RF PROJECT 1

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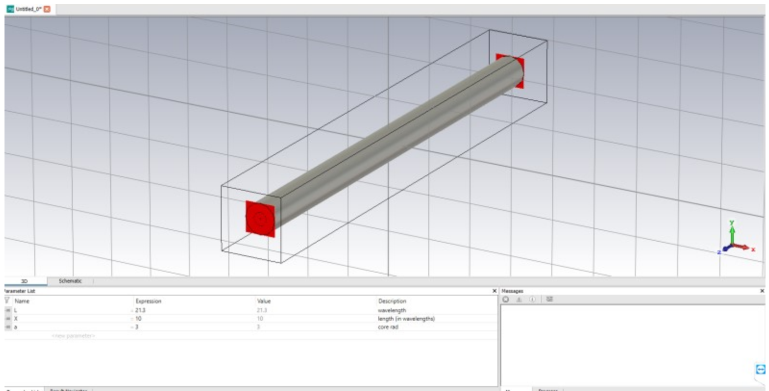
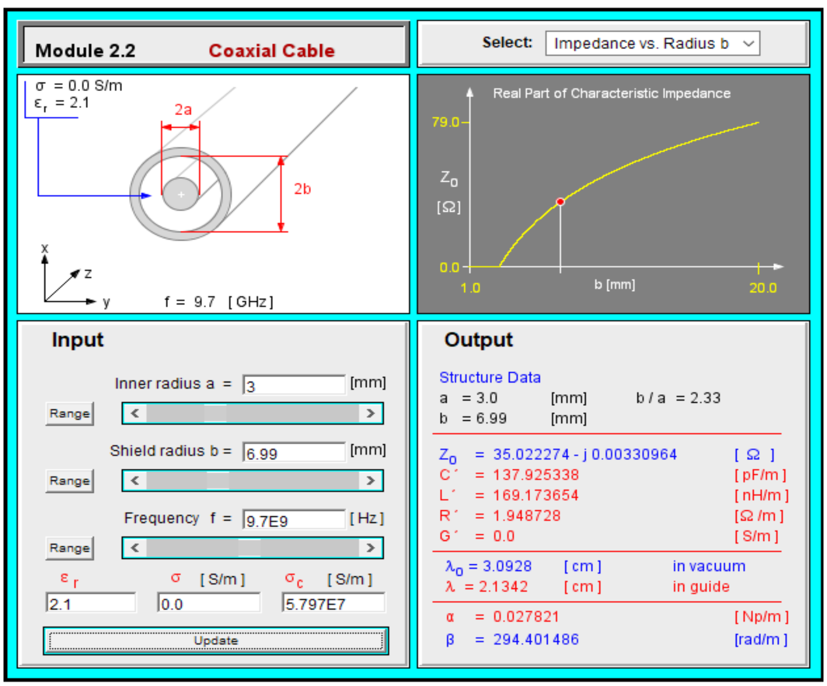
My Parameters			
Ground Plane	**Frequency f [GHz]**	**Coax Characteristic Impedance (Ω)**	**Array Parameters**
Disc, diameter 1.75λ	9.7	35	3 elements along Y-axis. $d = 0.9\lambda$

1. Design a coaxial cable with a characteristic impedance that is given by the table below. Specifically, set the radius of the inner core, a, and the radius of the external shield, b, while the medium in between the inner pin and the external shield is a dielectric material named "Teflon".

$$\lambda = 0.0213[m] = 21.3[mm]$$

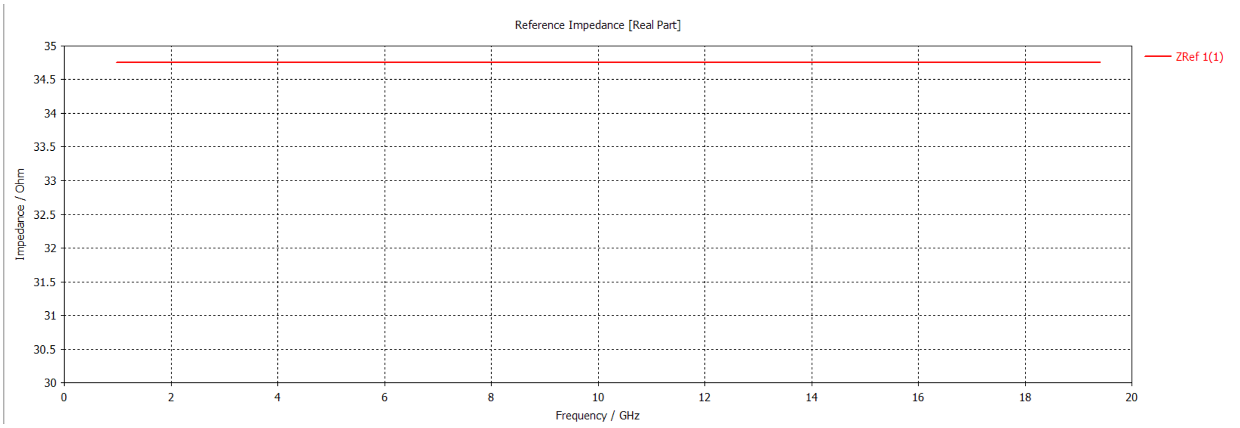


Instead of using a formula, I used a coax simulator by University of Michigan:



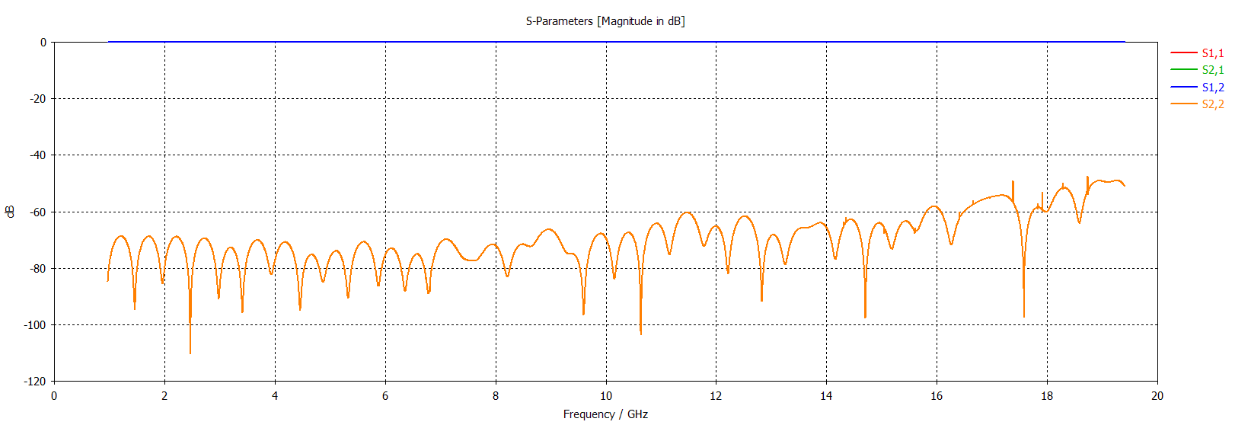
2. Build a CST model of the coaxial line that was designed in Section #1 above. The length of the coax cable should be 10 wavelengths (according to the frequency given in the table below). Place ports at the input and at the output of the coax line, with characteristic impedance (of the ports) according to that of the coax cable (as specified in the table) and simulate the 2-ports S-parameters over the frequency band 0.1f-2f.
   a. Optimize the parameters of the coax cable so that Sii (S11 and S22) will be below -25dB
   b. What is the insertion loss of the cable at the frequency f?
   c. Present the S-Parameters results of the optimized cable over the given frequency band.

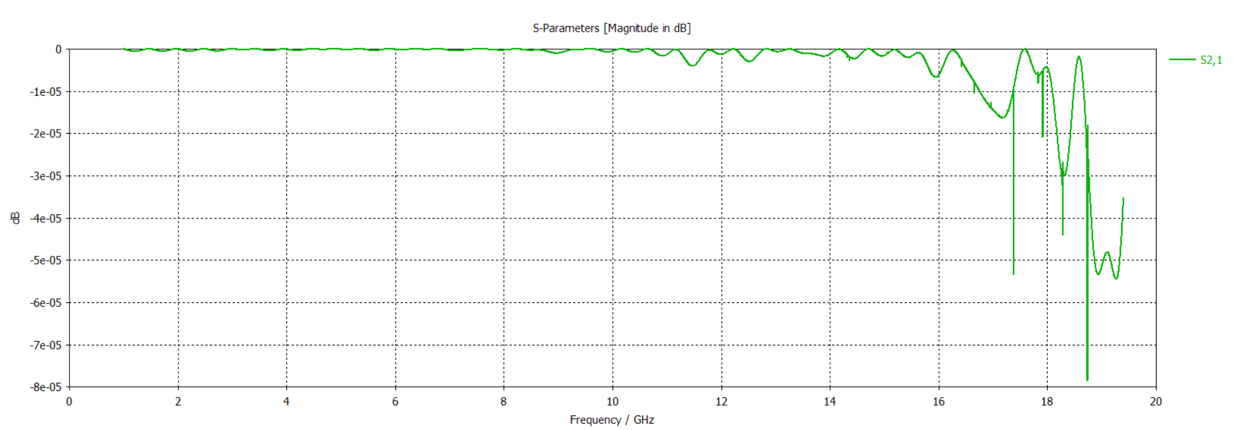
Simulating the cable with originally selected values:

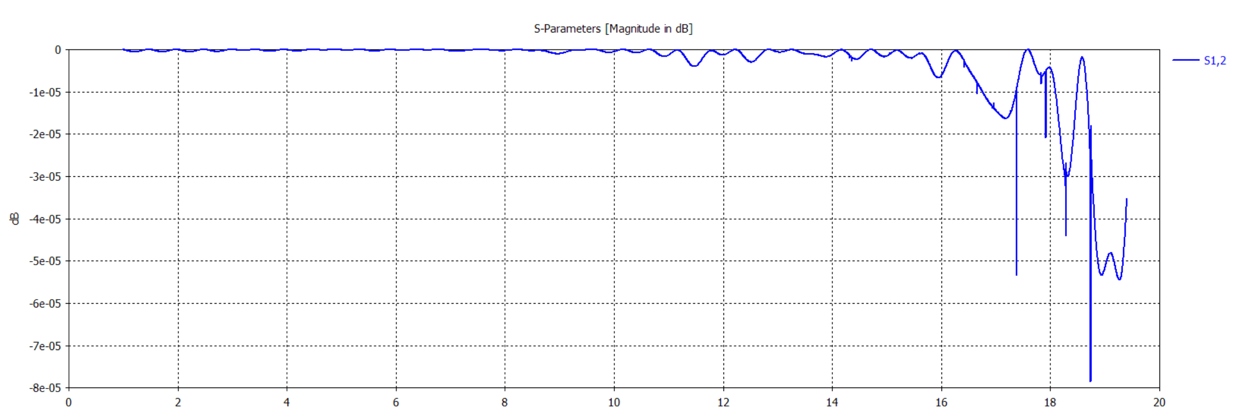


So the impedance is correct.

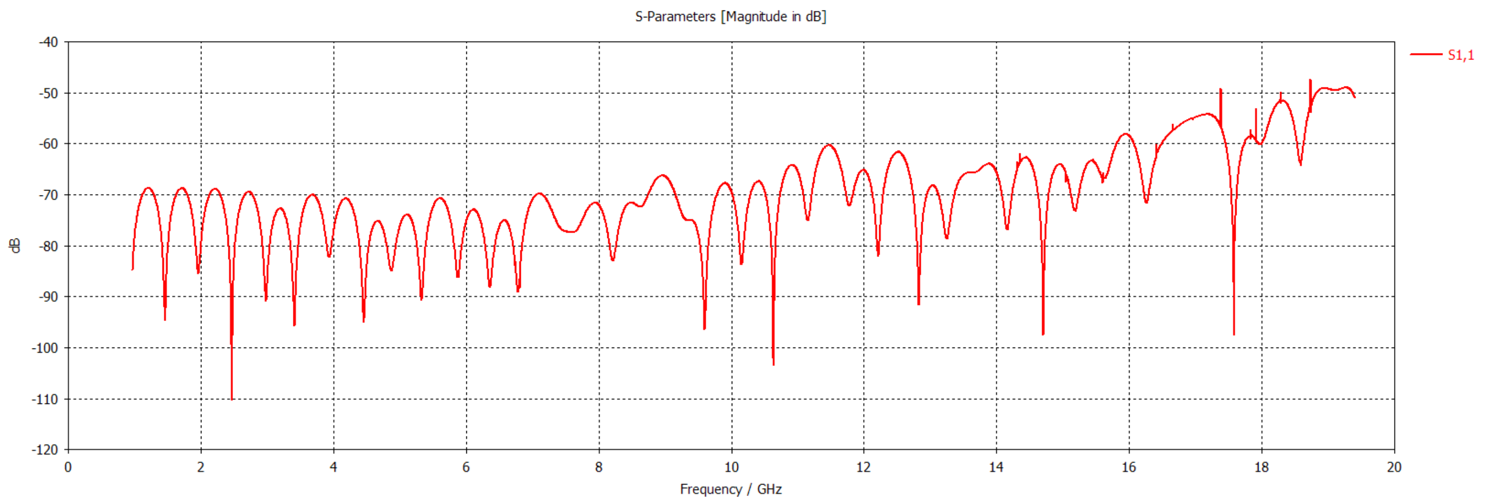
S parameters:

