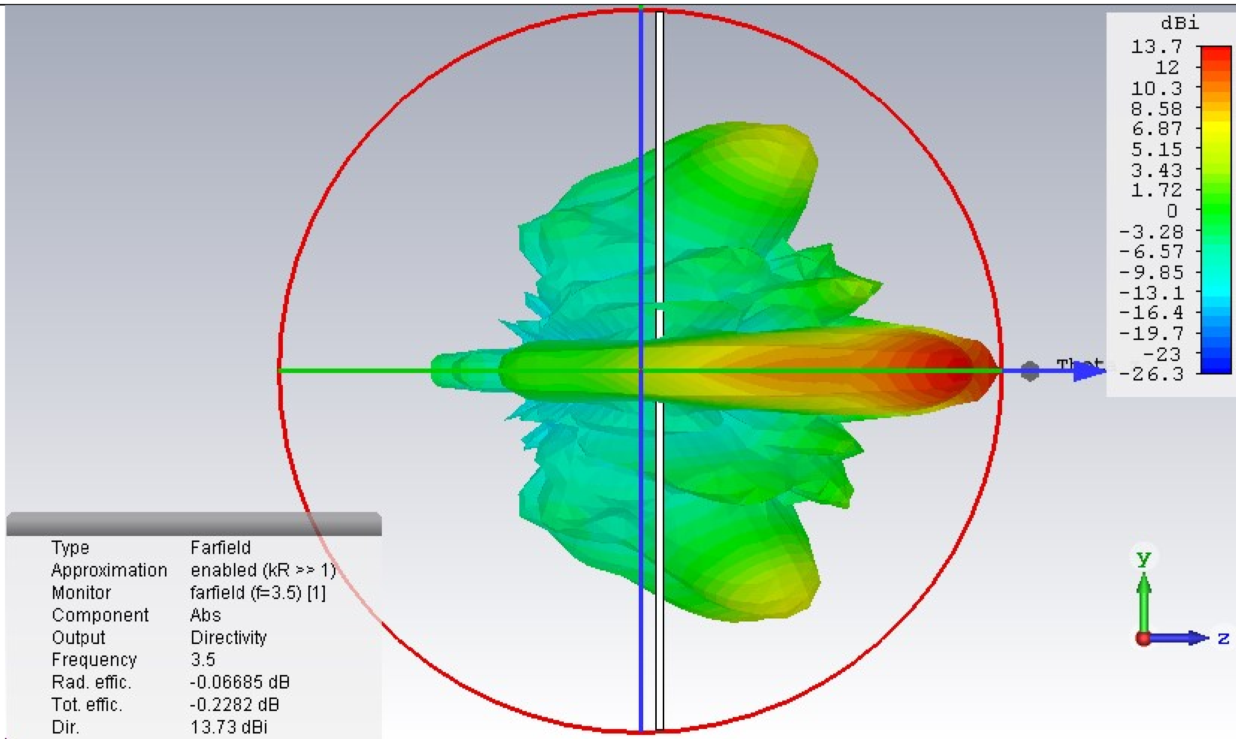
Perspective



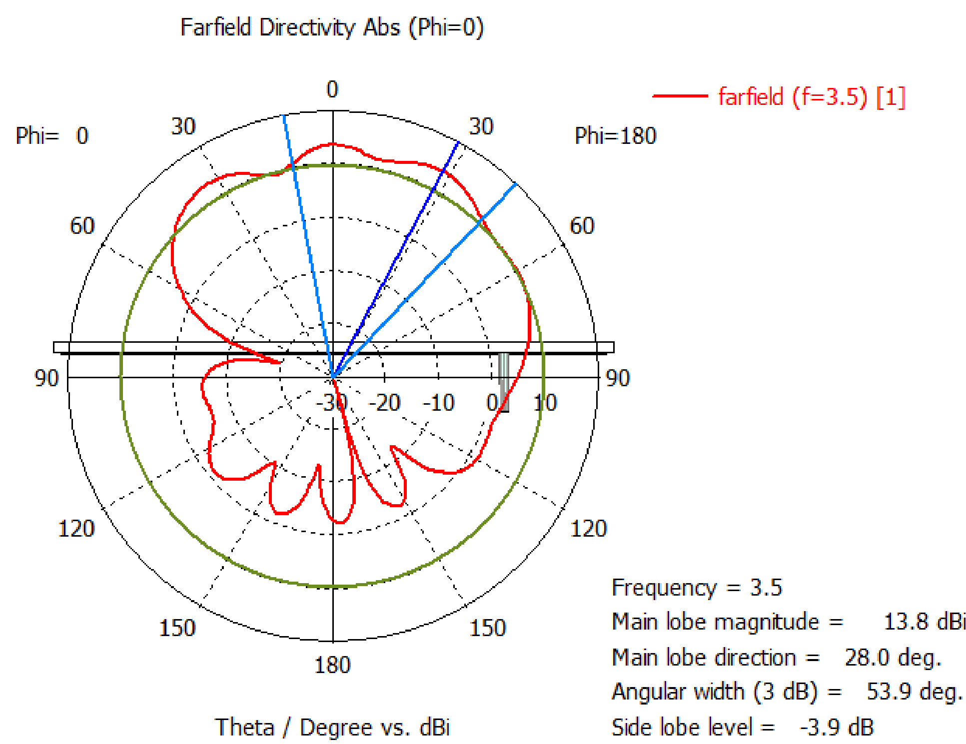
Front

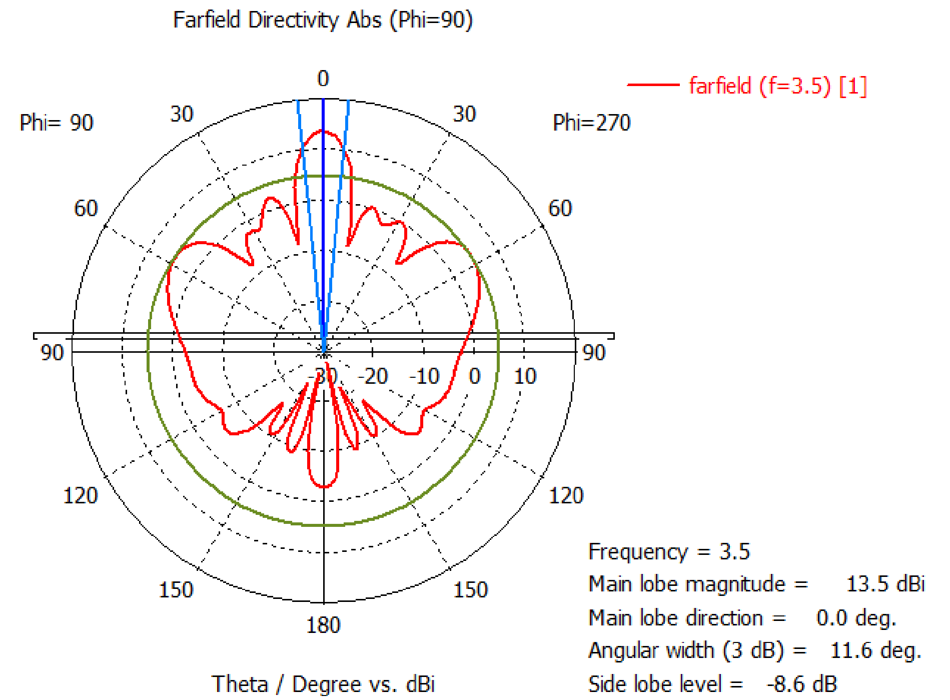
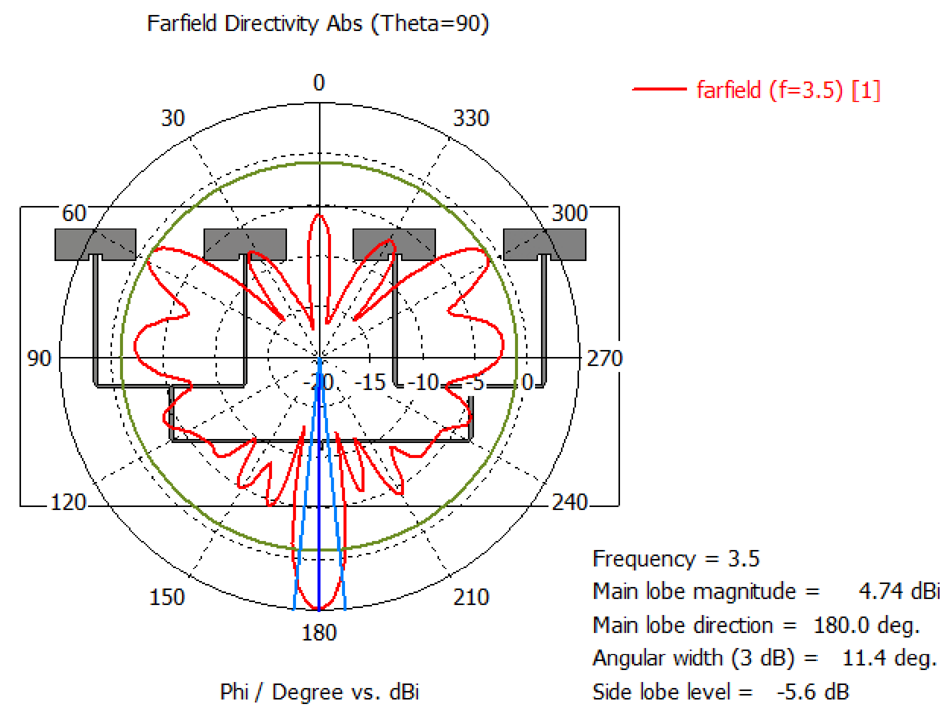


Side:



Y-Z Plane



<table>
<tr><td>X-Z Plane</td><td>
</td></tr>
<tr><td></td><td>
</td></tr>
</table>