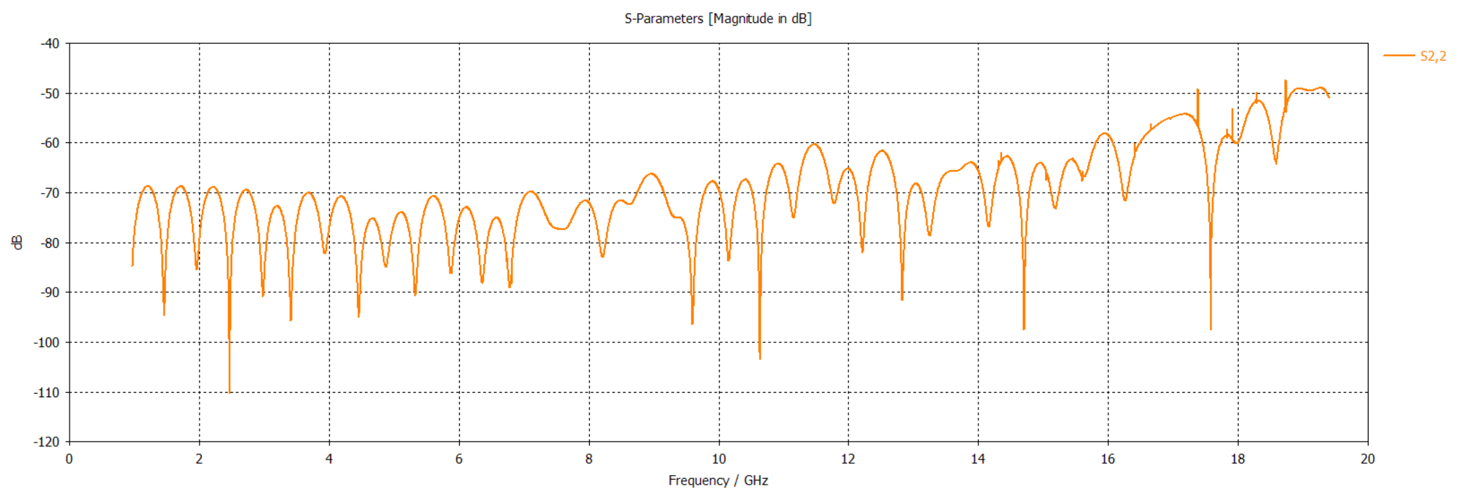






<u>Sii parameters:</u>

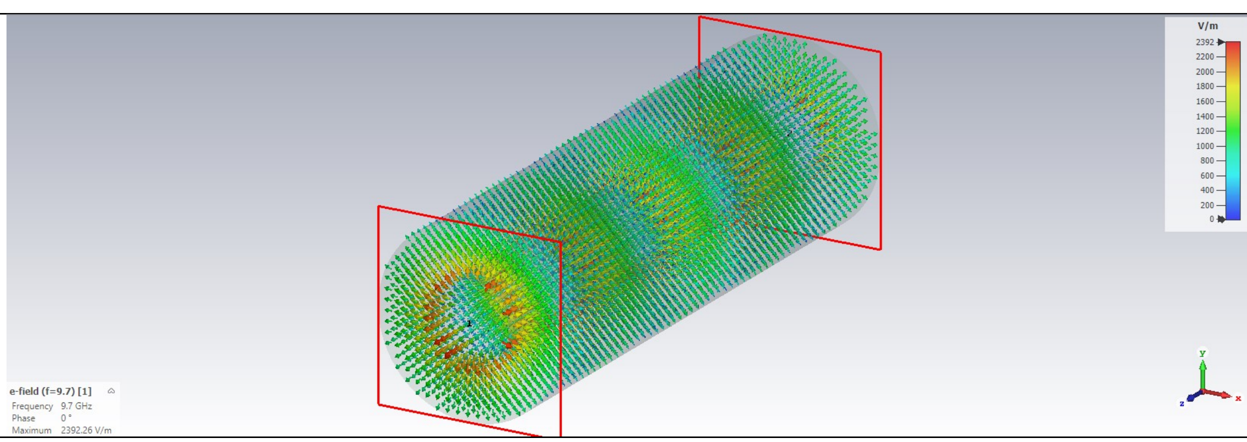


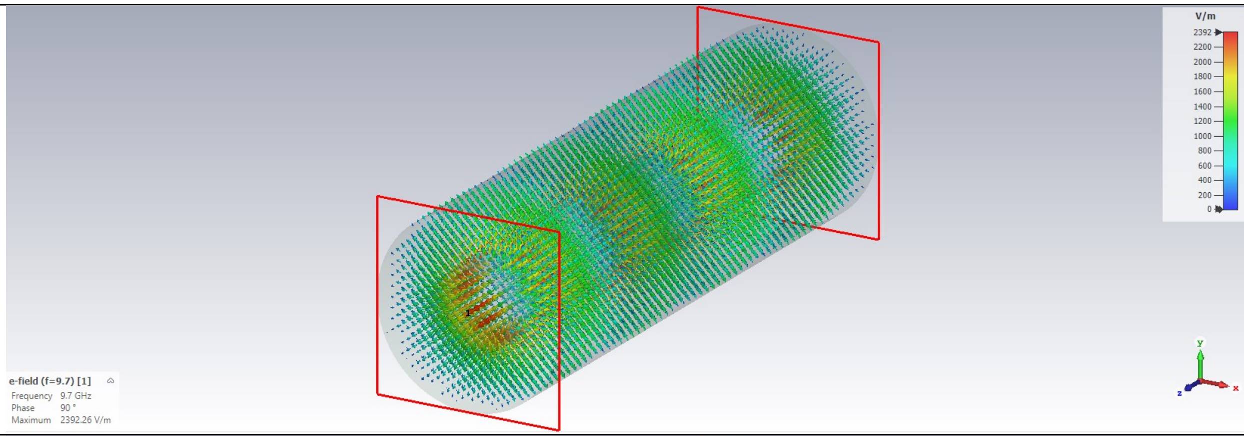
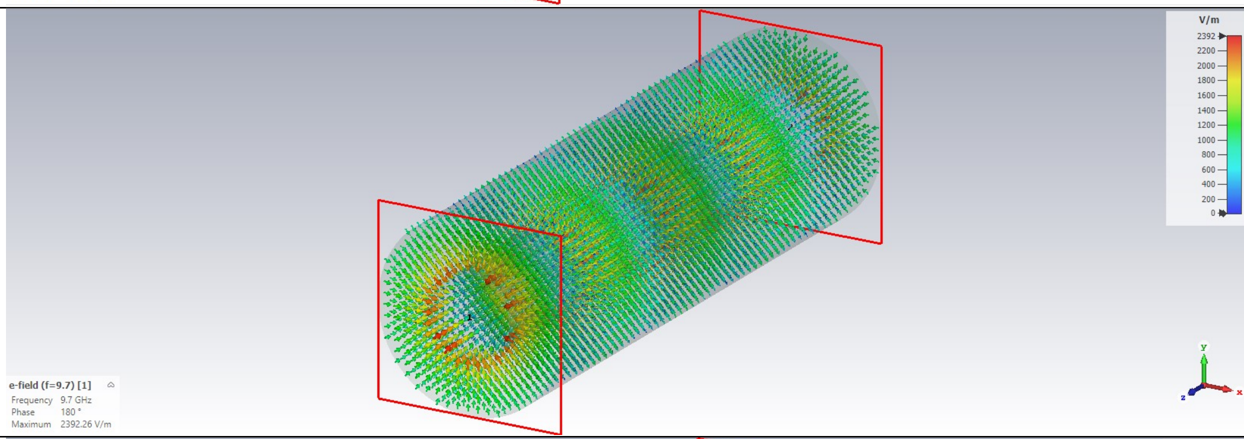
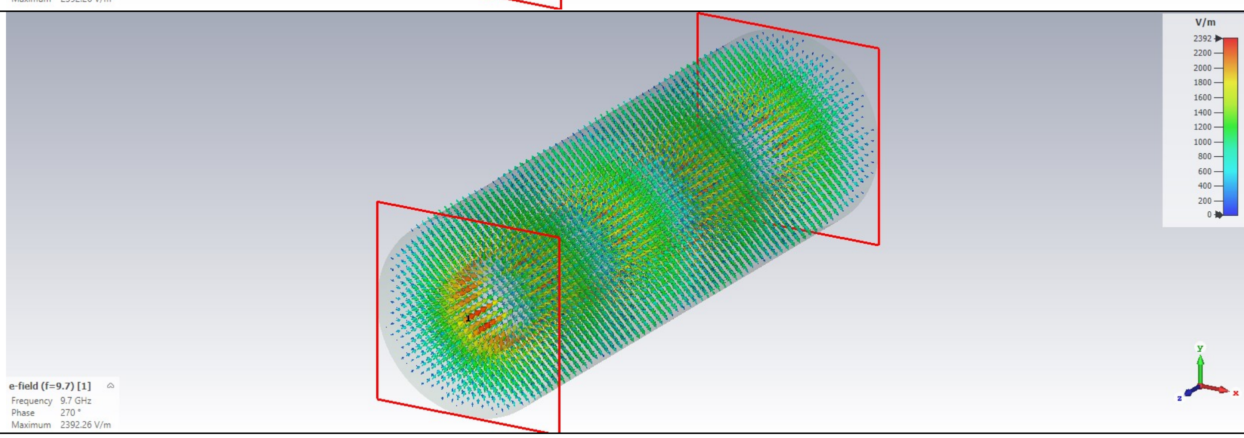


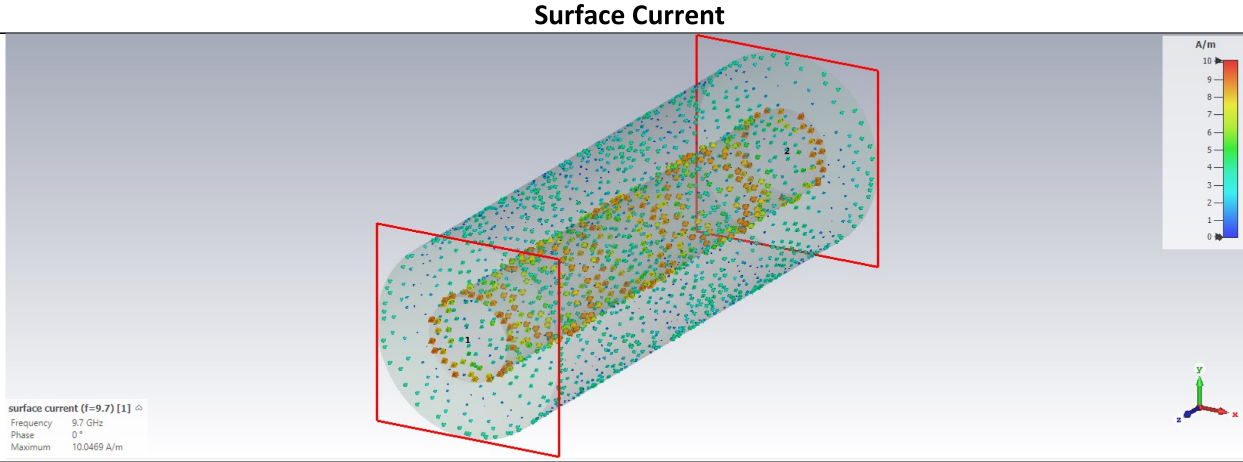
As evident from the attached simulations, Sii parameters are well below -25dB, so optimization is not necessary.

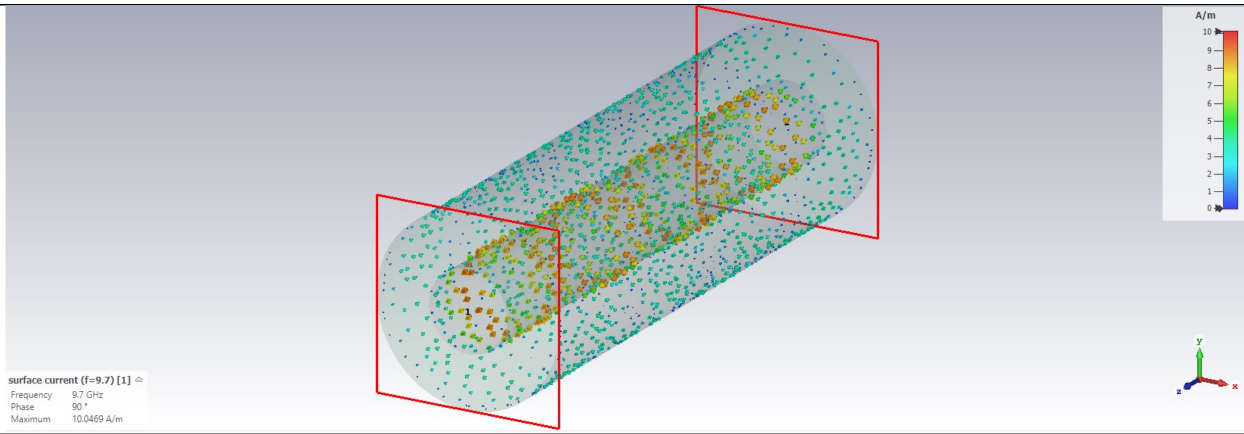
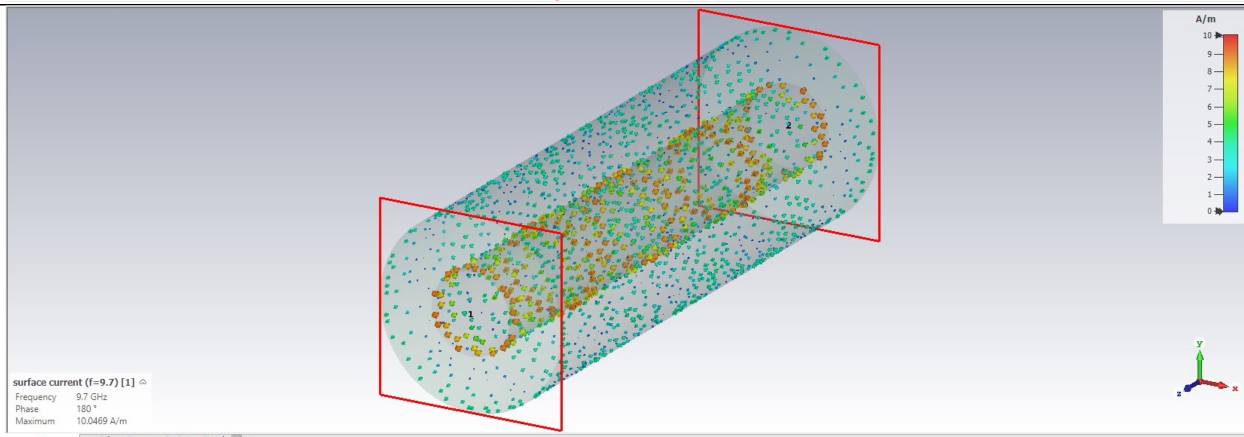
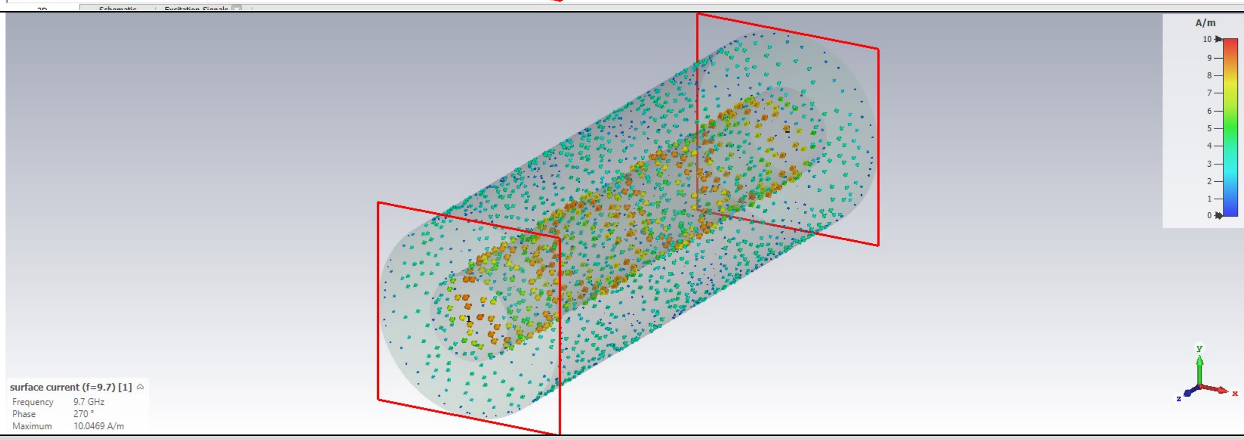
Insertion Loss at 9.7GHz is -5E-07 dB, which is essentially 0.

3. Change the length of the coax cable to two wavelengths and present the electric field (amplitude and direction) at the middle of the coax cable and the surface current on the coax conductors at the time points t=0, t=T/4, t=T/2, and t=3T/4

Time (xT)	**Electric Field**
0	

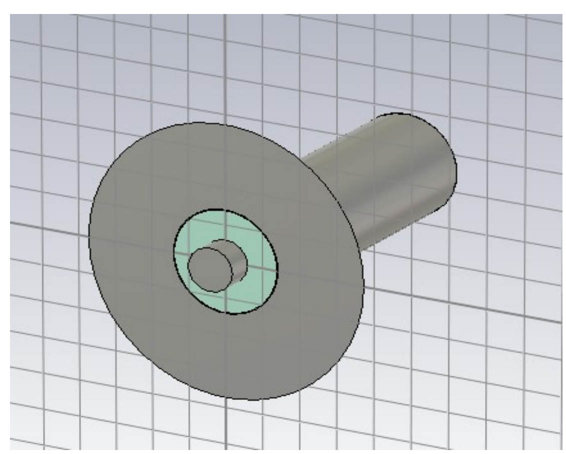
0.25	
0.5	
0.75	

Time (xT)	Surface Current
0	

0.25	
0.5	
0.75	

4. Now build a model of the monopole antenna along the Z-axis, and its ground plane, according to their parameters in the table below. Use the designed coax cable in order to feed the monopole antenna: create a hole in the ground plane in a diameter which is identical to 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 in order to implement the monopole antenna. Now, fine-tune the length of the monopole in order to achieve a matching (Return Loss, or S11in dB scale) of better than -10dB over the frequency band 0.95f-1.05f.

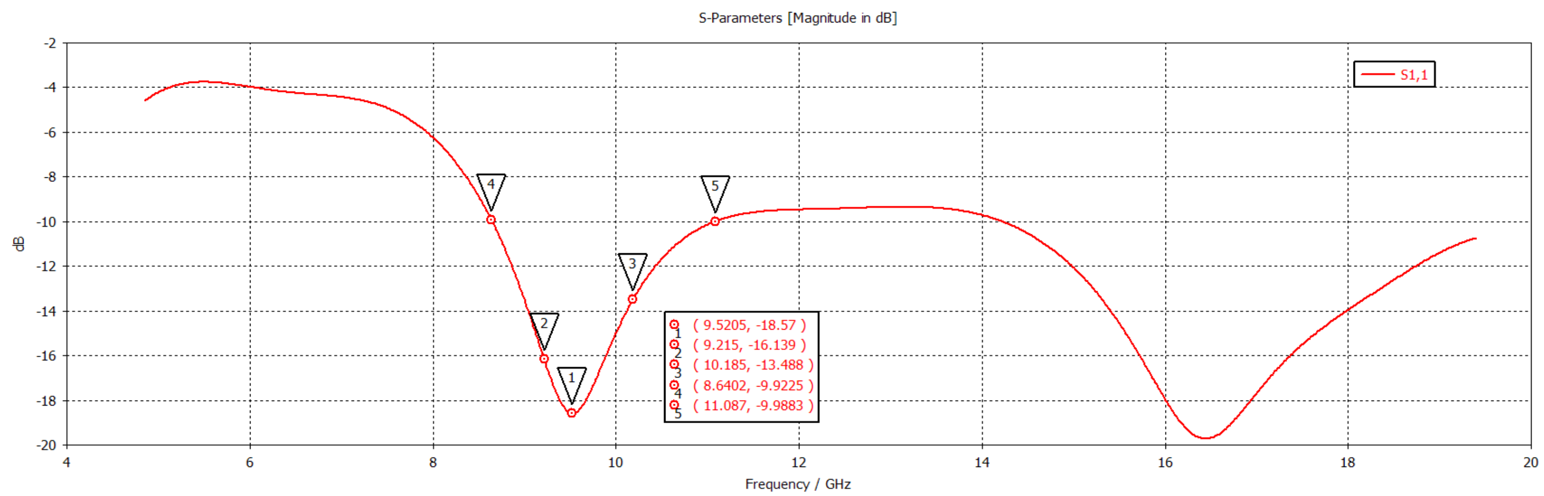
I built the monopole antenna in CST.



Next I optimized the length of the coaxial core protrusion past the ground plane. The length is measured in terms of wavelength. The optimization goal is to guarantee S11<-10dB for 0.95f-1.05f. The result of the optimization is $L_{\text{protrusion}} = 1\lambda$.

a. Present the input matching over the bandwidth 0.5f-2f.Use markers on the plot in order to demonstrate the achieved design goals.

Optimized S11:



Markers #2,3 show the bounds of the optimization interval for which I was supposed to guarantee S11<-10dB. As seen, the values at those markers are below -10dB. Markers #4,5 show the bounds at which S11 exceeds -10dB – 8.64G-11.087G, i.e 0.89f-1.14f, which is even better than the given design parameters.Marker #1 shows the minimal input matching inside the optimization interval: (9.52G, -18.57dB). This is very close to our operating frequency of 9.7G, so the input matching must be good at that frequency too.

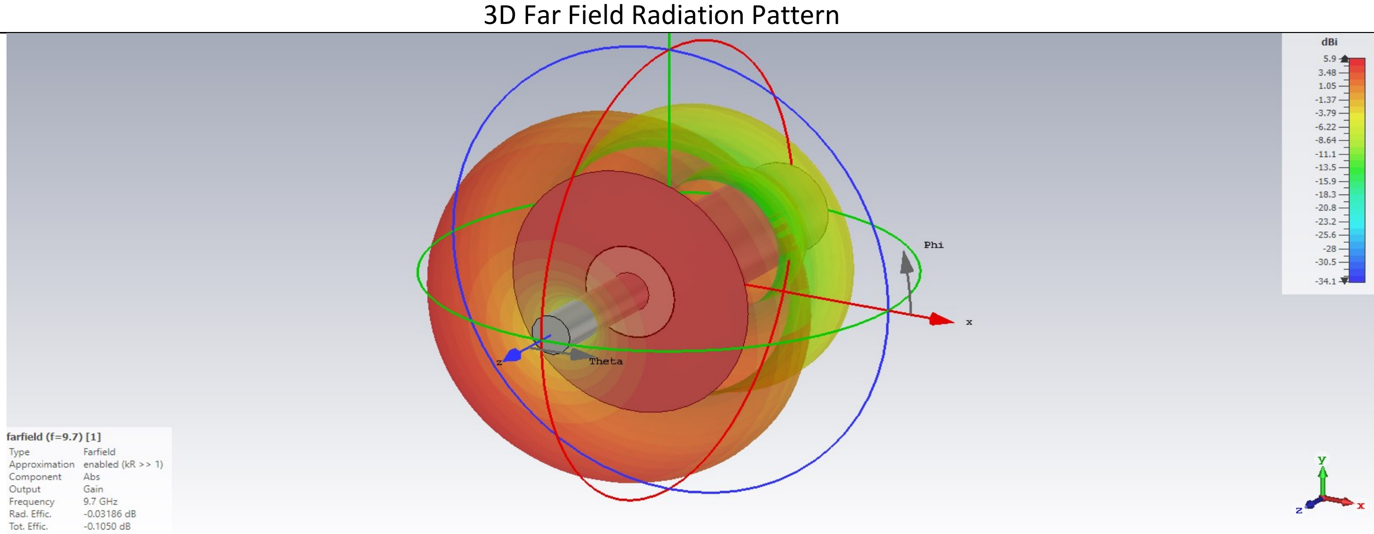
b. What is the value of the reflection coefficient at the frequency f?

The reflection coefficient is the same as S11, except the previous S11 plots are in dB, and Γ is given as a linear number. I therefore switch the display mode to linear, read marker #1's value: $\Gamma = 0.1179$

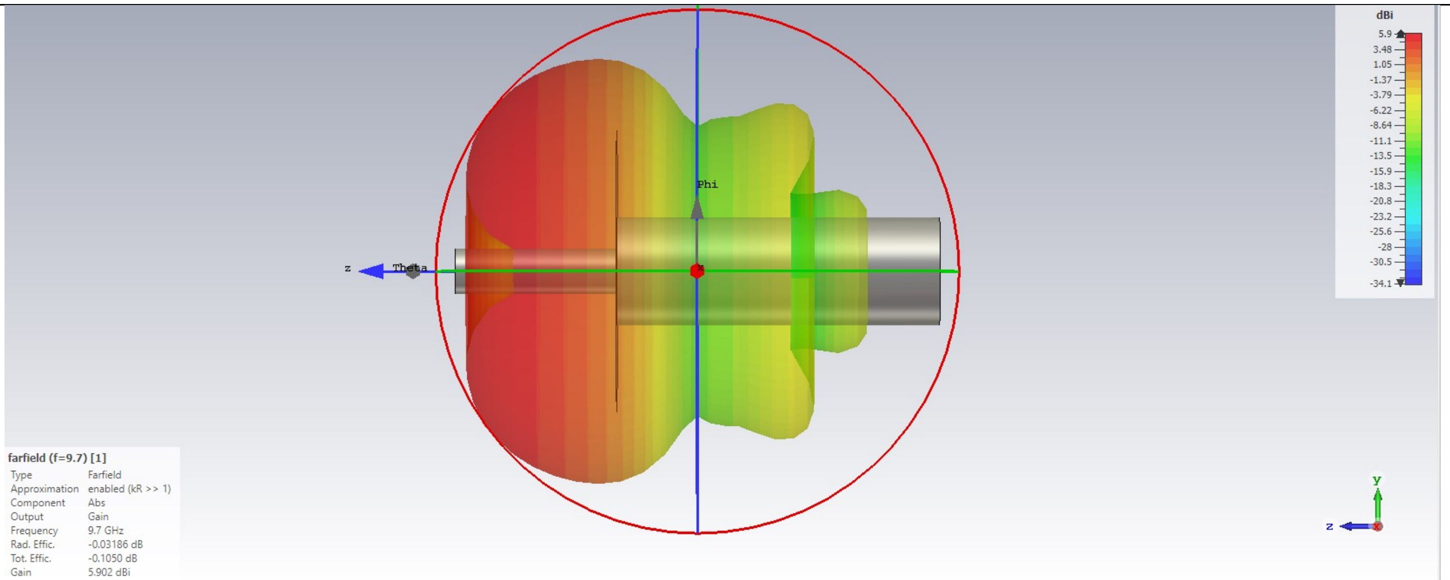
c. Compare the optimized length to the theoretical one. If there is any difference, what is the reason for that?

A popular monopole length is 0.25λ. Another one is 0.625λ, which is good for maximizing horizontally radiated power. Since both of these wavelength are theoretically valid, I believe the wavelength I chose is valid too. This does not seem to be a deviation from theory, but rather design which prioritizes input matching over things such as radiated power (as the task was to optimize for input matching)

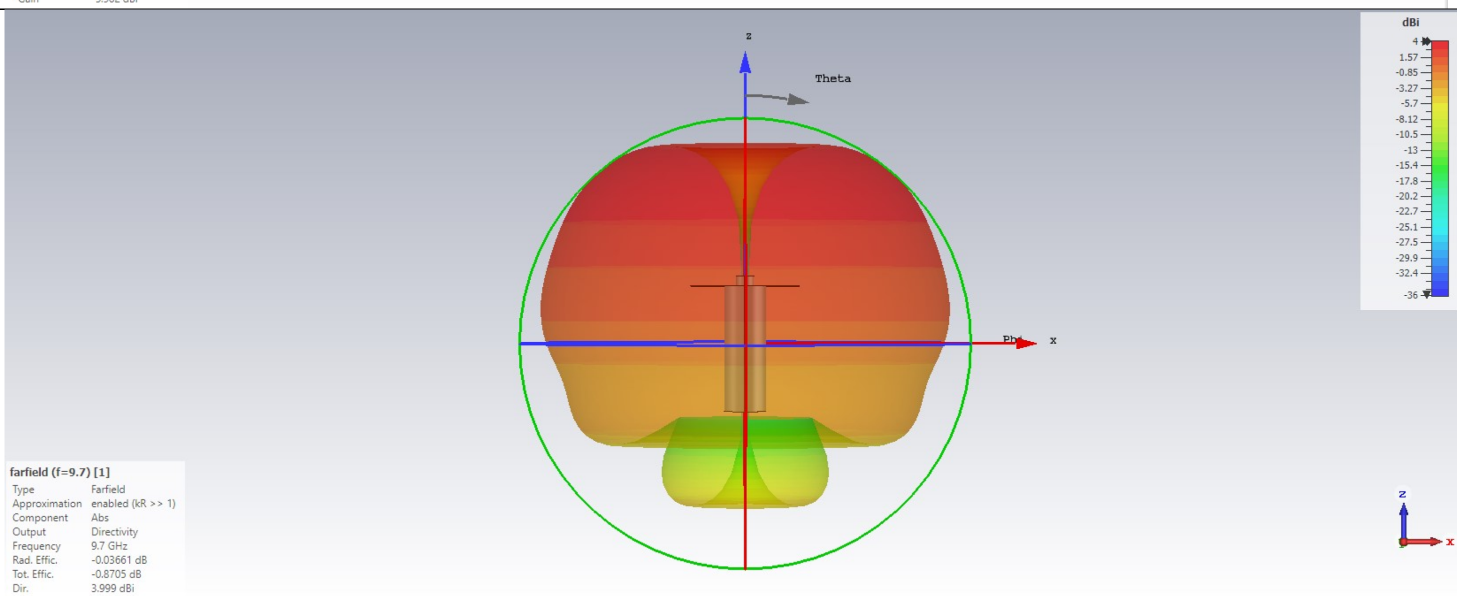
d. Present the 3D far field radiation pattern of the monopole at the frequency f, and the radiation pattern over the 2 main planes: the X-Z plane ("Elevation") as a function of q, and the X-Y plane ("Azimuth")as a function of φ. Compare it to the expected radiation pattern according to the theory and explain the differences

3D Far Field Radiation Pattern	
Perspective :	

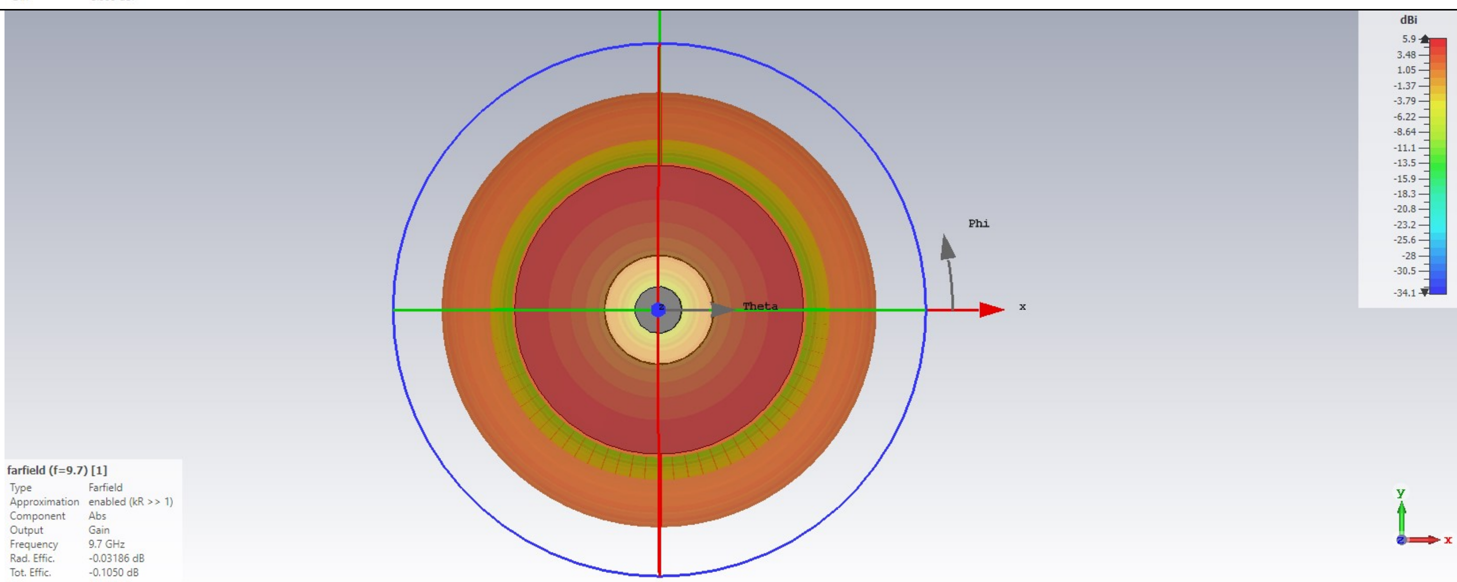
Side View:



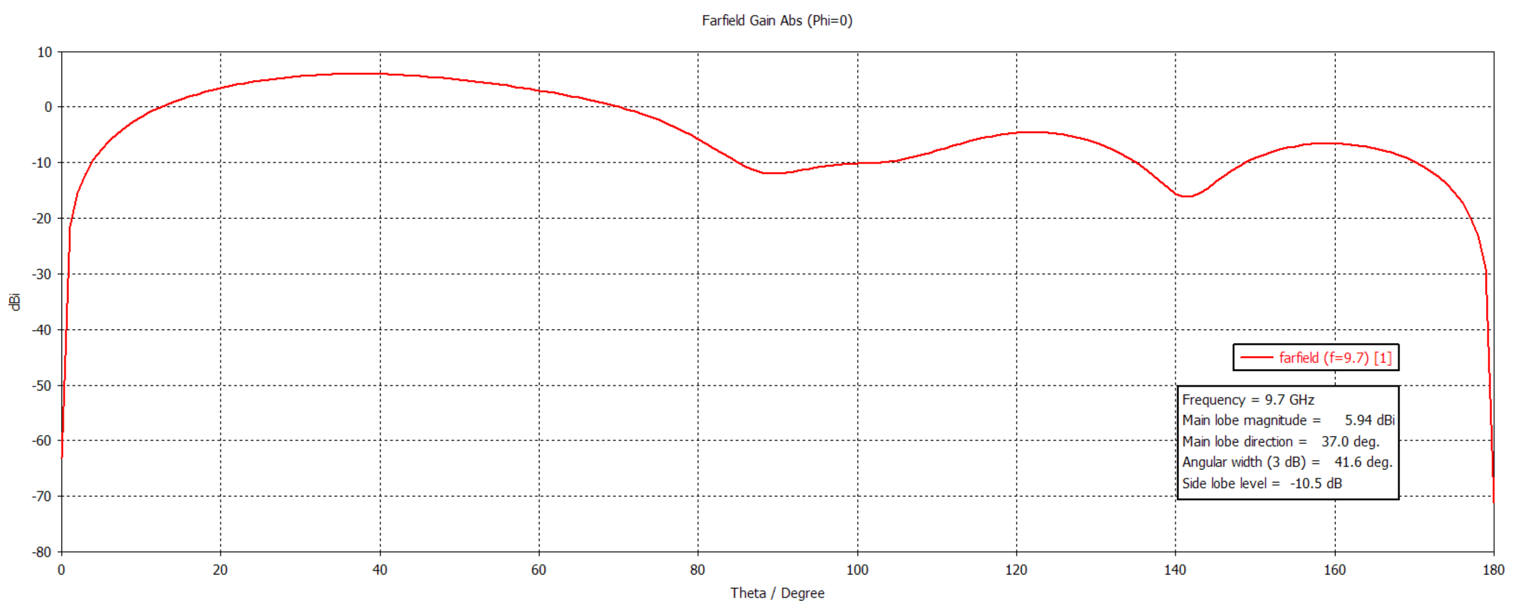
X-Z Plane Farfied (Elevation)



X-Y Plane (Azimuthal) Farfield:

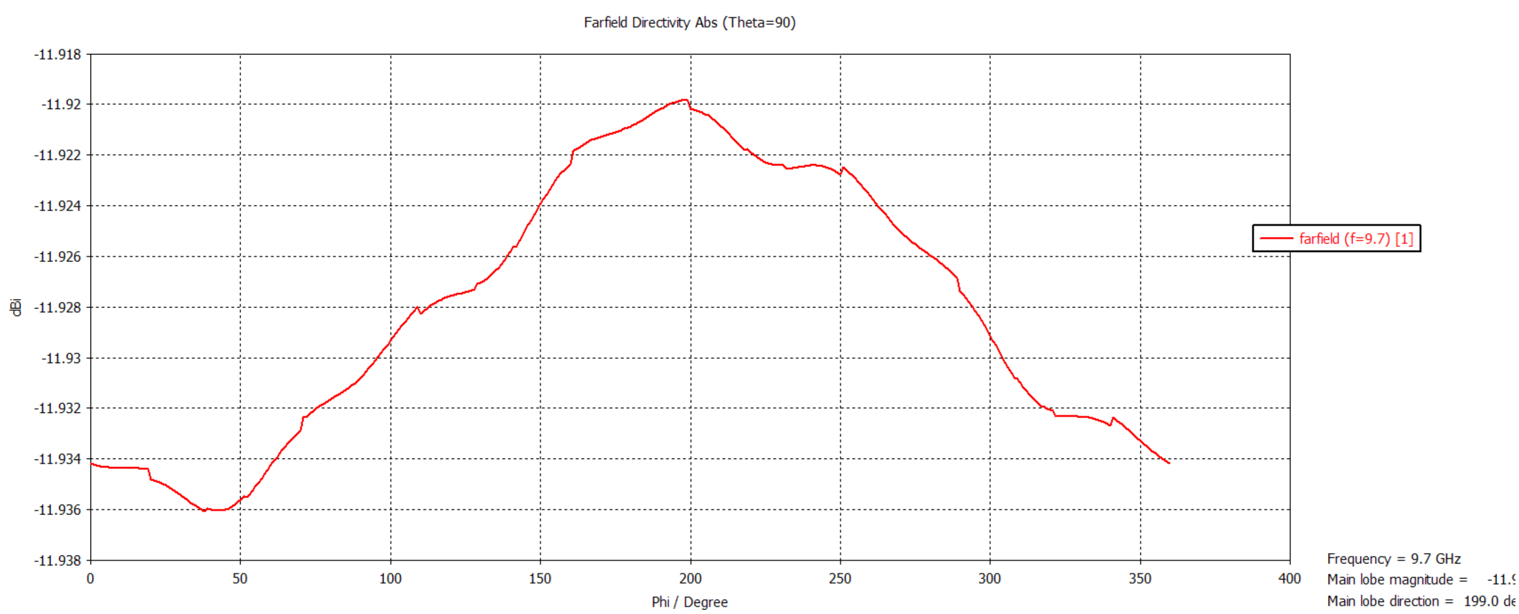


<u>X-Z Plane (Elevation) Radiation Pattern as a function of θ:</u>



To obtain this graph, I selected "Cartesian" in the farfield display window. I then selected to keep φ constant=0, thus putting me in the X-Z plane.

<u>X-Y Plane (Azimuth) Radiation Pattern as a function of φ:</u>



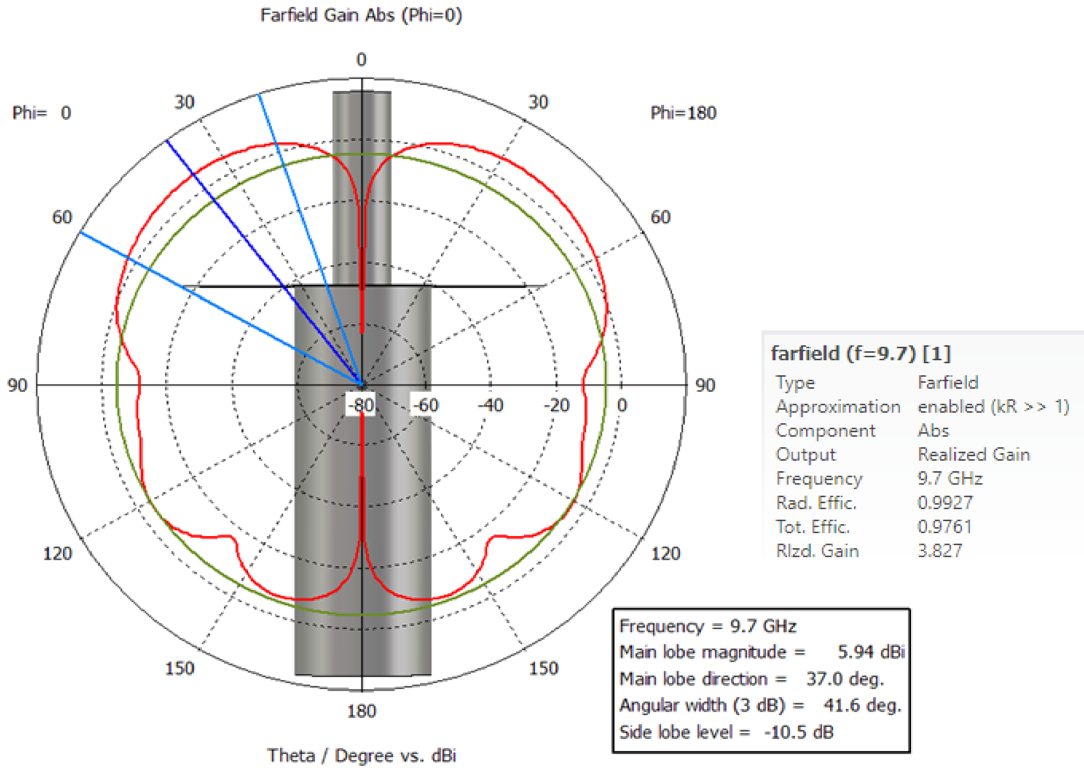
To obtain the graph, I held $\theta = \text{const.} = 90°$

Comparison to theory:

We would expect a monopole to have a maximum lobe, and the field strength should be decreasing as φ moves away from the main lobe. This behavior can be seen in the Azimuth plot, with a clear peak (lobe) at around 200 degrees.

In shape – it would be expected for the radiation pattern to be radially symmetrical, given that the monopole is radially symmetrical. Looking at the 3D plots – it can be seen that this is the case. It could also be expected that the presence of a ground plane would skew the radiation pattern away from the ground plane, and this does indeed happen. The direction of maximum radiation should depend on the ground plane's size, with a larger ground plane moving the maximum closer to the X-Y plane. My ground plane is relatively small, so the maximum occurs in the X-Z plane.

e. What is the direction of the peak gain of the monopole, and what is the peak gain and peak directivity values? –Compare them to the expected performance according to the theory and explain the differences. What is the antenna efficiency?