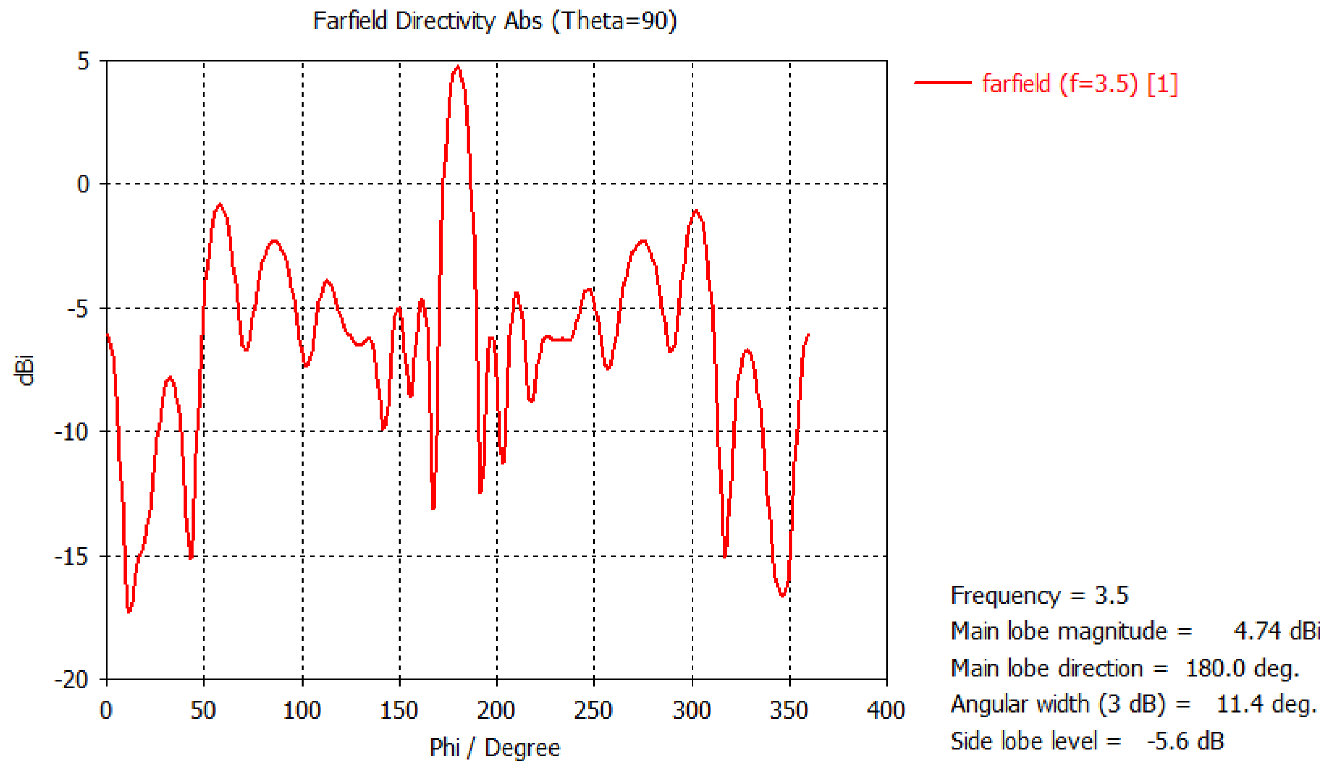
Directivity: 13.73 dBi

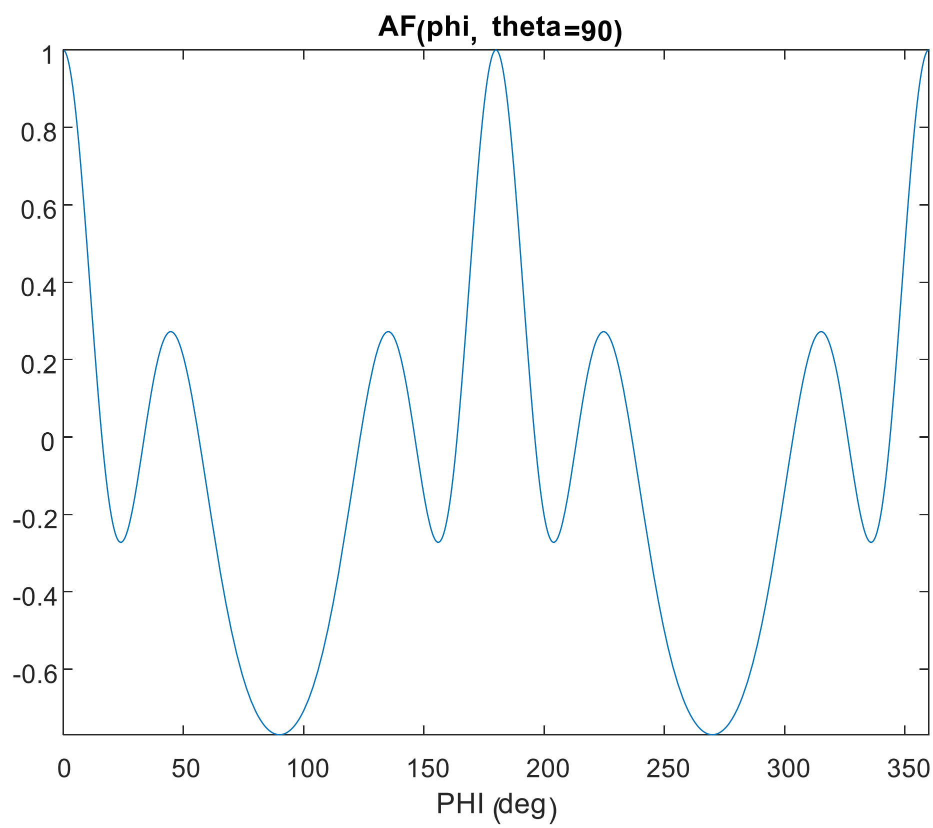
Realized Gain: 13.5 dB

Radiation Efficiency: 0.9847

Main Lobe direction: $\varphi = 0,\ \theta = 28°$

f) (3 points) Compare the radiation pattern along the array's axis to the theoretical radiation pattern of the array factor. Explain the differences.





There is some consistency between Matlab's pattern, and that which we obtain here. Both in the matlab case and in this case – we have a global maximum at 180°. The MATLAB also has local minima at ~150, 200 degrees, while in the simulate we have those same minima at 170, 190 degrees, which is a "narrowing" of the peak, but is still in the same neighborhood.

We have a lot of fluctuation in the simulated graph, where there is no fluctuation in the MATLAB. For example, the 50-140degree region in matlab is smooth, whereas in the simulation we have a bunch of oscillations. There is a minimum at 90degrees in matlab, but a maximum at that same location in the simulation.

So – the general features do match MATLAB, but there are significant differences. I believe that these differences are a result of our array not being isotropic, and because the microstrip feeding network might have some contribution to radiation. This is because the matching is not perfect, and there could be some backward propagating waves through the strip, which could potentially cause radiation.