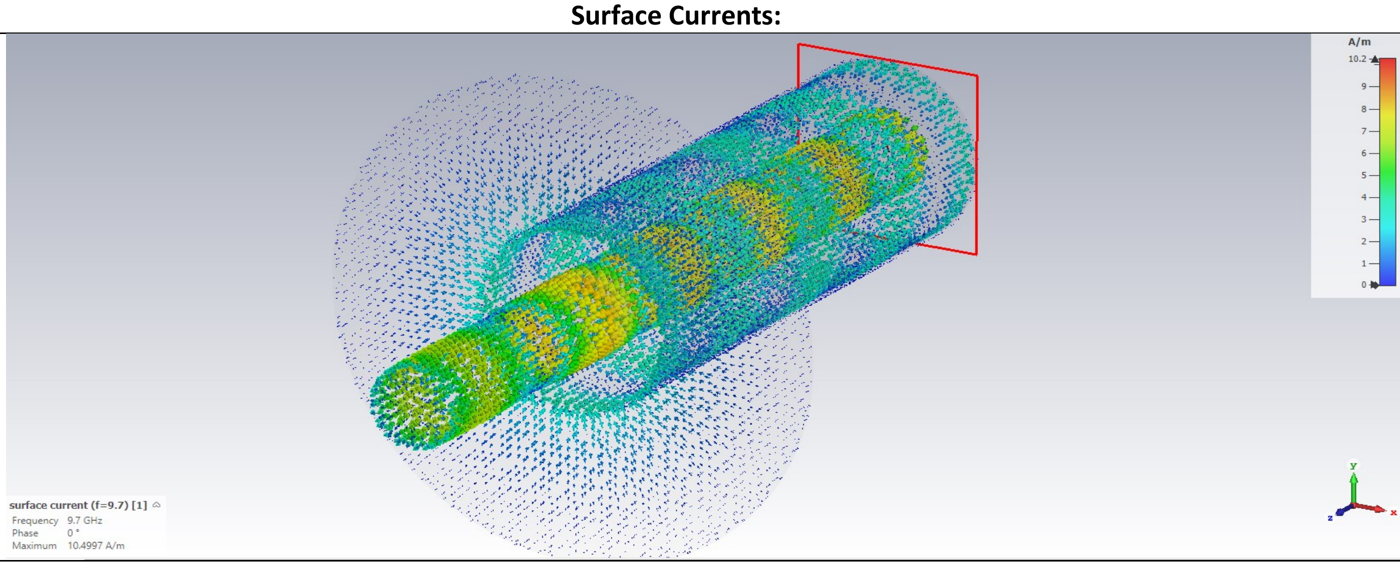
Peak directivity is 5.934 dBi, peak IEEE gain is 5.902dBi, peak realized gain is 5.829dBi, and the main lobe (peak gain) direction is $(\theta = 37°, \varphi = \text{anything})$. The value of φ is irrelevant here, because the farfield is completely radially symmetrical in φ.

The directivity makes sense, as we would expect a monopole with a ground plane to radiate more into one half-space than the other, but it is not a super focused beam, so the directivity couldn't be too high. The value we got seems about right. The gain is dependent on directivity by a constant factor, so since directivity makes sense, so does gain. *Efficiency*: 99.27%

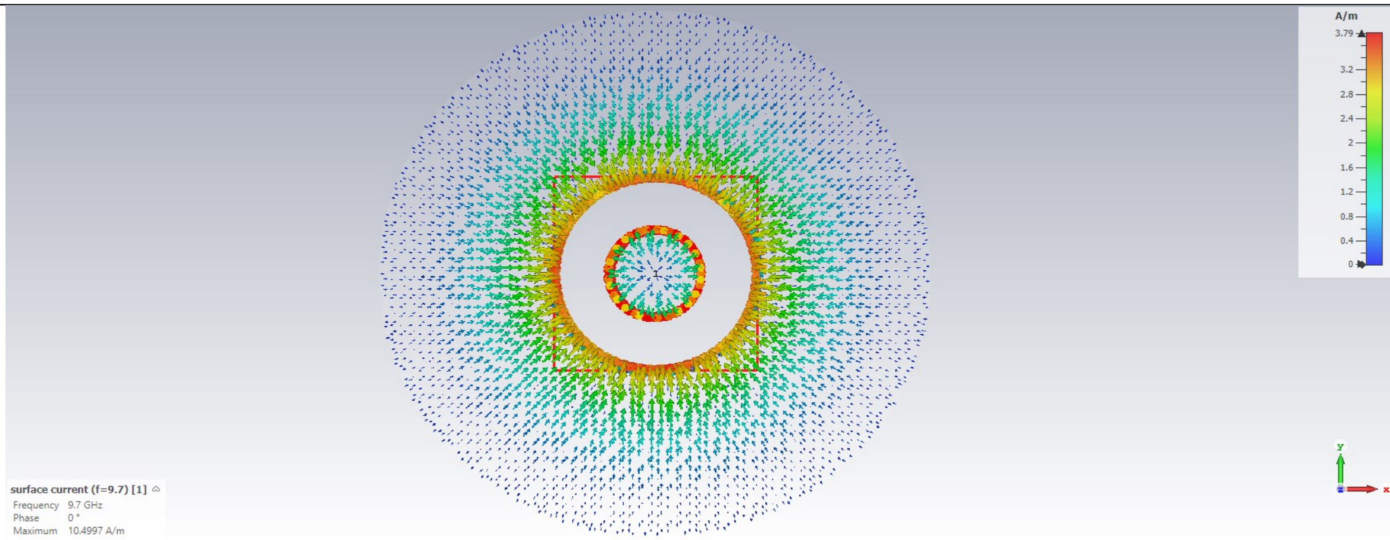
f. Present the surface currents on the monopole antenna and on the ground plane. Compare it to the expected results according to the theory and explain the differences, if those exist.

Surface Currents:

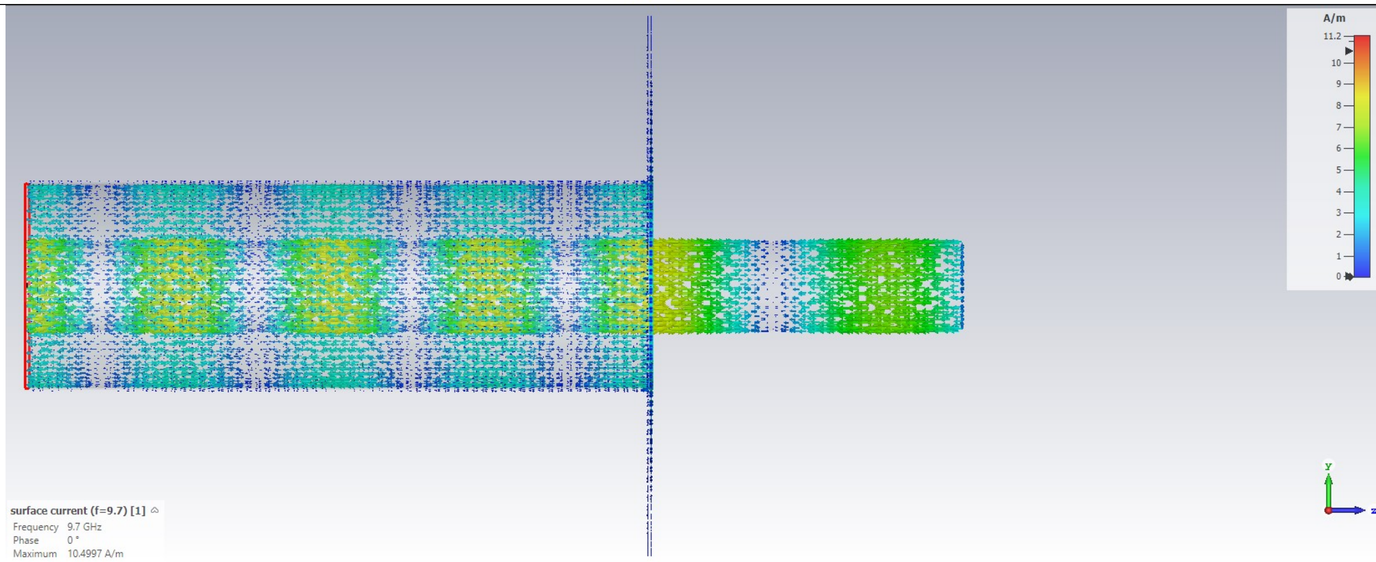
Perspective



Ground Plane



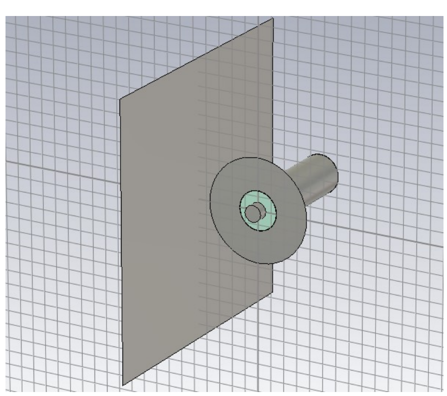
Antenna Itself



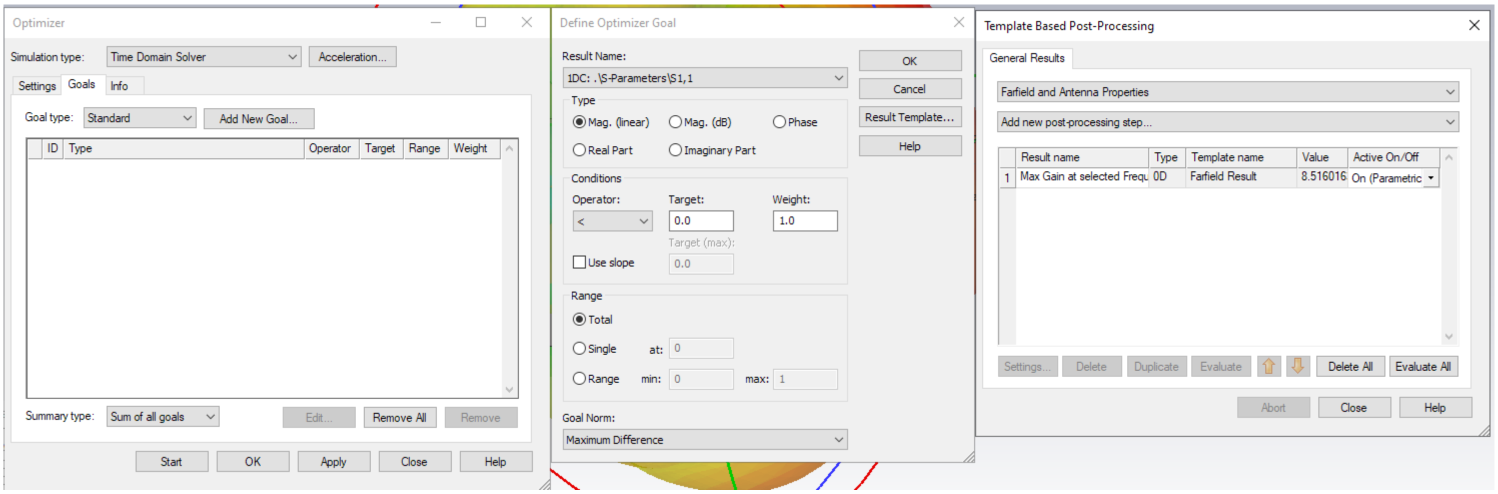
5. Next, add to the existing monopole model a "reflector" –another metal plate which is perpendicular to the ground plane, and has a size of 20cm x 20cm, where its normal is in the direction of the X-axis. Place this reflector at a chosen distance of 0.2lto 1 from the monopole, where this distance is optimized in order to achieve maximum peak gain for the antenna. Now, fine-tune the length of the monopole in order to achieve a matching of better than -10dB over the frequency band 0.95f-1.05f.

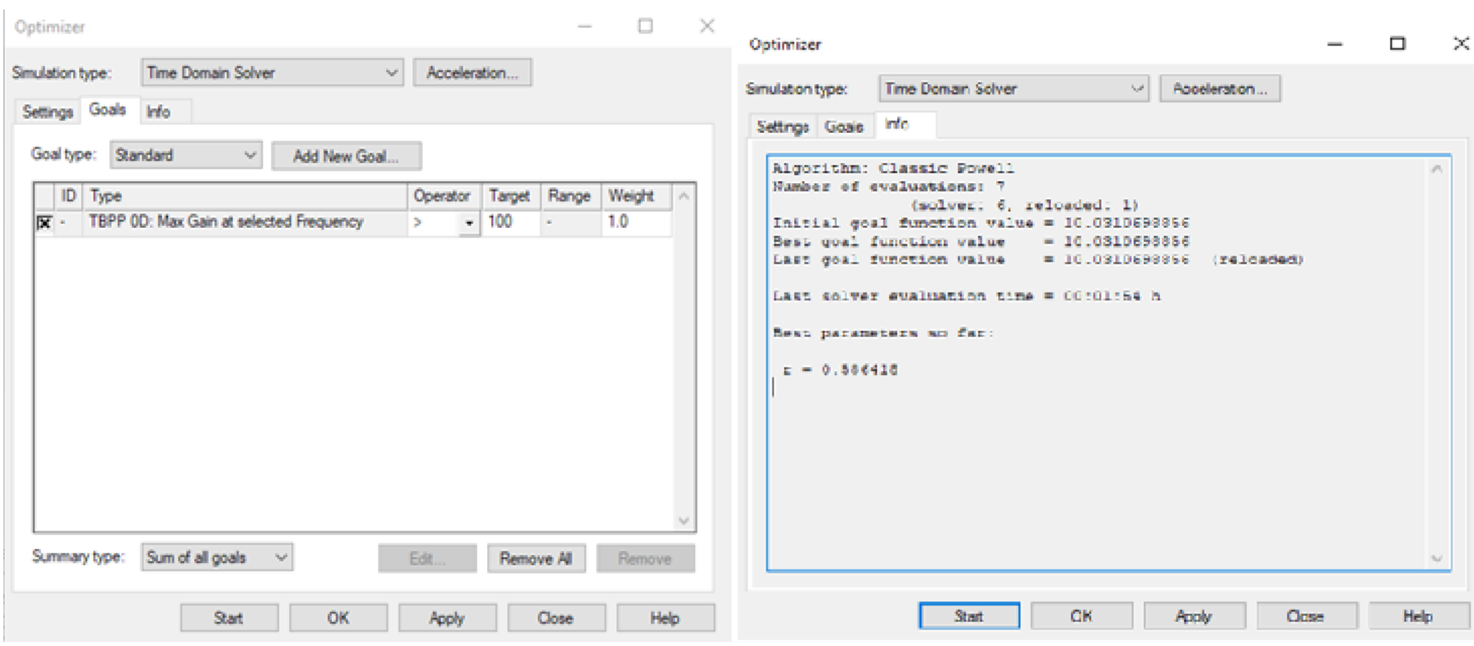
The reflector's normal is in the X axis, and it is orthogonal to the ground plane, which means the reflector is in the Z-Y plane. I am assuming that the reflector cannot clip through the monopole, and that the monopole is considered as the entire coax-ground plane-protrusion structure. Therefore the distance of the reflector from the monopole is actually the distance of the reflector from the ground plane. If I do not assume this, then distances less than ~~0.3λ clip through the ground plane and the coax.

<u>Reflector model at 0.2λ distance from the ground plane (before optimization):</u>



Now I must optimize the distance of the reflector for maximum peak gain. To do this I use the built-in optimizer. It does not by default support optimization for max gain. I used the result template editor to define this goal:



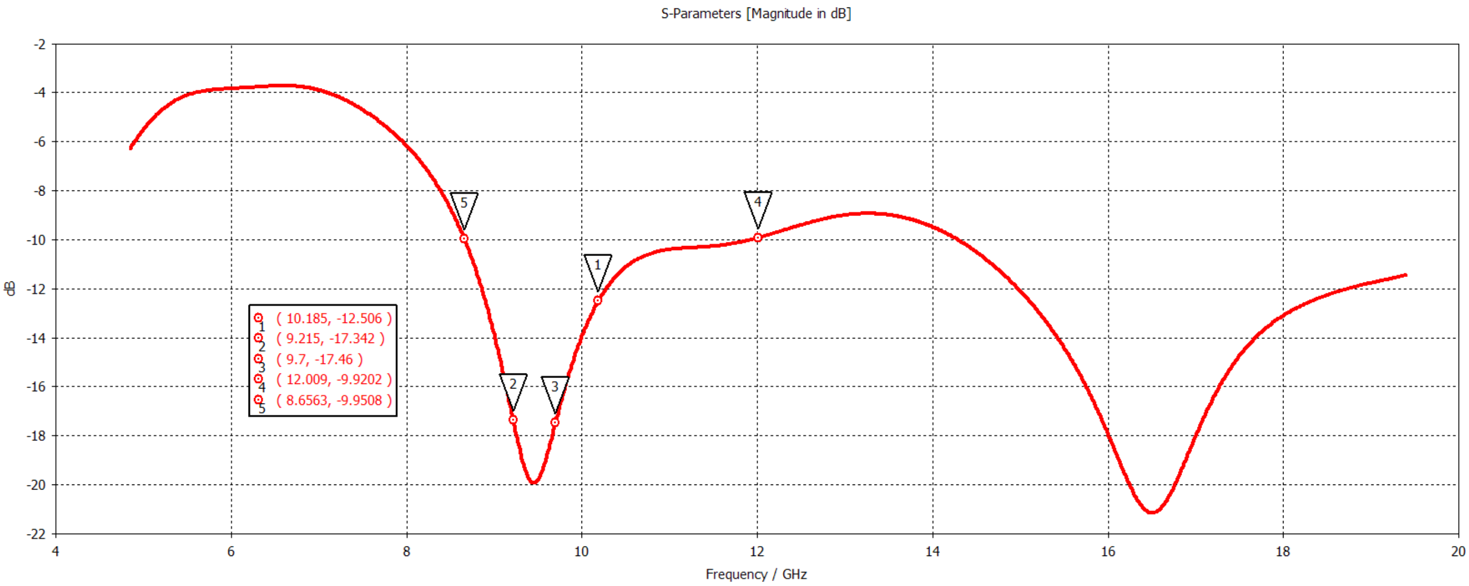


The goal function is $G_{\mathrm{MAX}} > 100$, because the optimization algorithm tries to minimize the goal function. Since my gain is extremely unlikely to be above 100, the optimizer will find the minimal value of the goal function, which would be the maximal gain.

$$\text{Optimized distance } d_{refl} = 0.586\lambda$$

The next task is to optimize the monopole protrusion length so that S11<-10dB for 0.95f-1.05f. This length does not require optimization in my case, as shown in the S11 plot in the next question:

a. Present the input matching over the bandwidth 0.5f-2f. Use markers on the plot in order to demonstrate the achieved design goals



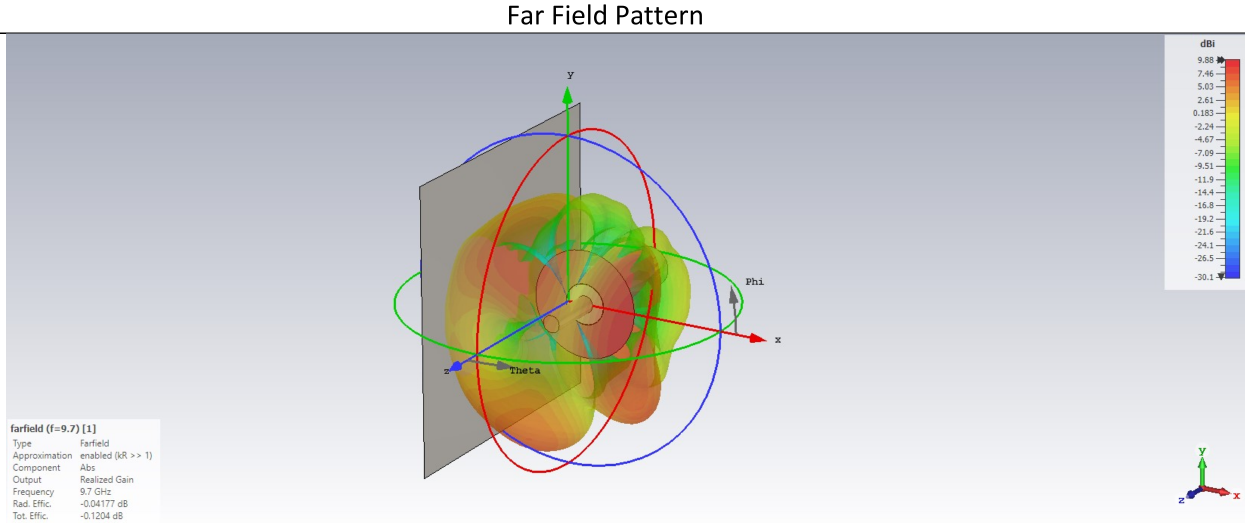
Markers #1 and #2 are positioned at 1.05f and 0.95f respectively. S11 at those markers is -12.5dB, -17.342dB respectively. All values in between markers #1 and #2 are smaller than -10dB, so the optimization requirement for 0.95f-1.05f is met. Markers #5 and #4 are at frequencies where S11 is equal to -10dB: 8.65G, 12G. The actual range for which $S_{11} < -10dB$ is satisfied is: $0.89f - 1.23f$, which is better than the given design parameter.