g) (5 points) Compare between the peak directivity and gain of the implemented array to the theoretical directivity and gain of the array of isotropic elements that you found above. What is the reason for the differences? Does it correspond with the expected results? What is the antenna efficiency

Directivity: 13.73 dBi

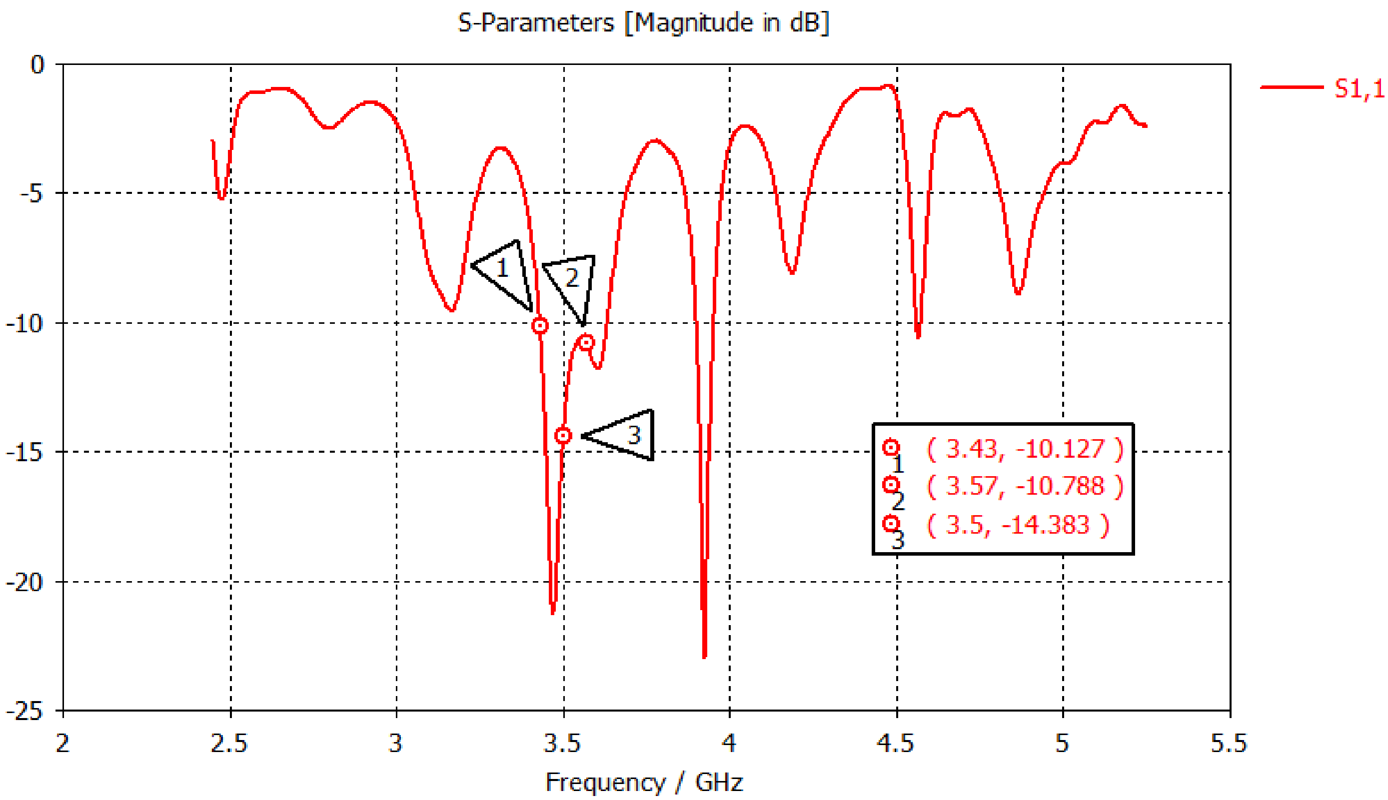
Realized Gain: 13.5 dB

Radiation Efficiency: 0.9847

Main Lobe direction: $\varphi = 0,\ \theta = 28°$

We have a much better gain and directivity than what predicted. Part of this difference can be explained by our use of the approximation $U \approx (AF)^2$. Another reason for the discrepancy is that the microstrip feeding network contributes to the radiation pattern (due to imperfect matching), and this is not accounted for by the isotropic array theory. We don't have a perfectly isotropic array– the element radiation is not uniform in all directions, and in fact has 2 lobes .

h) Present the input matching over the bandwidth 0.5f -2f of your array (as seen by the port at the input of the coax line). Use markers on the plot in order to demonstrate the achieved design goals – matching of -10dB or better at the frequency range 0.98f-1.02f. What is the reason for the difference between this matching performance and the one of a single patch antenna that was implemented in Section 4?



Markers 1,2 are positioned at $0.98f$, $1.02f$ respectively. They are both slightly under $-10dB$, which satisfies the requirement. The operating frequency $3.5GHz$ is marked by marker 3, and has a matching of -14.383, which also fits the design requirement.

The matching performance for the array is slightly worse than for a single element. This is due to coupling between the array elements, and is strongly related to the inter-element spacing. Having a different spacing would give a different result.

i) (5 points) Next, apply the electrical phase offset that you found (⍰⍰) between one array's element port and its neighbor, in order to steer the beam to the mechanical (geometrical) angle of 20° along the array's axis. Plot the 3D radiation pattern, as well as 2D the radiation pattern in the azimuth and in the elevation. Explain the results.

Using a microstrip calculator found online I found that 1mm of my micro strip introduces a 6.271879° phase shift (electrical length).

Required phase shifts & length shift :

$$\phi_1 = \phi_1 \rightarrow L_1 = L_1$$

$$\phi_2 = \phi_1 + 110.82^\circ \rightarrow L_2 = L_1 + \frac{110.82}{6.271879} = L_1 + 17.669[mm]$$

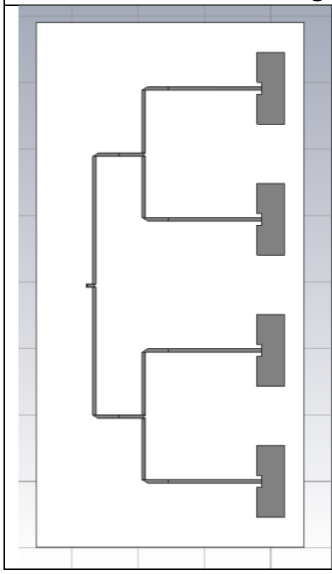
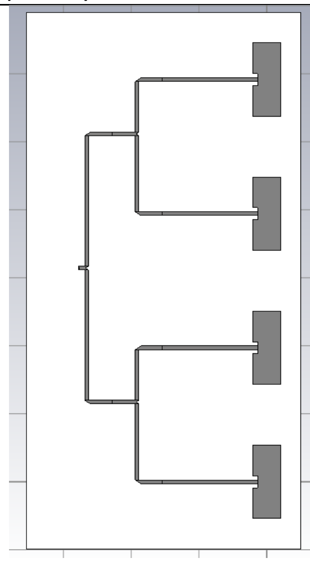
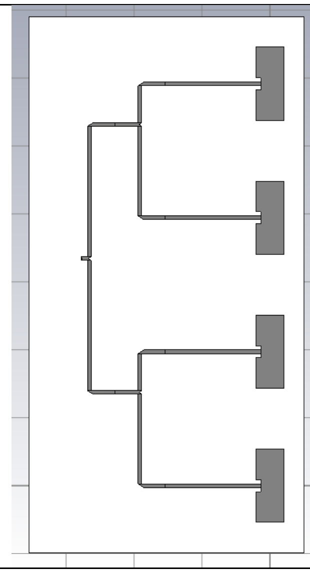
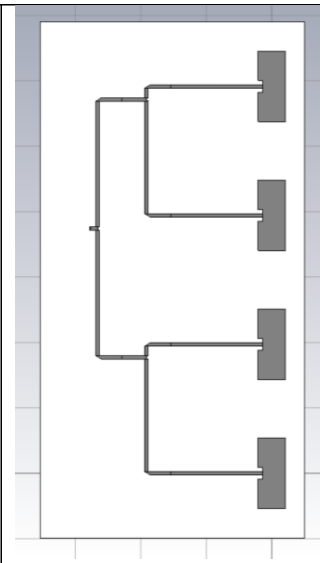
$$\phi_3 = \phi_1 + 221.64^\circ \rightarrow L_3 = L_1 + 35.338[mm]$$

$$\phi_4 = \phi_1 + 332.46^\circ \rightarrow L_4 = L_1 + 53[mm]$$

Applying this shift to the model does not steer the angle to 20°. This is probably because our unphased array's main lobe isn't at 0° to begin with. Another reason for this is that the phase angle that we calculated theoretically is meant for isotropic arrays, which this is not.

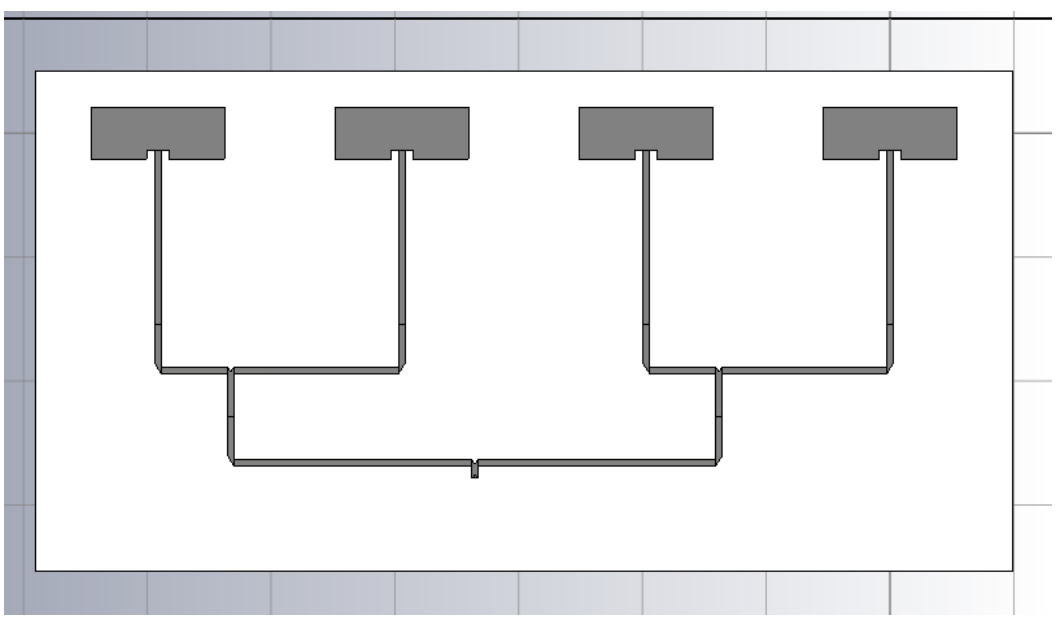
In any case – I will manually steer the beam using CST's capabilities.

I implemented the phase shifting by introducing a Y-offset into the T-junctions within my feeding network. I parametrically defined the feeding network such that the shift in the junctions can be specified as a parameter, and the network will transform the various lengths and edges to conform to the new positions.