Marker #3 is positioned at the operating frequency 9.7G, and S11 at this point is -17.46, which is considerably lower than the upper limit of -10dB.

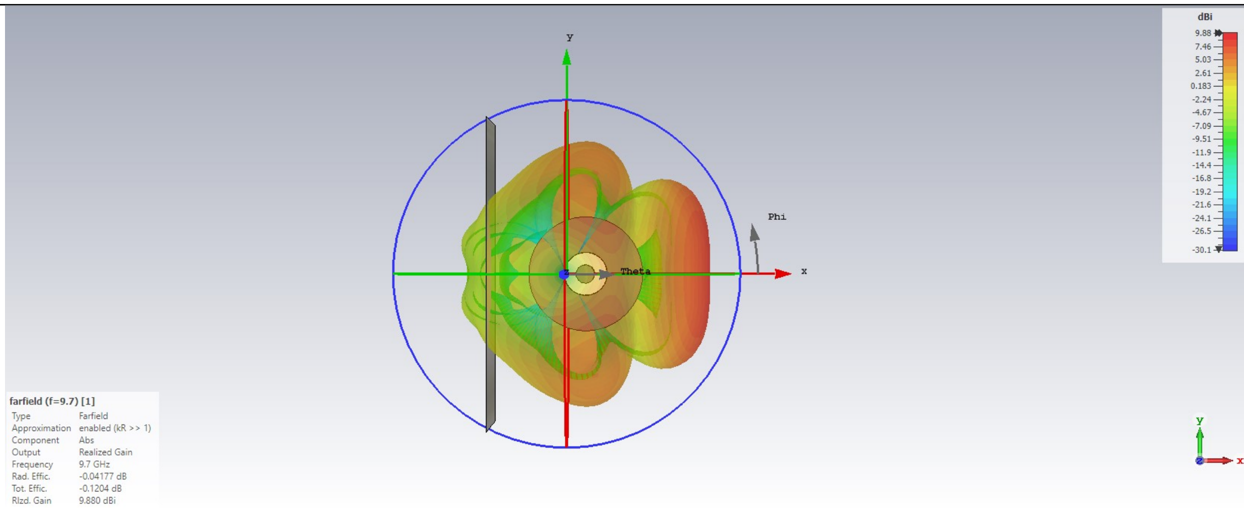
b. Compare the optimized length to the theoretical one. If there is any difference, what is the reason for that?

The optimized length is the same as without the reflector, which makes sense, because the reflector "redirects" a part of the radiated field, but it does not induce any backward waves in the monopole – so there is no reason for the S11 parameter to change.

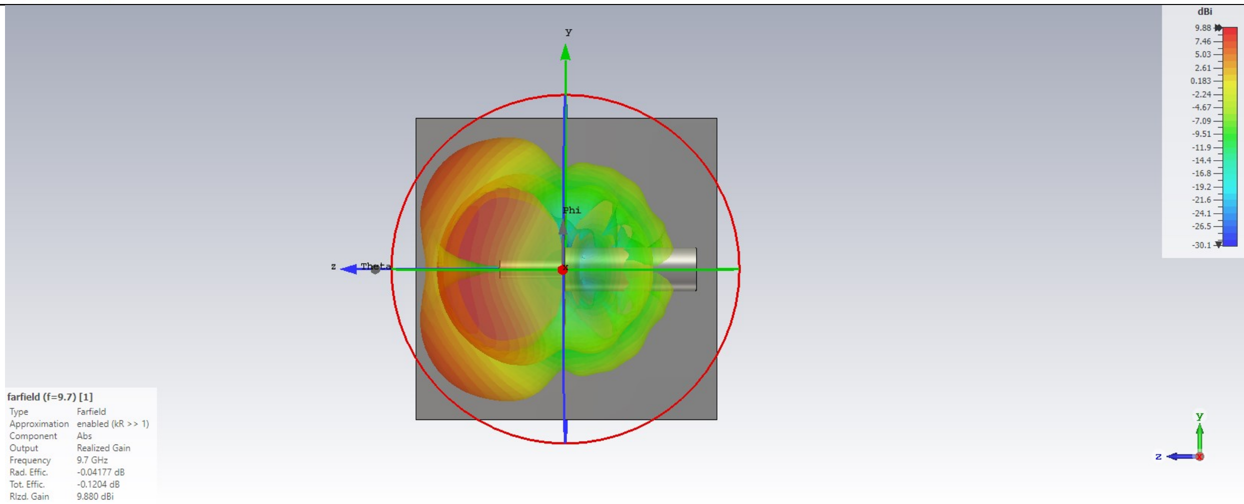
c. Present the far field radiation pattern and the gain and directivity of the monopole at the frequency f. Compare it to the expected radiation pattern according to the theory and explain the differences. What is the antenna efficiency?

Far Field Pattern	
Perspective	

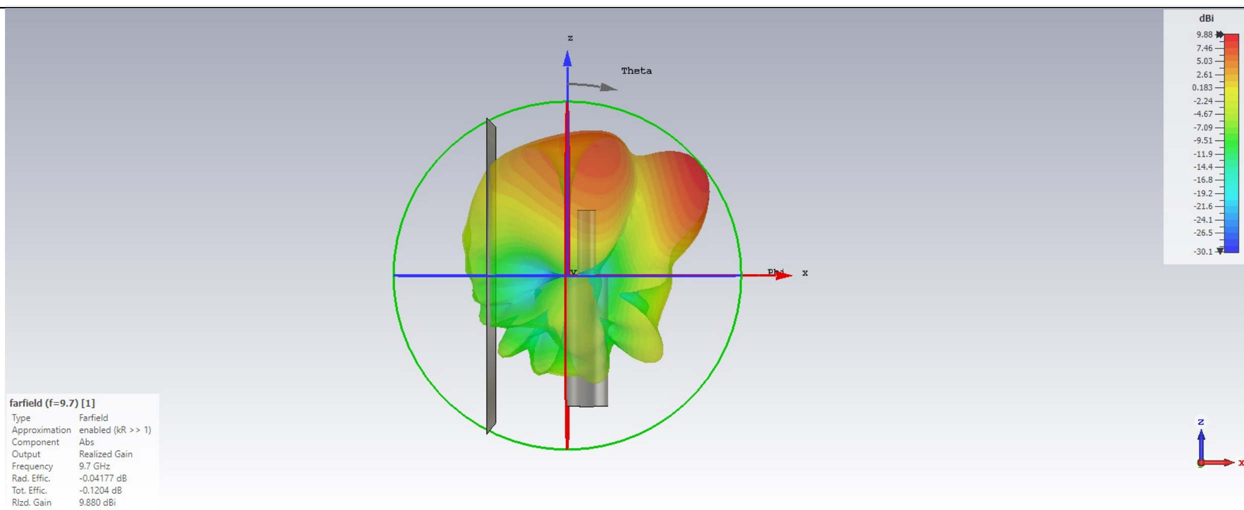
Front View



Side View



Bottom View



Directivity at f: 10.0 dBi

IEEE Gain at f: 9.959 dBi

Realized Gain at f: 9.58 dBi

Antenna Efficiency: $\eta = 99.04\%$ (radiation efficiency)

A reflector is meant to improve directivity by reflecting radiation that would have passed its way, into another (opposite) direction. Since directivity is a measure of the total "directedness" of the antenna, and we started at ~D=5 without a reflector, it would make sense that almost bisecting the space with a reflector would double our directivity, since we essentially halved the space where radiation could go.

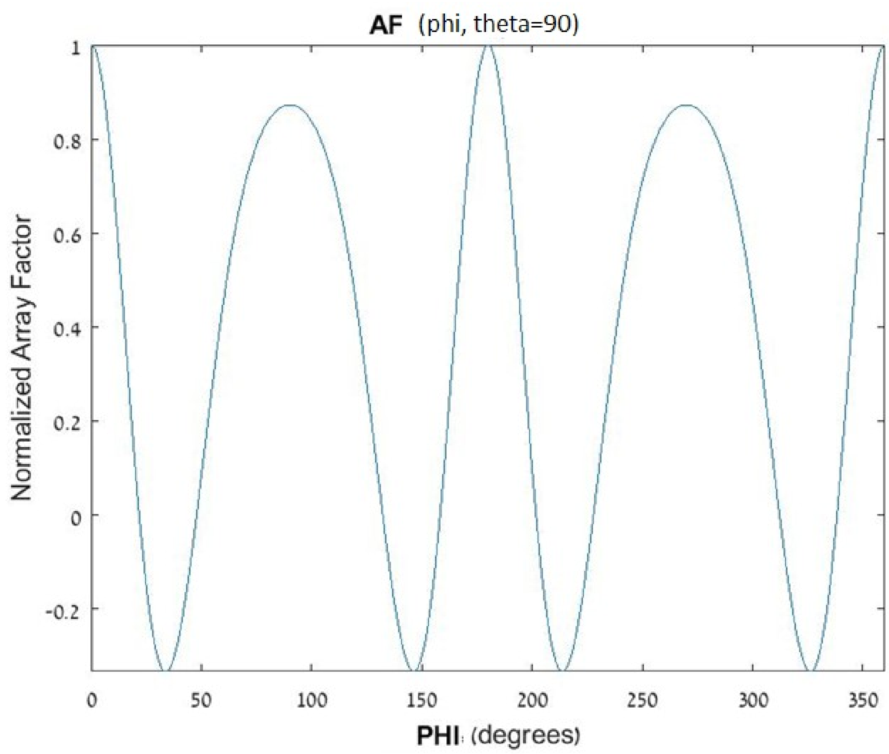
6. In this section you are requested to use again the same monopole that was optimized in Section #4 (before adding the side reflector) in order to implement an array as described in the table below. Follow the sections below:
   a. Write down the expression for the normalized Array Factor of the array that you should implement.

The "default" normalized array factor is $(AF)_n = \frac{\sin\left(\frac{N}{2}kdcos(\theta)\right)}{Nsin\left(\frac{1}{2}kdcos(\theta)\right)} = \frac{\sin\left(\frac{N}{2}\psi\right)}{Nsin\left(\frac{1}{2}\psi\right)}$

We are along the Y-axis, so $\psi = kdsin(\theta)\sin(\varphi)$

Therefore $(AF)_n = \frac{\sin(\frac{N}{2}kdsin(\theta)\sin(\varphi))}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)}$ $;N = 3, k = \frac{2\pi}{\lambda}, d = 0.9\lambda$

   b. Plot in Matlab the normalized array factor as a function of the jangle (where φ is defined as the angle between the X-axis and the Y-axis, in the X-Y plane). Attach your code file to the solution.



   c. 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.

$$(AF)_n = \frac{\sin(\frac{N}{2}kdsin(\theta)\sin(\varphi))}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)} \quad ;N = 3, k = \frac{2\pi}{\lambda}, d = 0.9\lambda$$

Normalized radiation intensity is therefore:

$$U(\theta,\varphi) = ((AF)_n)^2 = \left(\frac{\sin(\frac{N}{2}kdsin(\theta)\sin(\varphi))}{Nsin(\frac{1}{2}kdsin(\theta)\sin(\varphi)}\right)^2$$

Average radiation intensity:

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

The array length $L = Nd = 3 \cdot 0.9\lambda = 2.7\lambda$

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

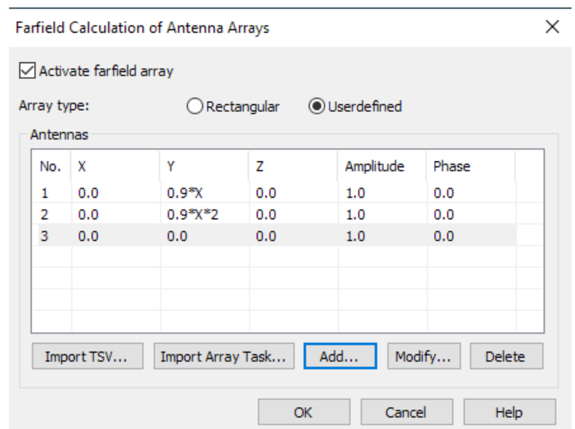
I found U_0 using numerical integration, because the integral solution is not trivial. $U_0 = 0.26844925 \rightarrow D = \frac{1}{U_0} = 3.725$

d. Calculate the required electrical phase $\Delta\phi$ that is required in order to steer the beam to an angle φ=30°. Note the configuration of your array (along the X-axis or the Y-axis)!

$$\Delta\varphi = -\left(\frac{180}{\pi}\right) \cdot 0.9 \cdot 2\pi sin(30) = -162°$$

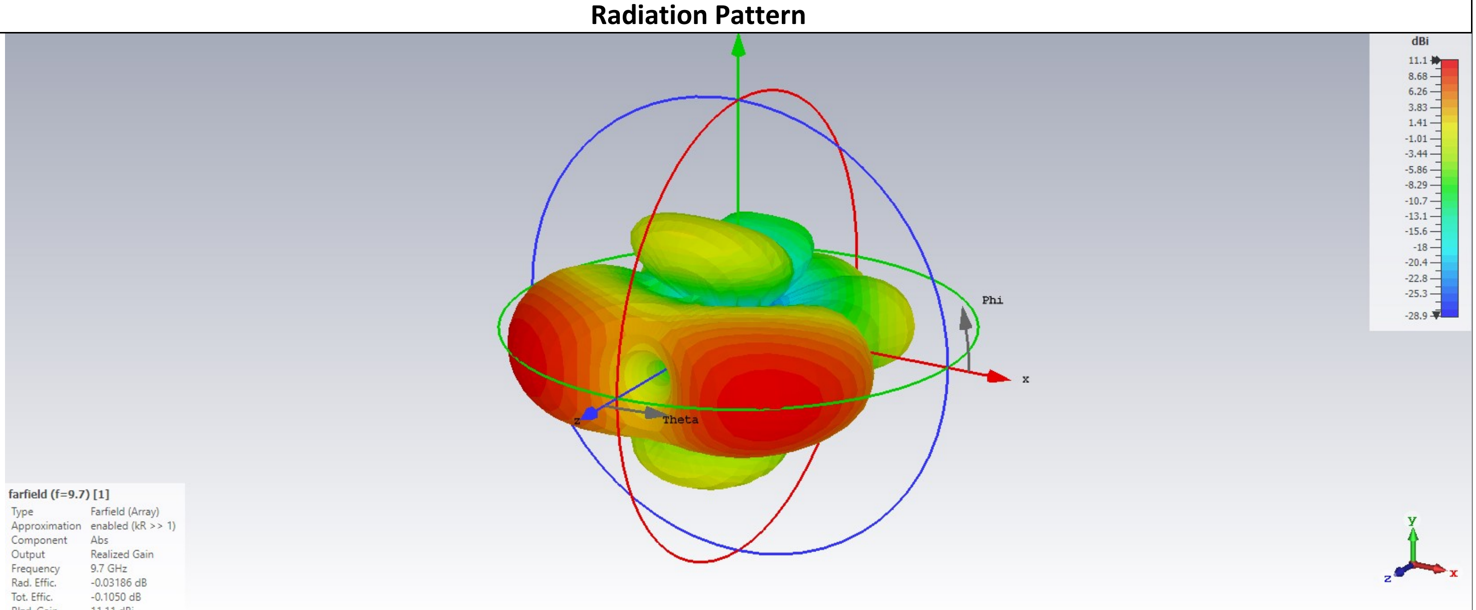
e. Plot in Matlab the normalized array factor as a function of the θ angle for the array that has its beam steered to the angle $\varphi = 30°$. Attach your code file to the solution.