Demonstration of shifting capability			
			

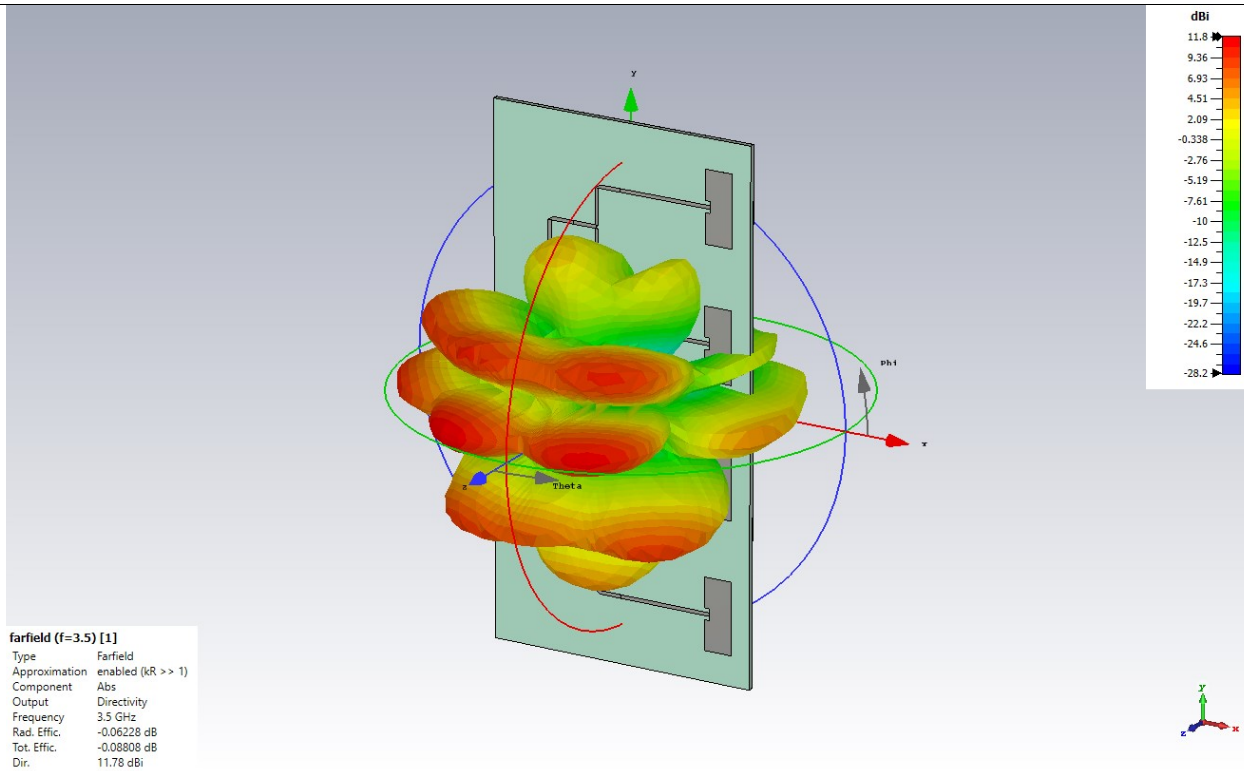
The shift needed to steer the beam to $\theta = 20°$ was 20.5mm, whereas the theoretical shift was 17.7mm per junction. This is reasonably close to the theoretical value. The discrepancy can be explained by the various deviations of my array from the theoretical model.

Feeding network which gave me the correct angle:

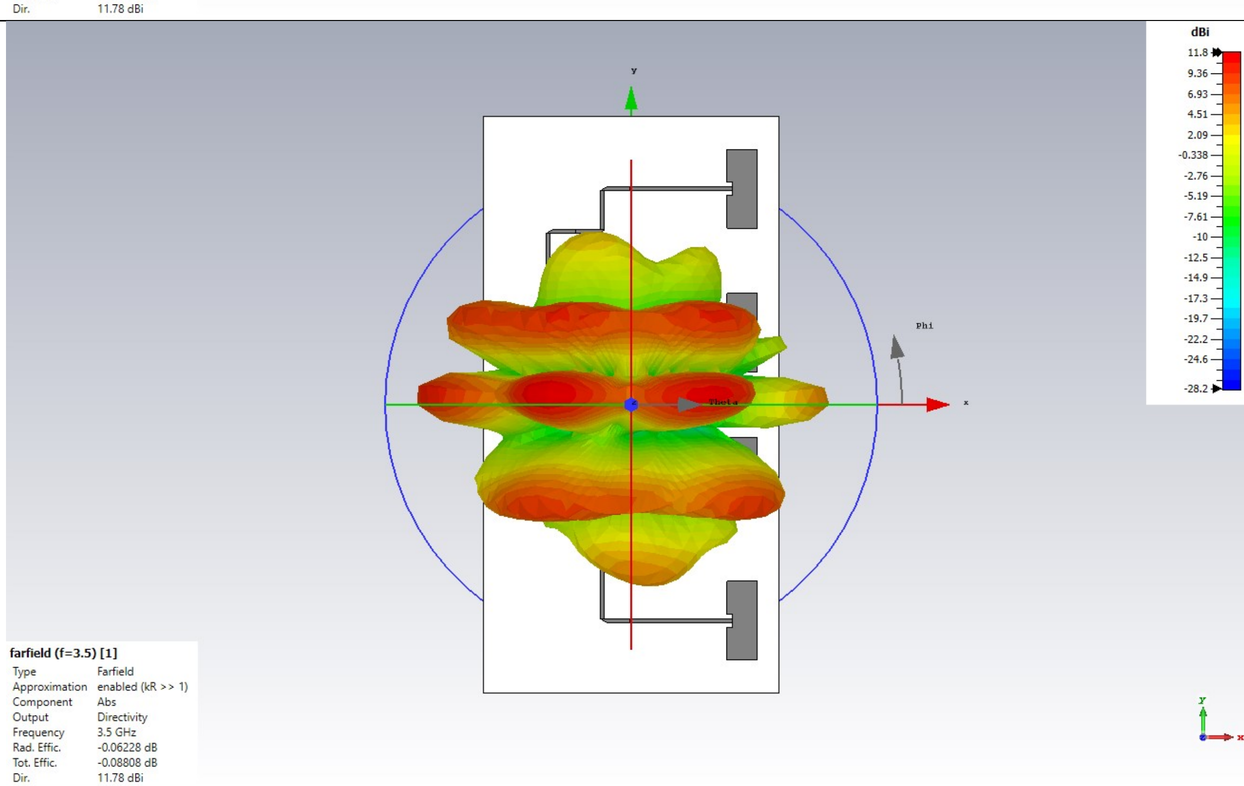


Steered beam radiation pattern:

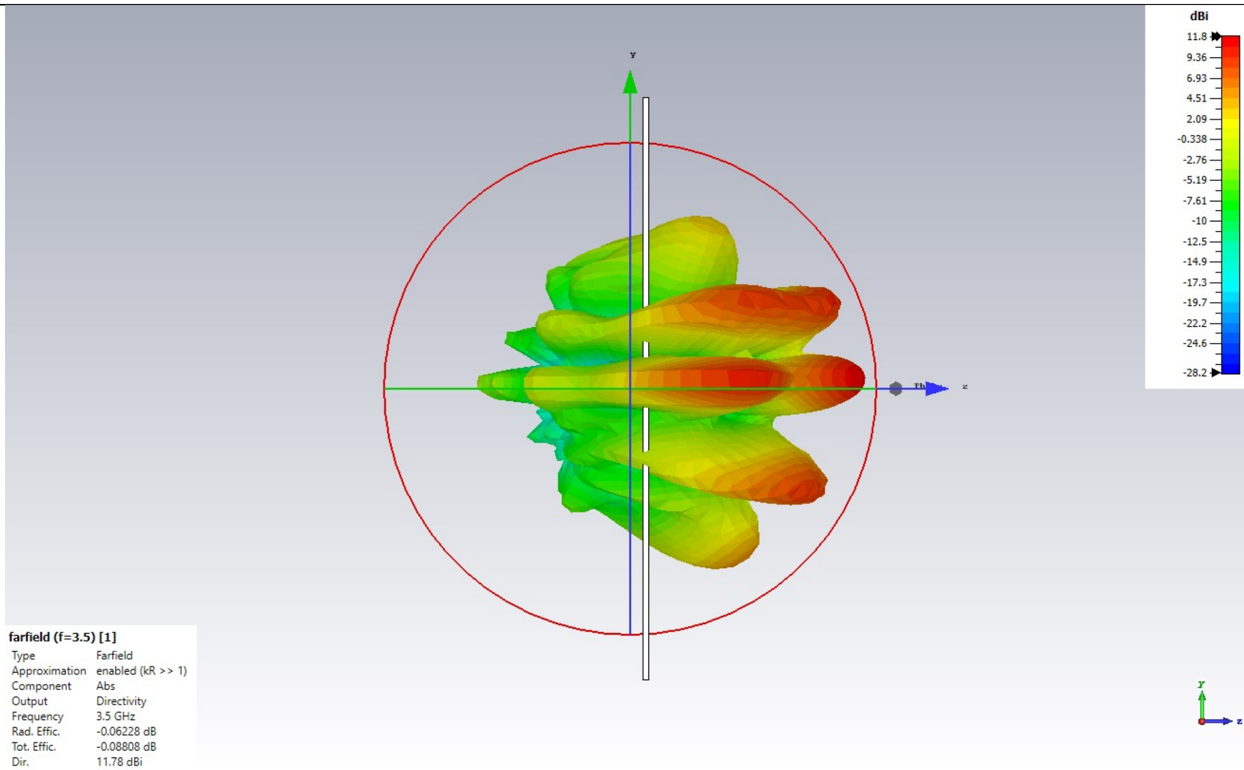
Perspective



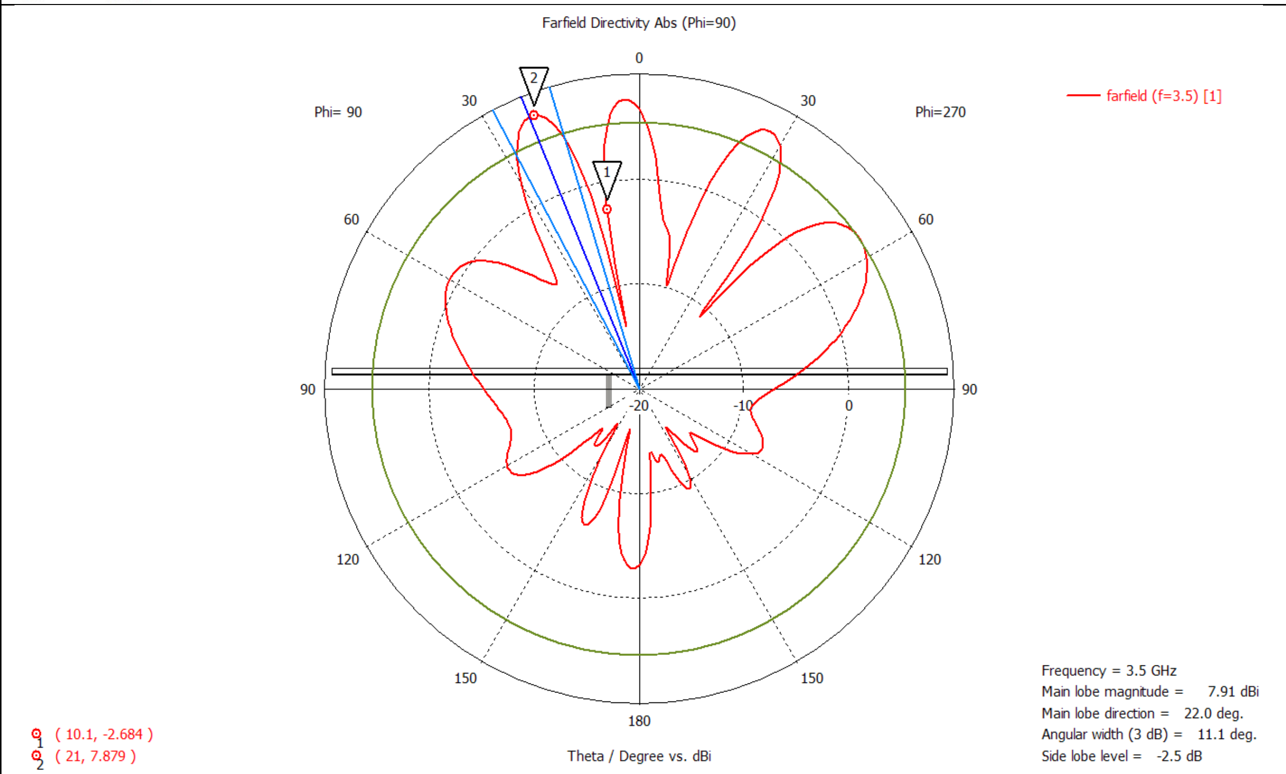
Front



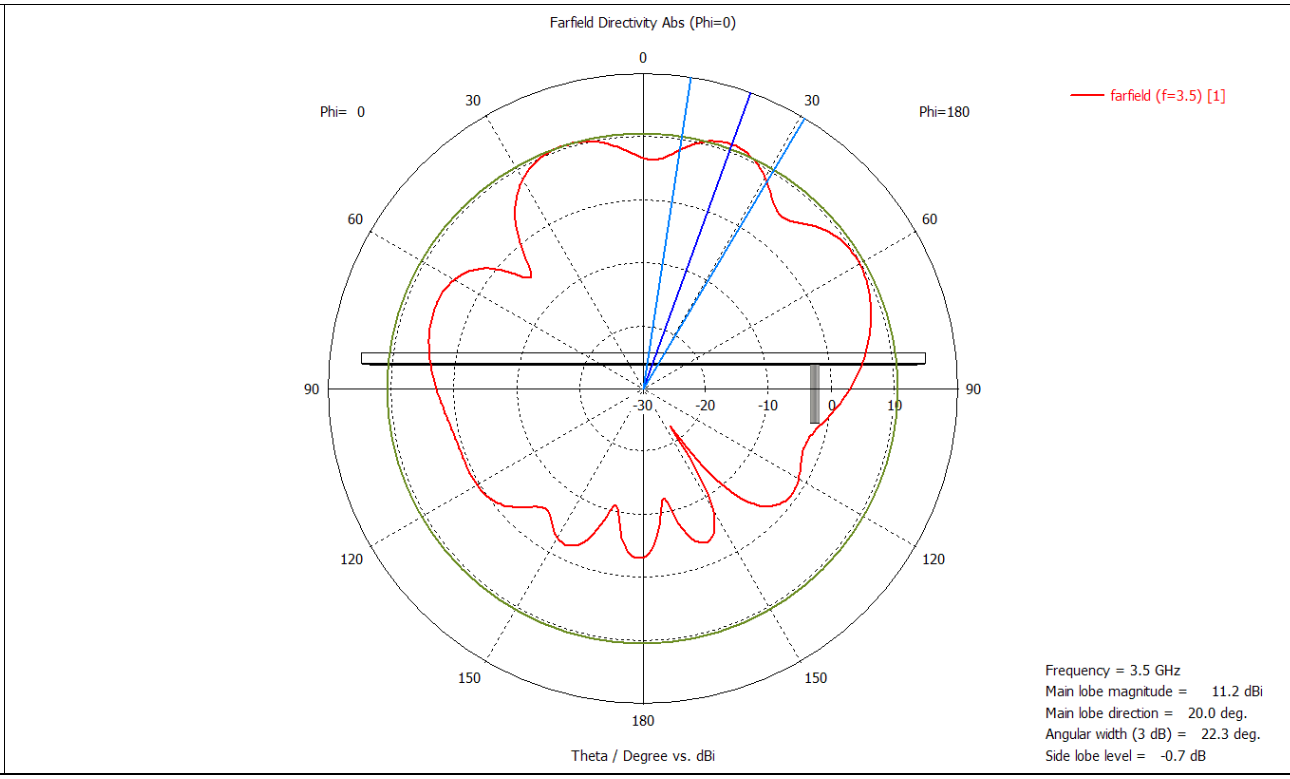
Side:



Y-Z Plane

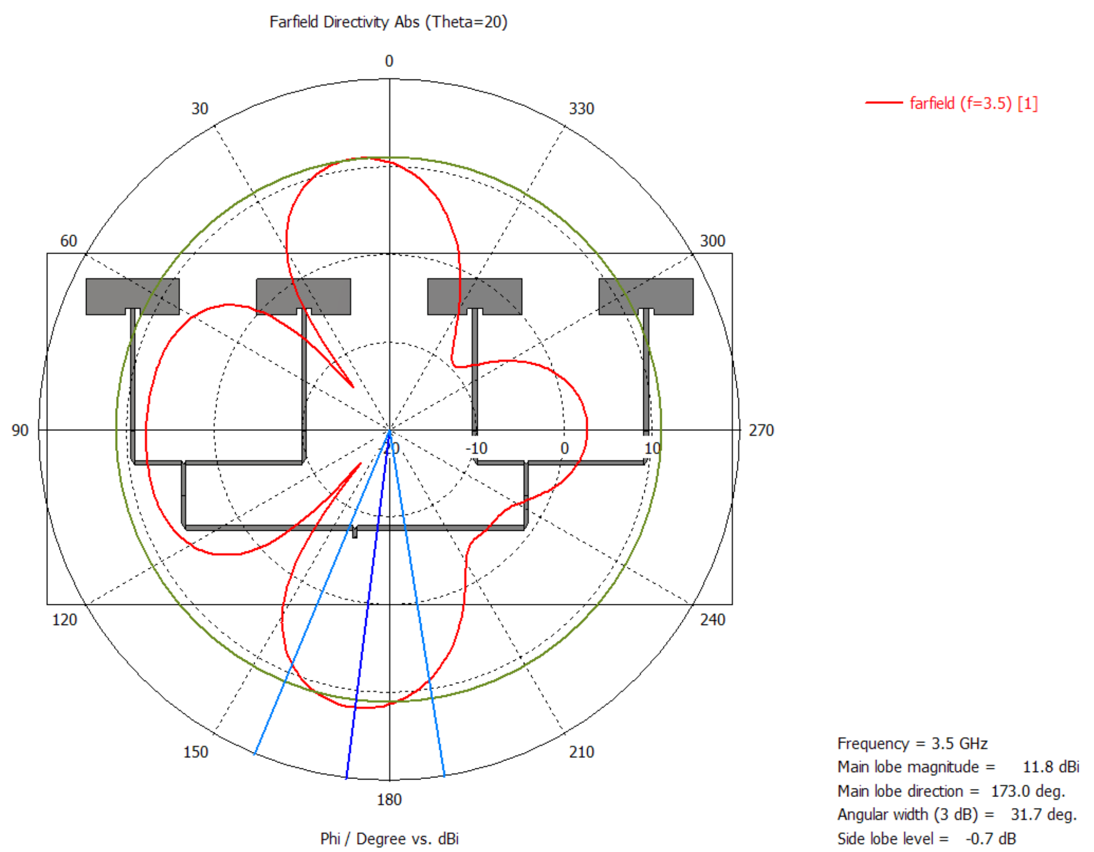


X-Z Plane



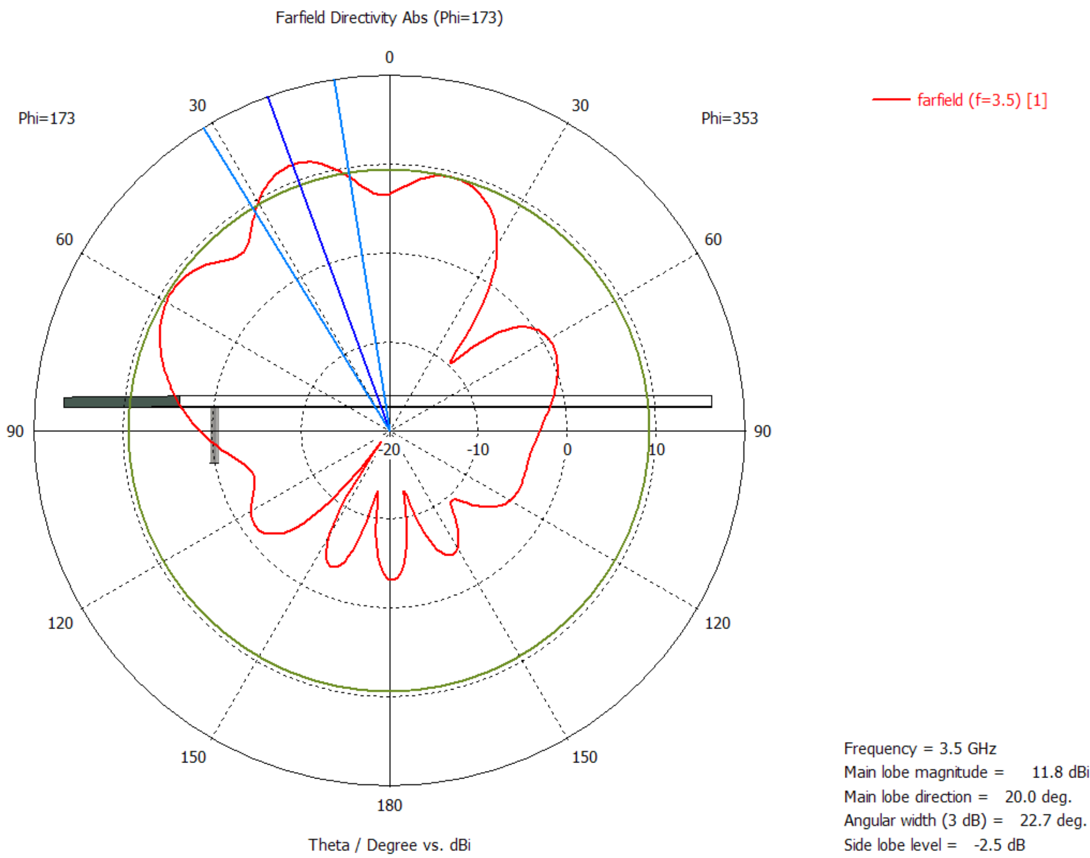
The main beam is not centered – it is offset on both angles.