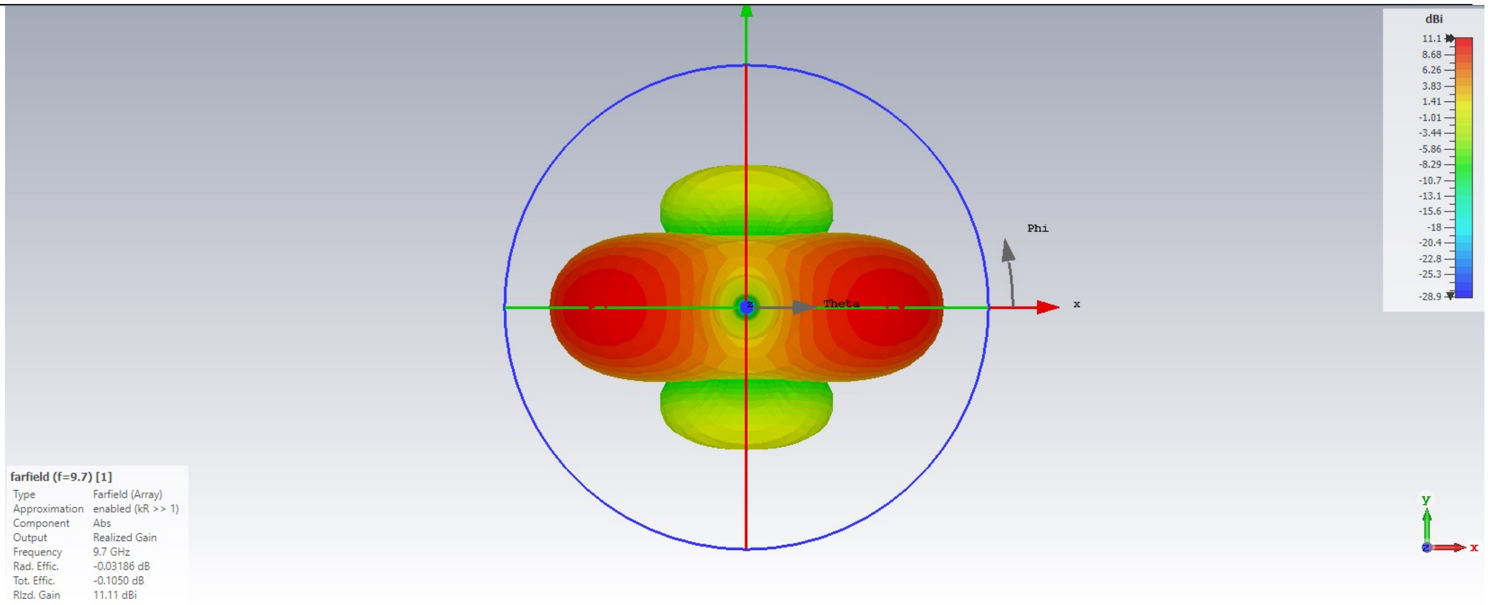
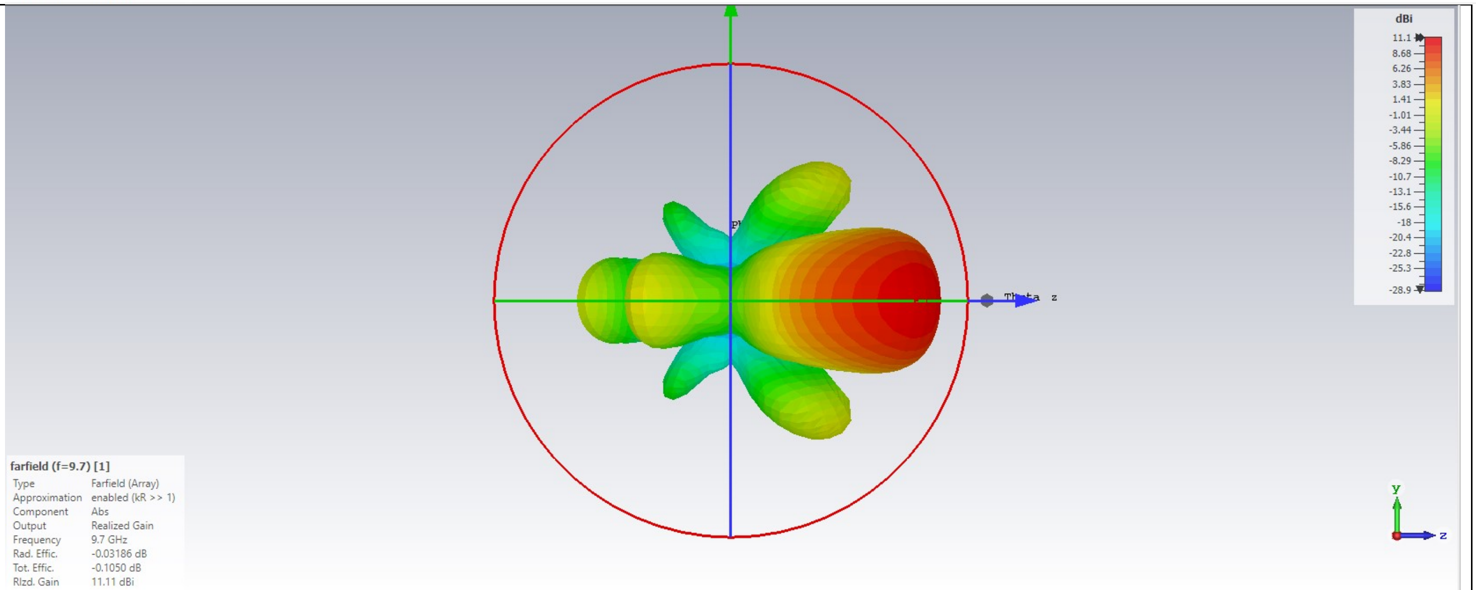
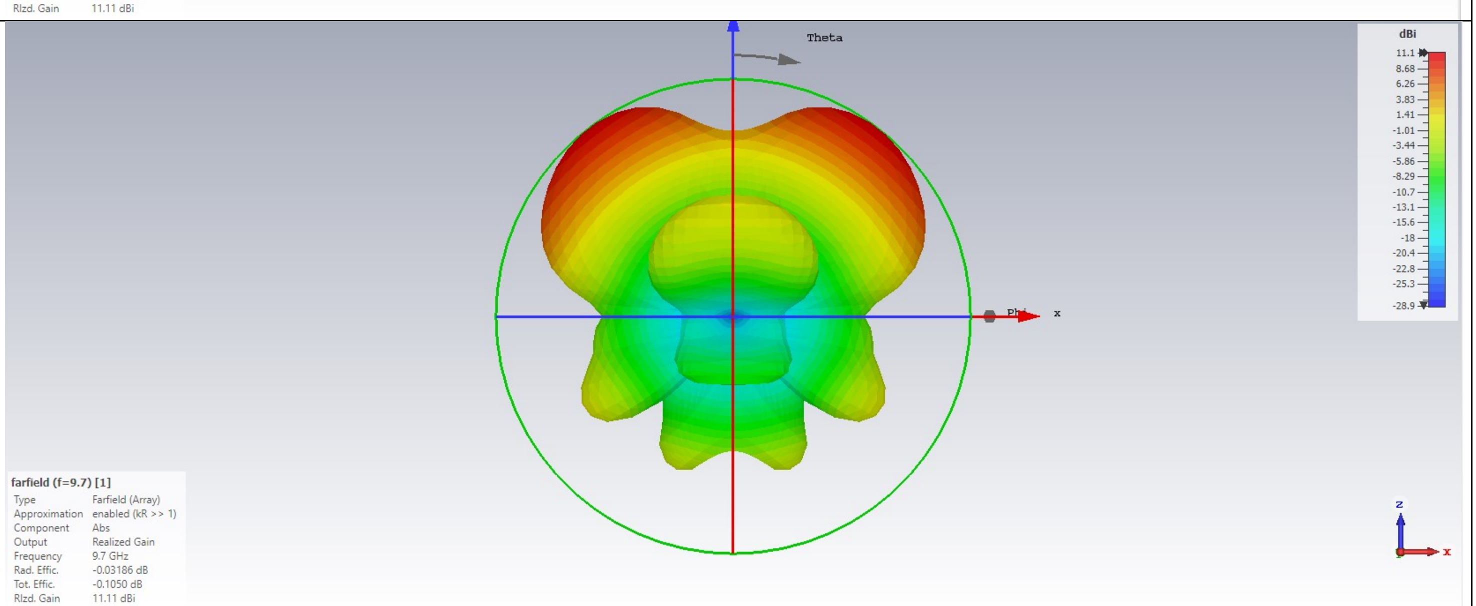
f. Implement the array in CST by using CST's Array Tool. This tool takes the radiation pattern of the simulated antenna ("the "element factor") and combines it with the theoretical array factor of a specified array. Fill the array parameters according to the total number of elements of your array. Simulate this structure while feeding all of the monopoles with the same electrical phase and plot the 3D radiation pattern, as well as the radiation pattern in the X-Y plane (over the φ angle)



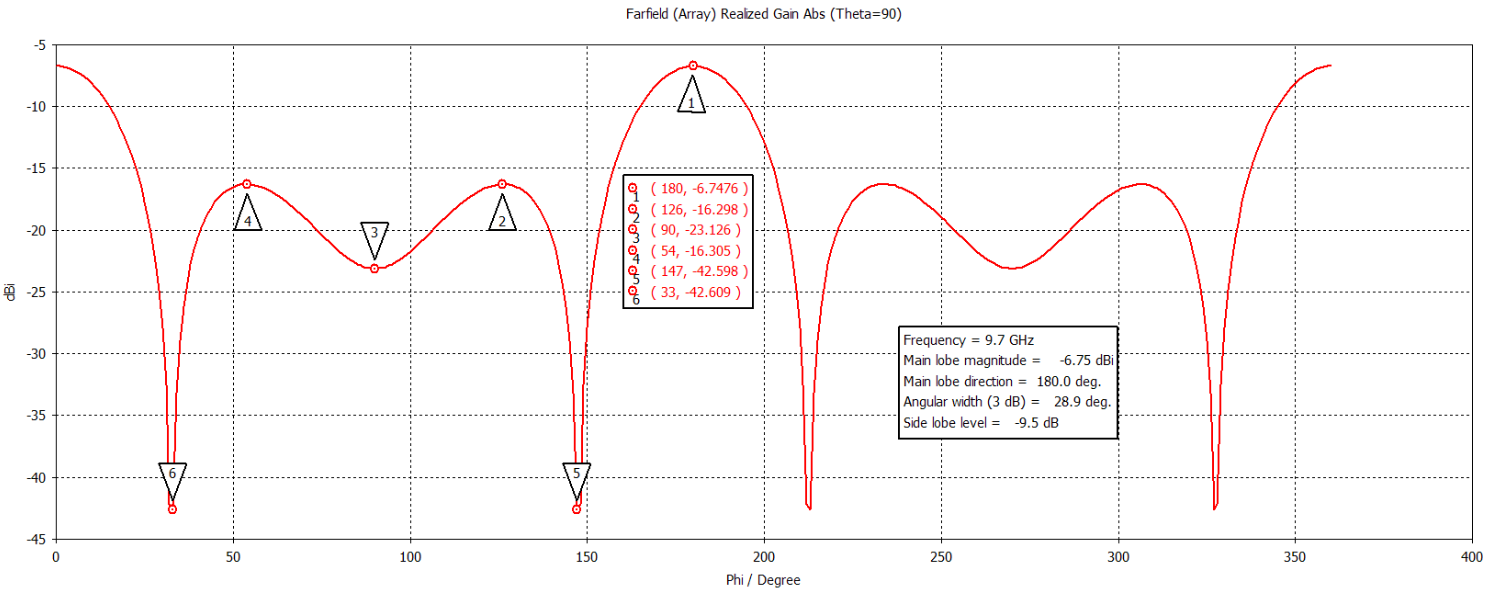
Radiation Pattern

Perspective



Front	
Side	
Bottom	

Radiation Pattern (X-Y Plane):



g. Compare the radiation pattern in the X-Y plane to the theoretical radiation pattern of the array factor that you found using Matlab.

The graphs look similar – both have periodic global maximums at $180°$, which repeat every $180°$ in either direction. This is indicated by Marker #1 in the simulated plot. These maxima correspond to the big "ears" seen in the 3D "front view". In other words – the main lobe predicted by Matlab agrees with the simulation.

The theoretical Matlab result has a local maximum in between the global maxima, such as at $90°, 270°$. The simulated result exhibits a local minima at the 90°, 270° points(Marker #3), with local maxima surrounding the minimum from both ends, at roughly $60°, 130°$ (Markers #2, 4).

The Matlab also has absolute minima at $30°, \sim 150°$ (Markers #5,6). We observe the same thing in the simulated result.

h. Compare between the peak directivity of the implemented array to the theoretical directivity of the array of isotropic elements that you found above. What is the antenna efficiency?

$$D_{theory} = \frac{1}{U_0} = 3.725$$

$$D_{simulated} = 13.22$$

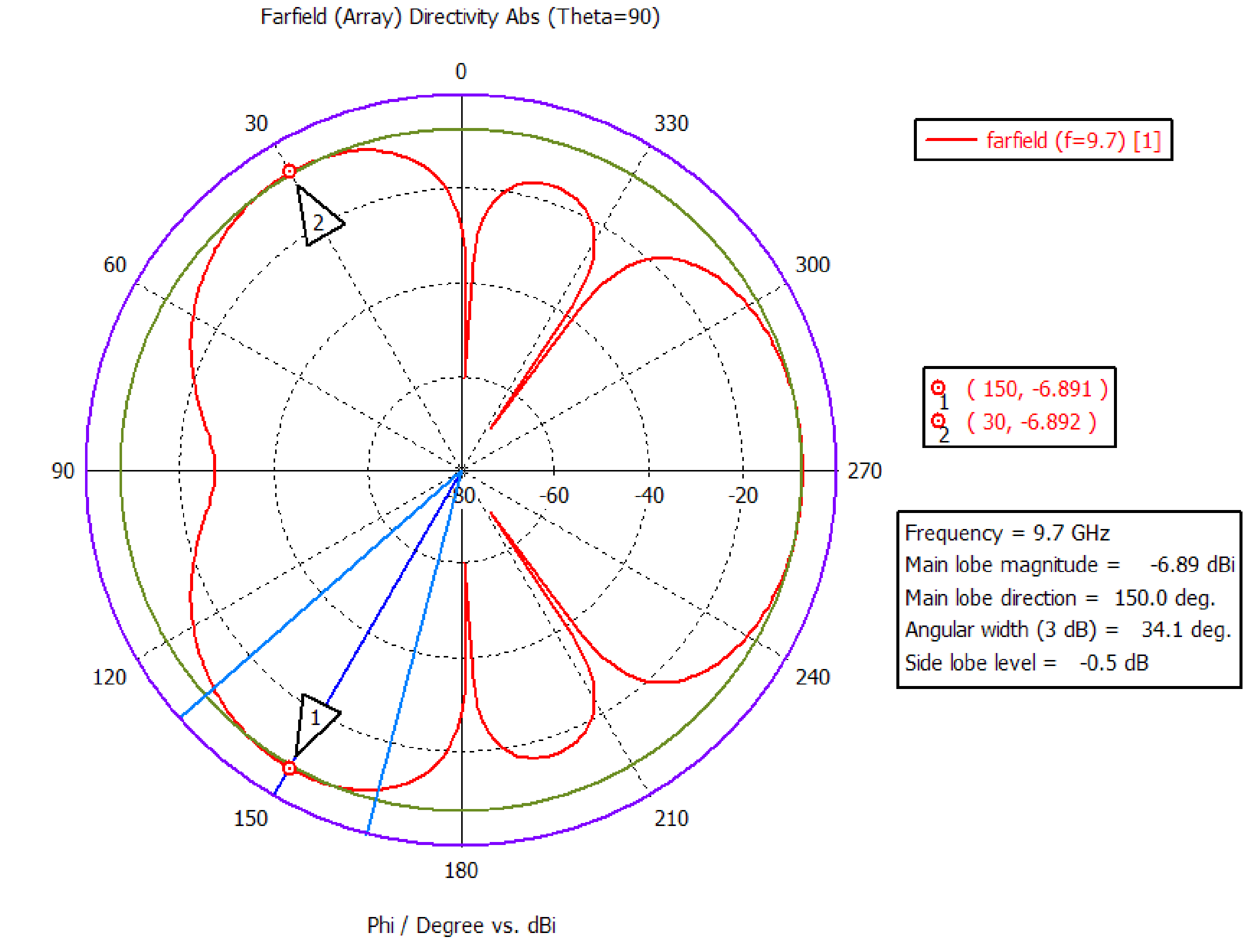
$$\eta_{sim} = 0.9758 = 99.27\%$$

The theoretical directivity is a lot lower than the simulated directivity. This could be because of the approximations used in finding the theoretical directivity, or a straight-up mistake in finding the theoretical directivity. I am not sure.

i. Next, using the Array Tool, apply the electrical phase offset that you found ($\Delta\varphi$) between one array's element port and its neighbor, in order to steer the beam to the geometrical angle $\varphi = 30°$. Plot the 3D radiation pattern, as well as the radiation pattern in the X-Y plane (over the φ angle)

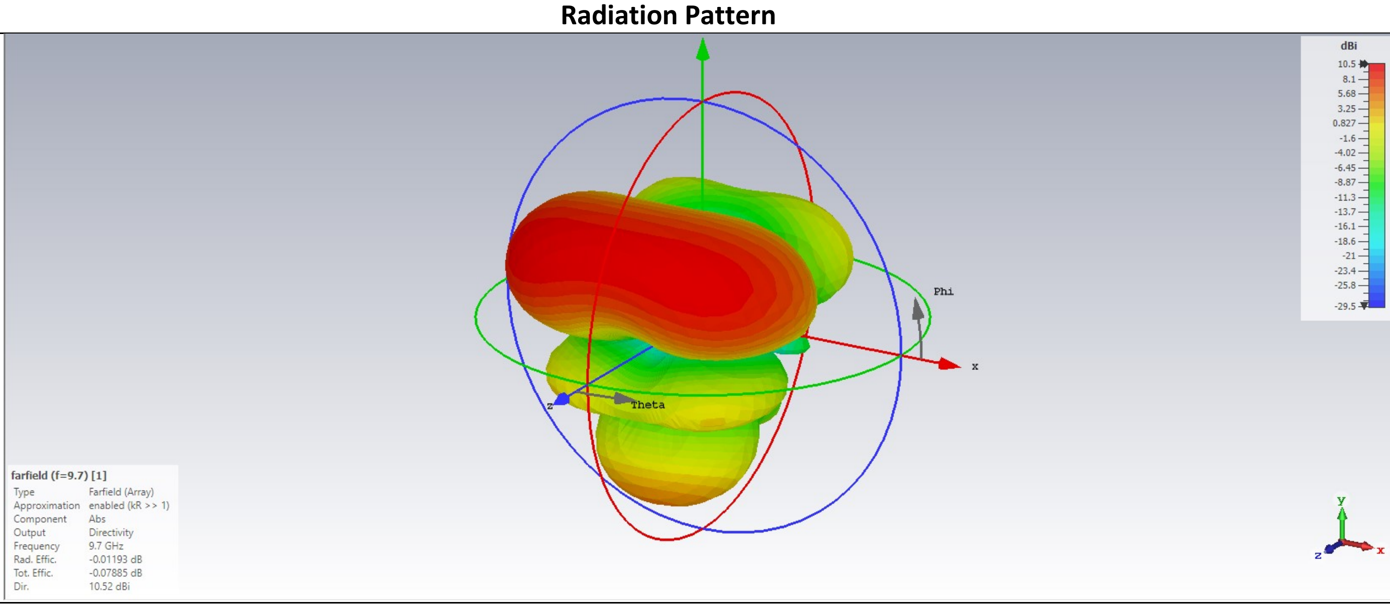
Applying the angle I calculated steers the beam to $242°$, instead of $30°$.

The theoretical angle clearly does not apply to this array. To get to $30°$, I instead used a phase angle of $-112°$: I suspect that the difference between the theoretical phase angle and the one I had to use is caused by the presence of ground planes, which do not exist in the phase array used to derive the theoretical formula.