I know that the main lobe direction in the X-Z plane is 20°, so I fix $\theta = 20°$ and look at variation in φ



We have $\varphi = 173°$

Therefore, we should be looking for the main lobe's angle when $\varphi = 173°$:



This main lobe has a magnitude of 11.8dBi.

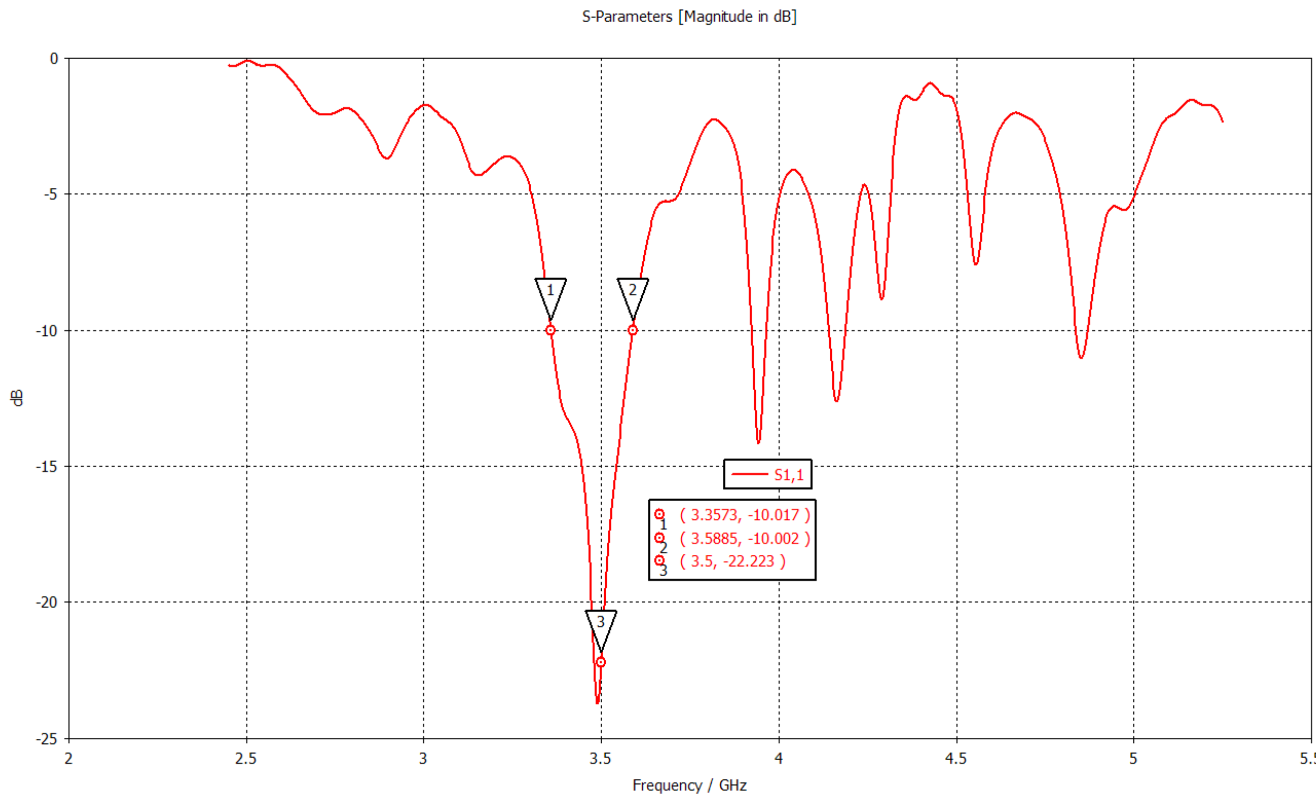
Looking at the 3-D Farfield view, we see the following information:

farfield (f=3.5) [1]	
Type	Farfield
Approximation	enabled (kR >>
Component	Abs
Output	Directivity
Frequency	3.5 GHz
Rad. Effic.	-0.06228 dB
Tot. Effic.	-0.08808 dB
Dir.	11.78 dBi

So the maximum directivity of this arrangement is $11.78 \approx 11.8dBi$. Therefore, the lobes presented in the Y-Z or X-Z sections of the radiation pattern table do not pass through the maximum of the main lobe. The "true" main lobe is located at $\varphi = 173°, \theta = 20°$, as proven by the fact that this lobe has the same magnitude as the maximum magnitude in the entire radiation pattern.

This main lobe has $\theta = 20°$, so we steered it exactly to the requested angle.

j) (5 points) Present again the input matching over the bandwidth 0.5f -2f, when the monopoles are fed with a linear phase. Use markers on the plot in order to demonstrate the achieved design goals. What is the reason for the difference between this matching performance and the one of a single element in the array where no electrical phase was applied?



Markers 1,2 are placed at edges of the bandwidth, at -10dB. Our band is: $3.357G - 3.589G \rightarrow 0.959f - 1.025f$

This is slightly better that the required bandwidth of $0.98f - 1.02f$.

Required bandwidth: 4%

My bandwidth: 6.6%

Marker 3 is positioned at our operating frequency, and has a matching of -22.23dB, which is good. Interestingly – the global minimum of S11 within the simulated range happens to fall on pretty much exactly out operating frequency.

In general, the reason for input matching to change in a single-feed phased array is because we alter the feeding point location, which is a determining factor in input matching. However, in this specific array, each microstrip segment has a characteristic impedance of 100Ω, and this impedance is independent of strip length. Therefore, each T-junction “sees” two 100Ω paths, and thus the input impedance stays around 50Ω, which is matching the Coax.