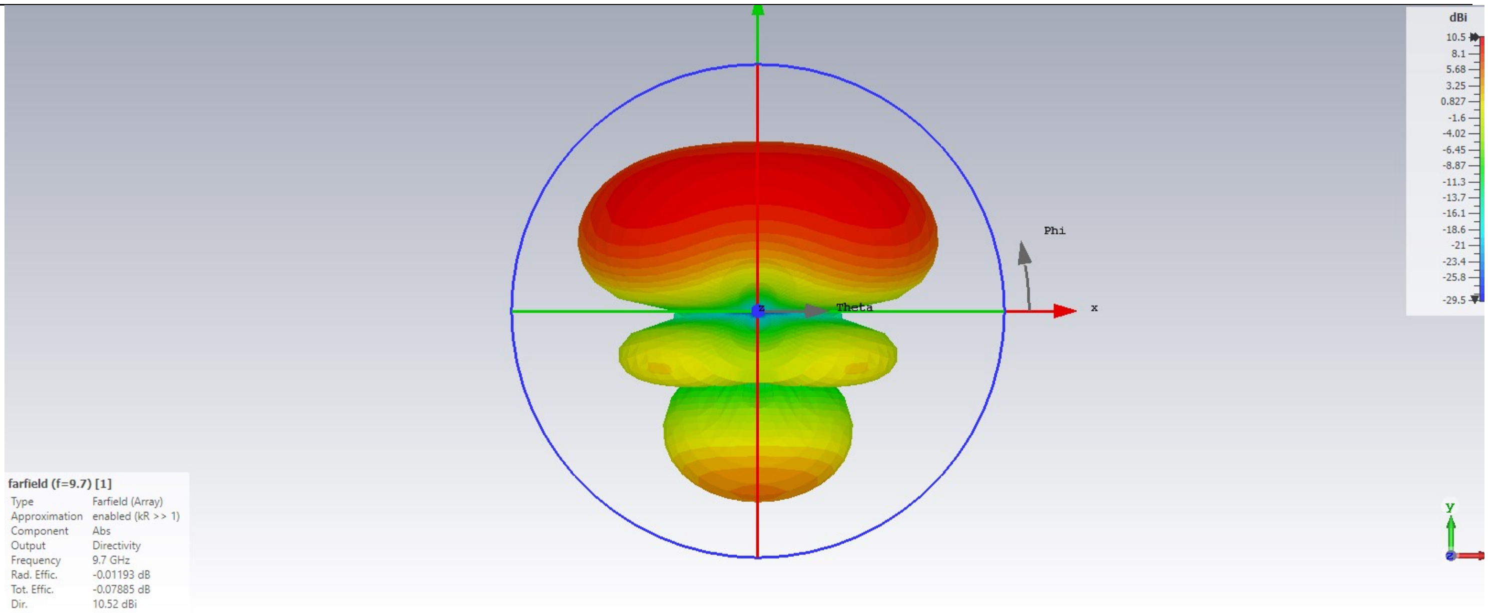


CST says that the main lobe direction is 150°, which is technically true, but it is also 30°. The field is completely symmetrical around the central horizontal axis of the above plot, and the two lobes on the left half "plane" have essentially the same magnitude, as demonstrated by markers 1 and 2. CST chose the "main lobe" to be at marker #1, with magnitude -6.891, as opposed to marker #2's magnitude of -6.892. These are clearly the same lobes- they are both "main", and the angle of the lobe at marker #2 is 30°.

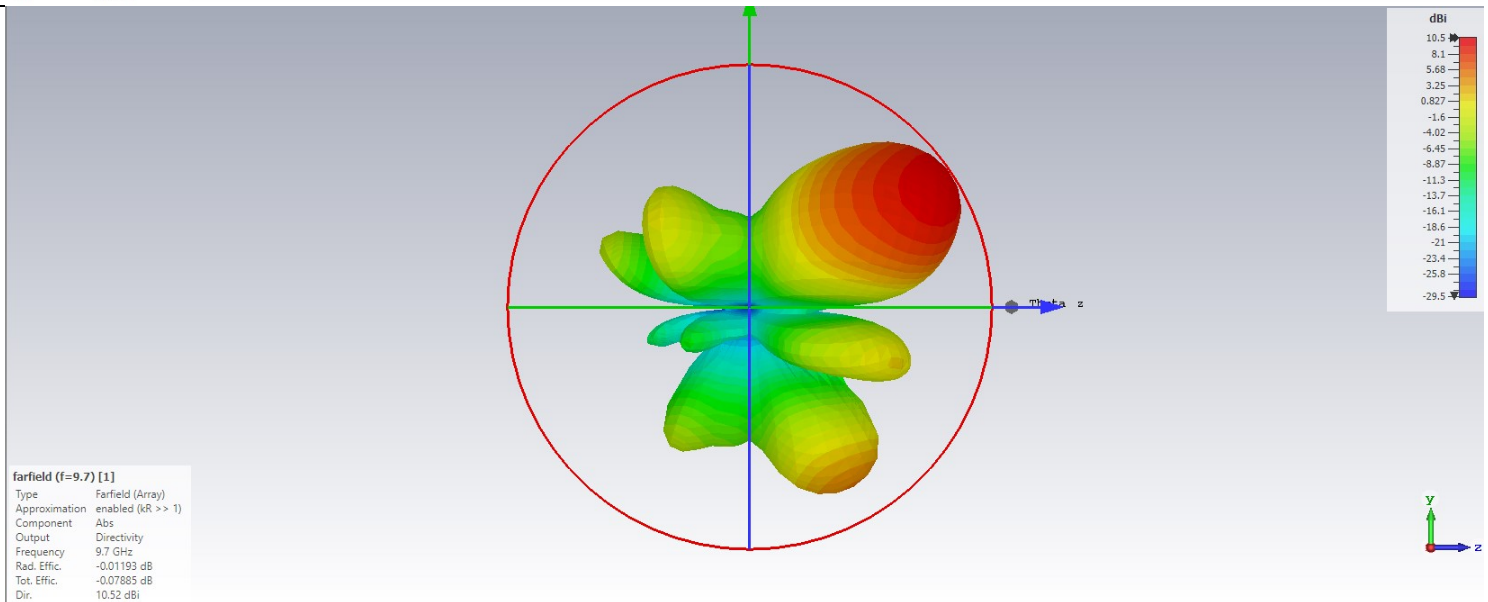
Therefore, applying a phase angle of $-112°$ steers the main lobe(s) to 30°.

Radiation Pattern		
Perspective		

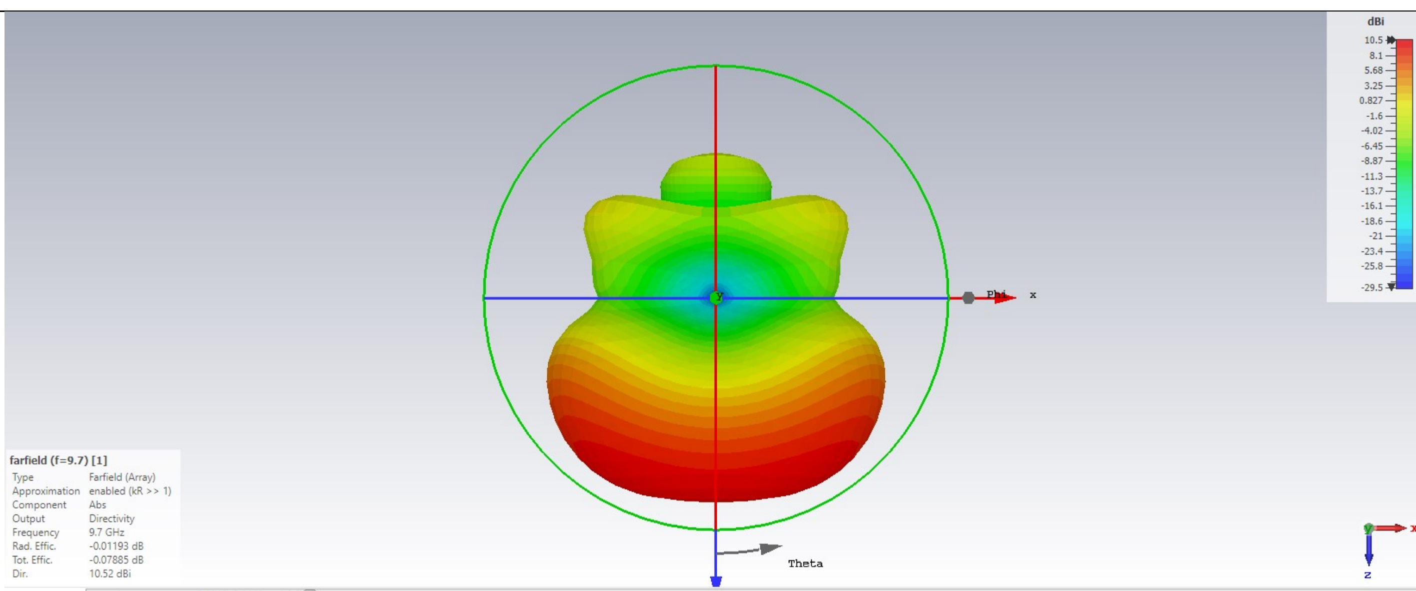
Front



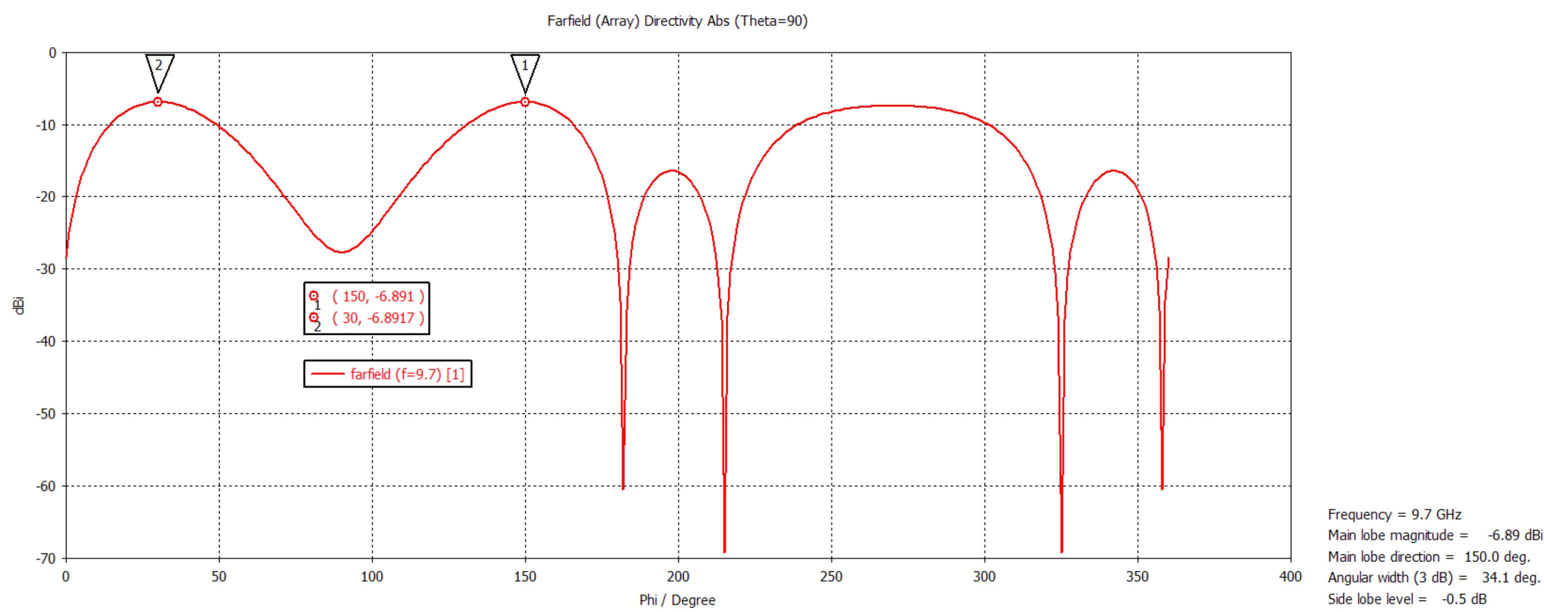
Side



Top



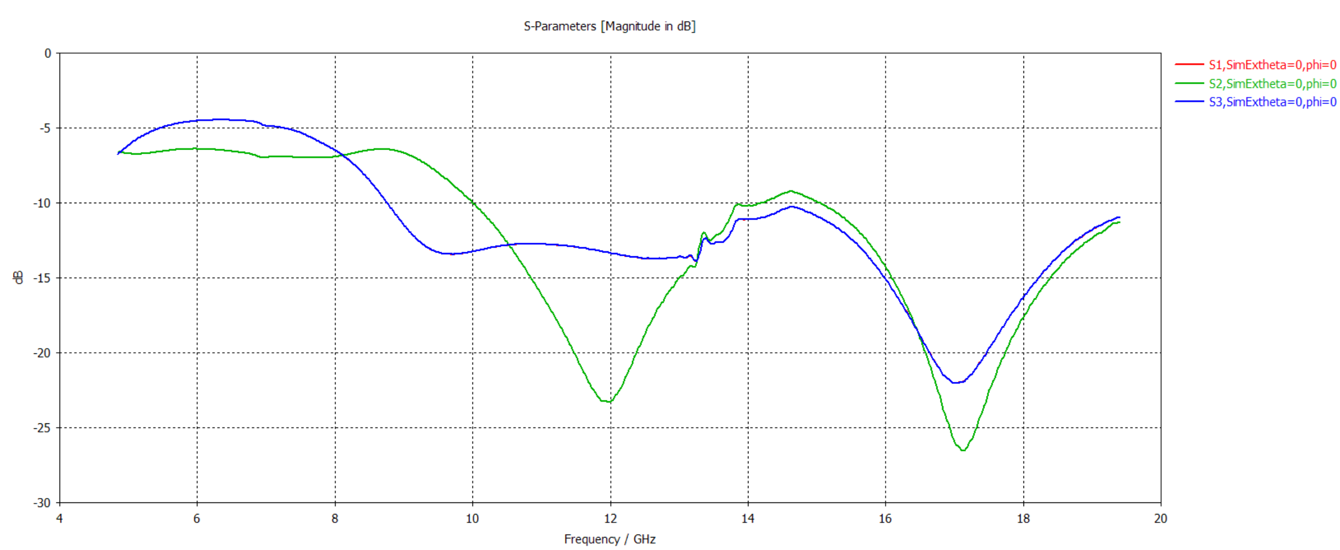
Radiation Pattern in the X-Y Plane:



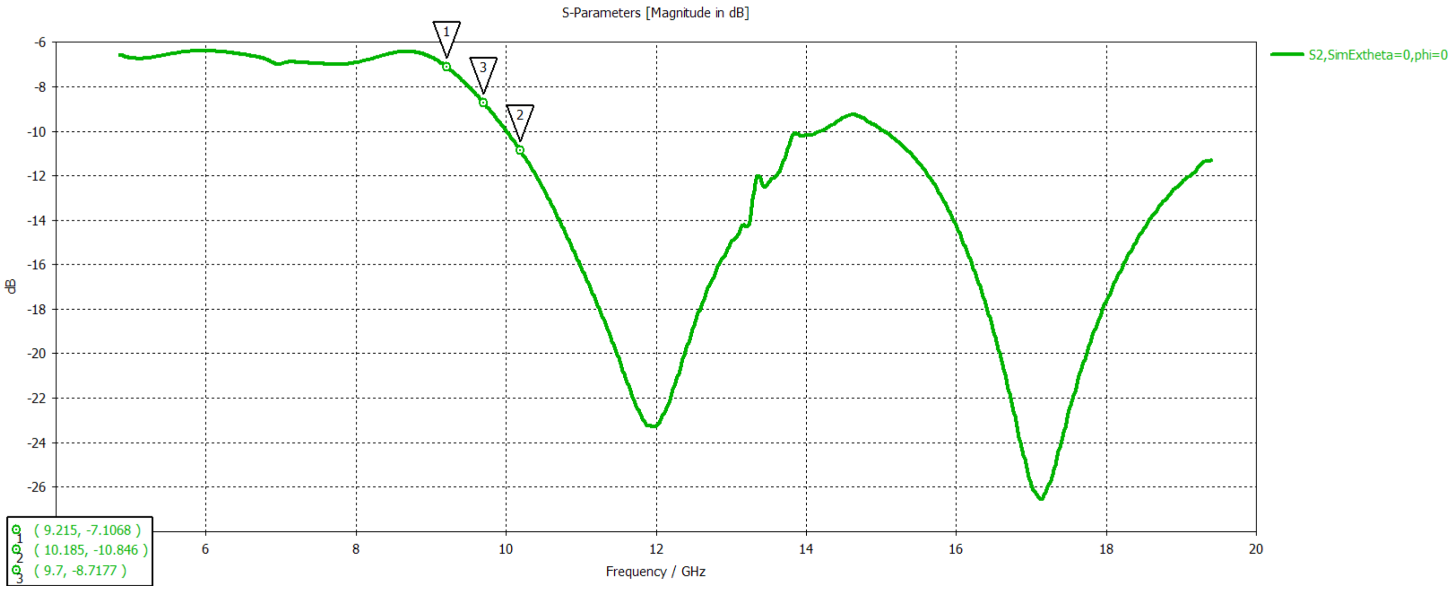
j. Now, implement a model of the array: duplicate the single monopole and its feed, according to the total number of elements of your array. If the metal ground planes of the monopoles are not overlapping, fill the entire gap with PEC. Simulate this structure while feeding all of the monopoles with the same electrical phase. Present the input matching over the bandwidth 0.5f-2fof one of the middle elements of your array. 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 monopole?

Instead of manually building the array, I used the array wizard macro to generate it in a new model. It did however; make a "mistake" where the ground planes of each monopole would overlap the Teflon in other monopoles, so I cut those overlaps out.

All S parameters:



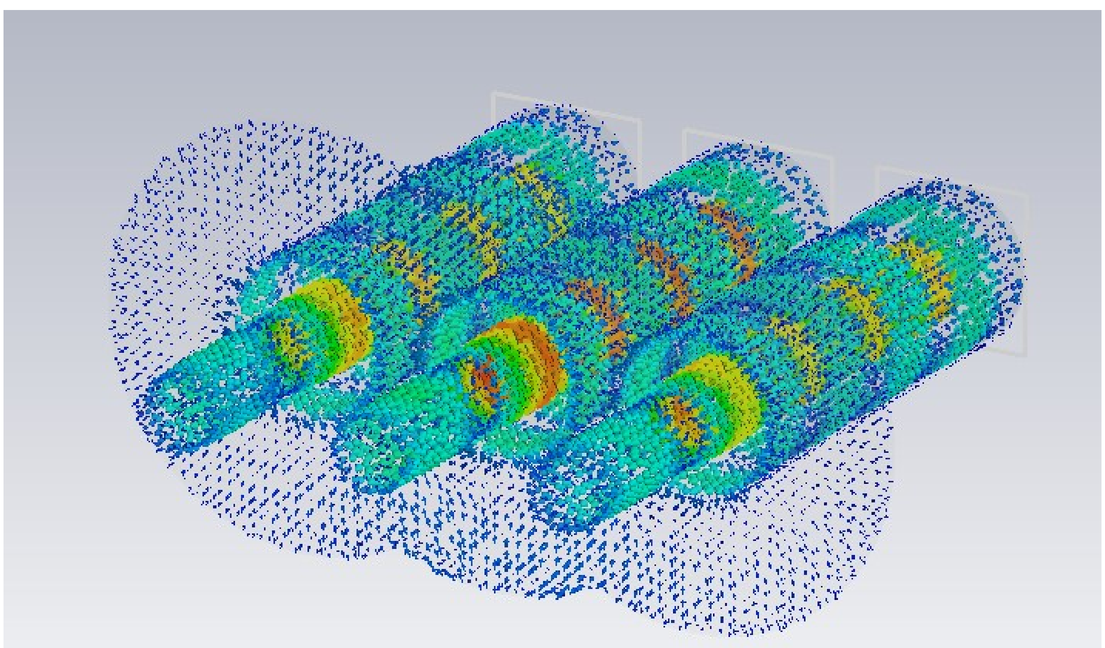
<u>Input Matching of the Middle Monopole:</u>



Markers #1,2 are the edges 0.95f-1.05f. It can be seen that this range is no longer under -10dB. Marker 2 is at -10.846, which is OK, but marker 1 is at -7.1. Marker #3 is at 9.7GHz – the operating frequency, and it's value is -8.7177.

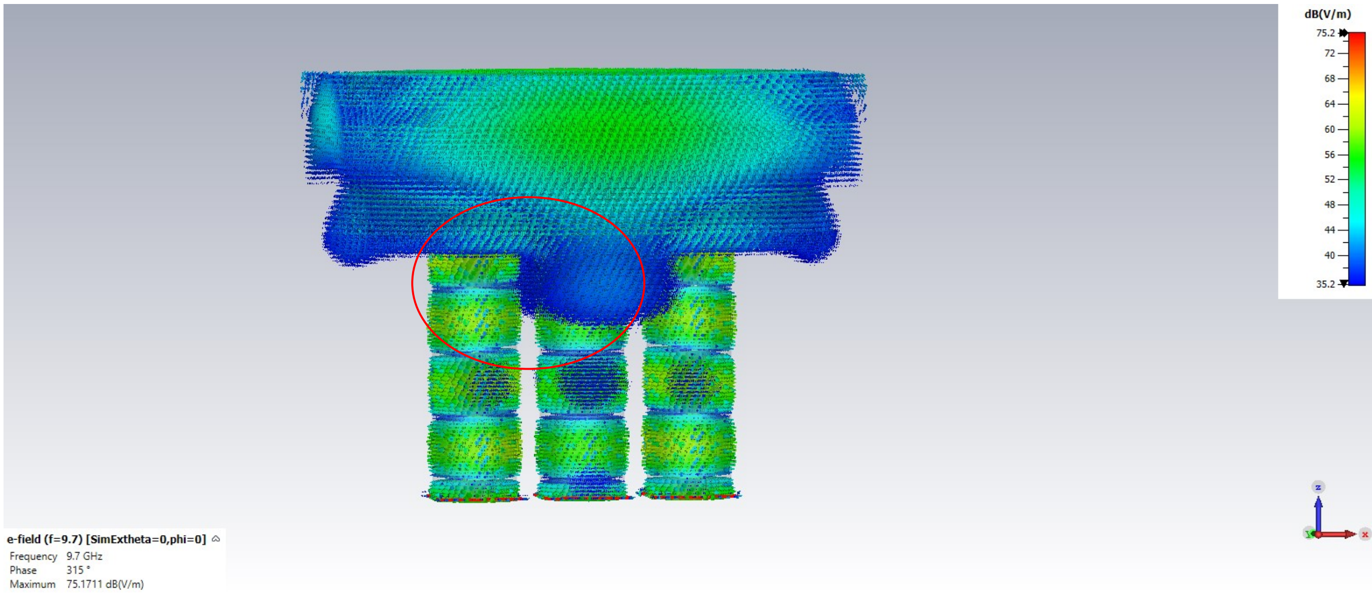
This is much worse performance than for a single monopole – the S11<-10dB requirement is not met anymore for 0.95f-1.05f.

This seems to be because the surrounding monopoles affect the central one for which the input matching was given above. Input matching is Γ in dB, and $\Gamma = \frac{V^-}{V^+} = \frac{I^-}{I^+}$. The surrounding monopoles induce currents throughout the central one. This is confirmed by looking at the surface current:

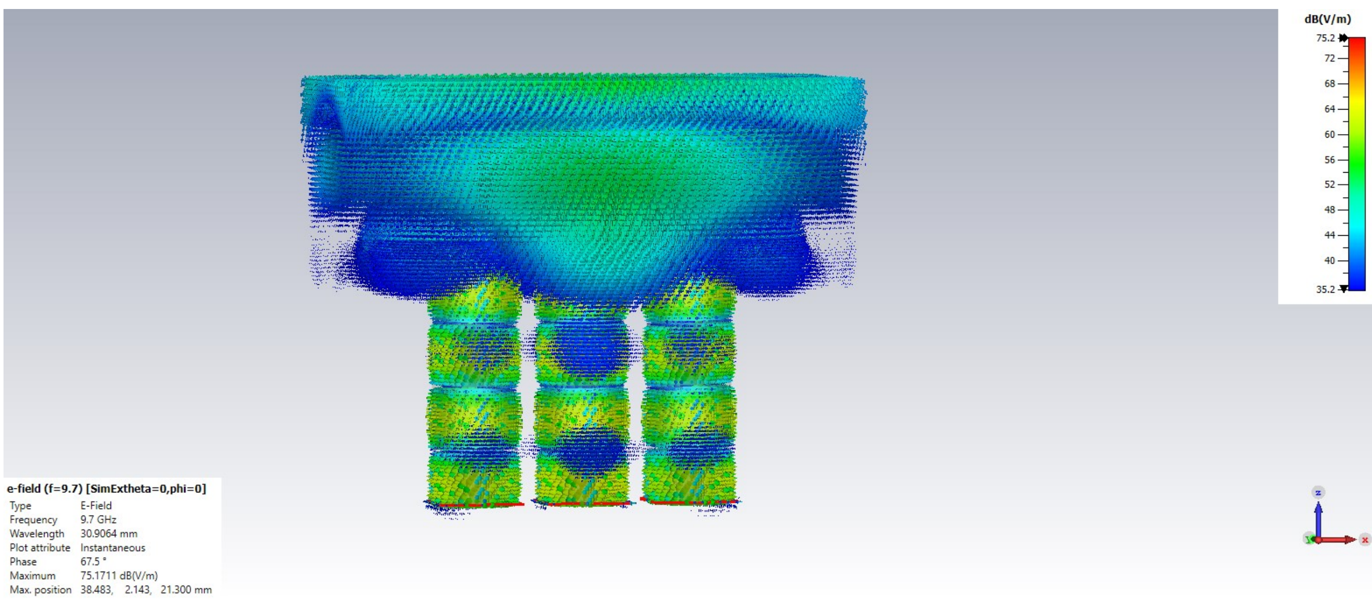


It can be clearly seen, that the surface current in the central monopole is greater than in the edge monopoles. Since they all receive the same excitation, this difference must be the result of interaction with the other 2 monopoles.

To confirm this, I look at the animation of the electric field:



The circled “bubble” is an electric field pulse that periodically propagates down the central monopole. Below is a freeze-frame of this same simulation at a later time:

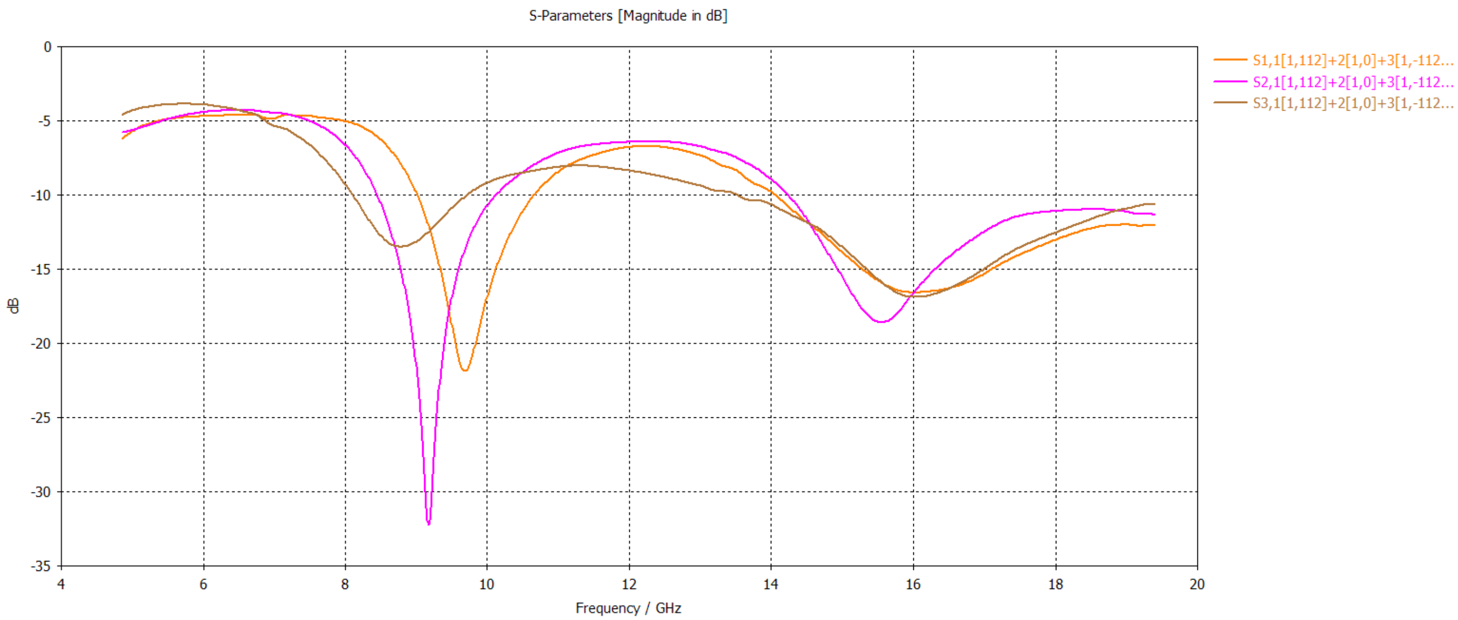


The pulse can be seen making its way down the central coax. Similar pulses exist for the other 2 cables, but they are way smaller. The presence of this backward pulse indicates a backward propagating wave through the monopole, which damages the reflection coefficient and thus input matching.

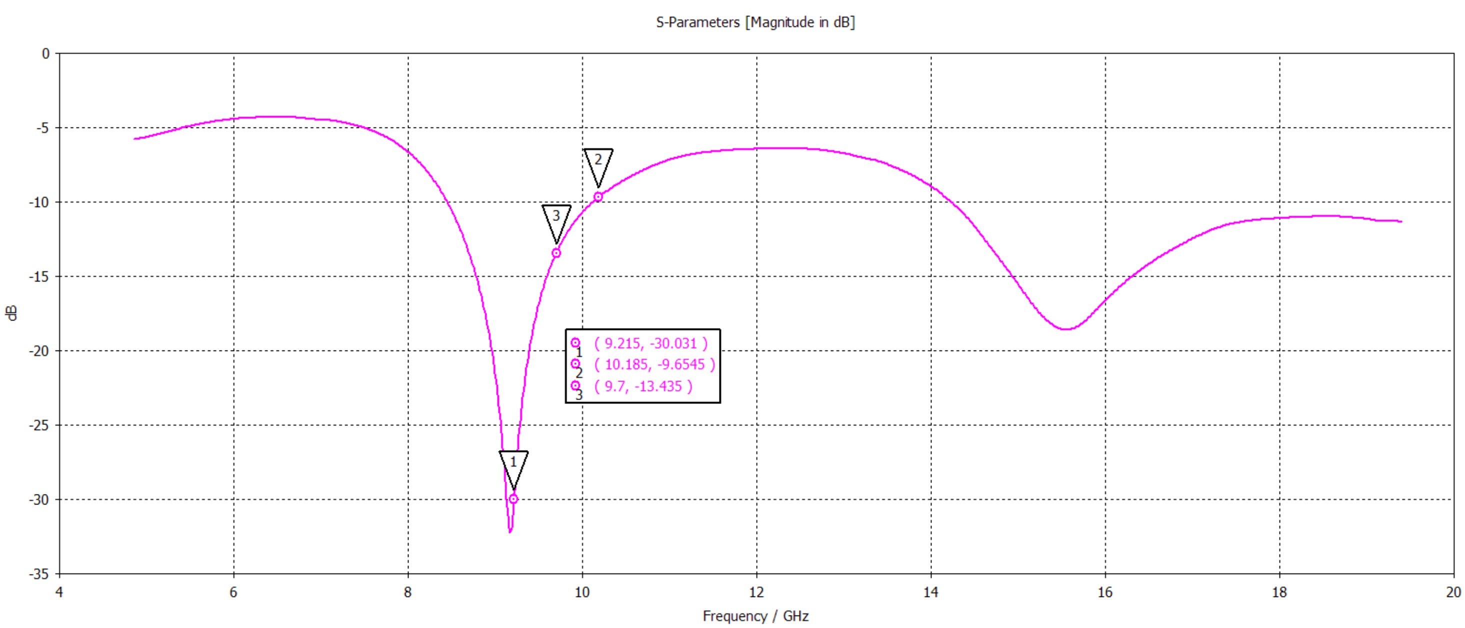
k. Present again the input matching over the bandwidth 0.5f-2f, now when the monopoles are fed with a linear phase(modify the phase of each port). Use markers on the plot in order to demonstrate the achieved design goals. What is the reason for the difference between this matching performance and the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

I fed the monopoles with the same linear phase I used for steering: -112°.

<u>Input matching of all 3 monopoles:</u>

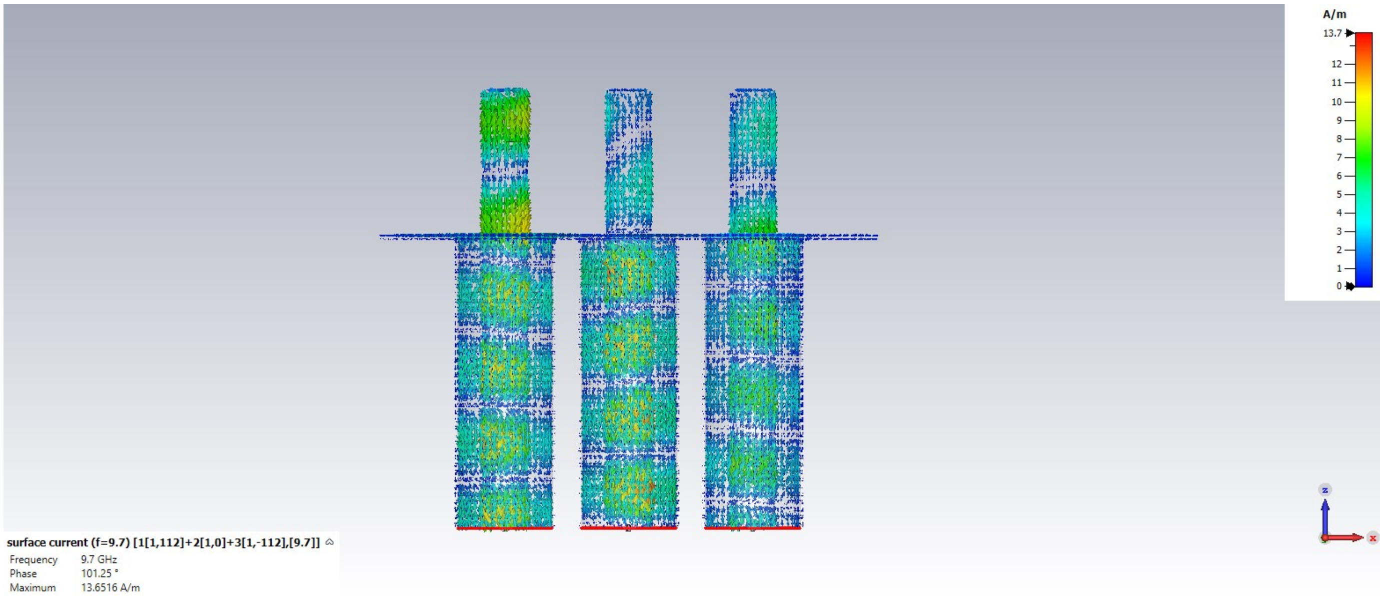


We can see that the input matching got better for all ports. Let us specifically examine the central monopole:



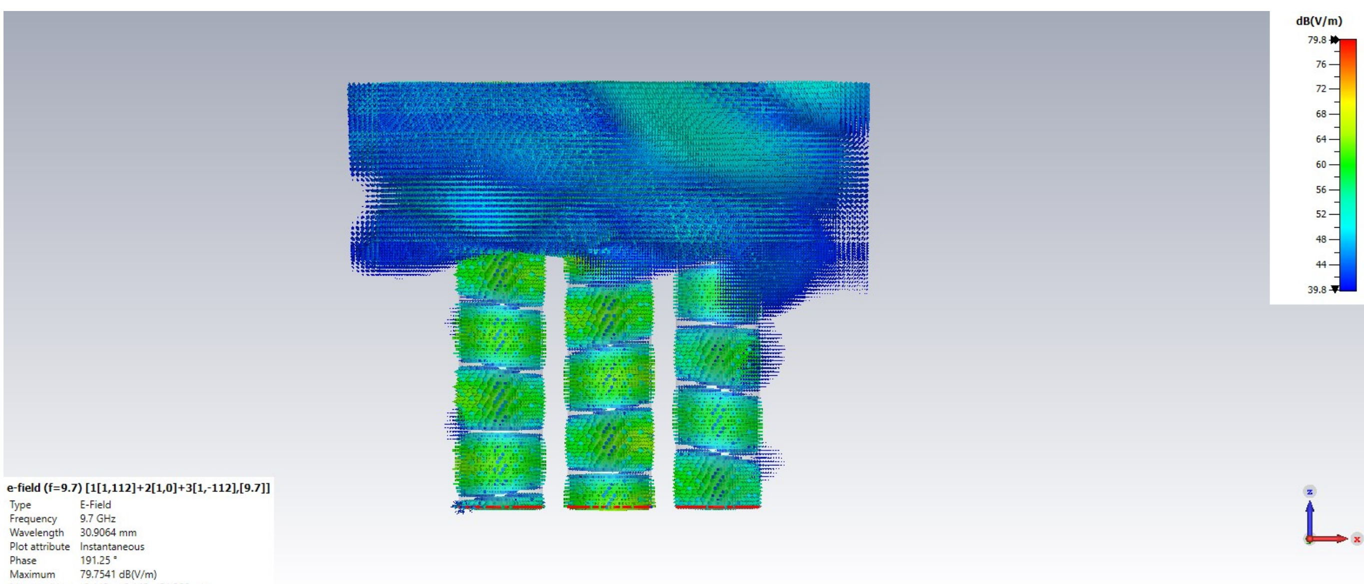
Markers #1,2 are placed at 0.95f-1.05f. We can see a clear improvement over the no-phase case – as we are now below -10dB for the vast majority of the interval. Marker #3 is placed at 9.7GHz – the operating frequency, and input matching here is -13.435, which fits the -10dB constraint, unlike the no-phasing case.

Taking a look at the surface currents:



It can be seen that there are no more red flares on the central monopole, which confirms that phasing the elements decreased the induction of backward propagating waves in the central monopole. This means that the reflection coefficient improves, which in turn improves the input matching. When looking at the surface currents in animation, I can see that the “high current” pulses are staggered, instead of propagating through all three monopoles at once.

Looking at the electric field:



The field is very “ripply”, but there is no longer a large pulse traveling down the central monopole – thus no backward propagating wave (or at least less of it), which improves Γ, and thus our input matching. This is the reason why we got a better matching result for a phased array.