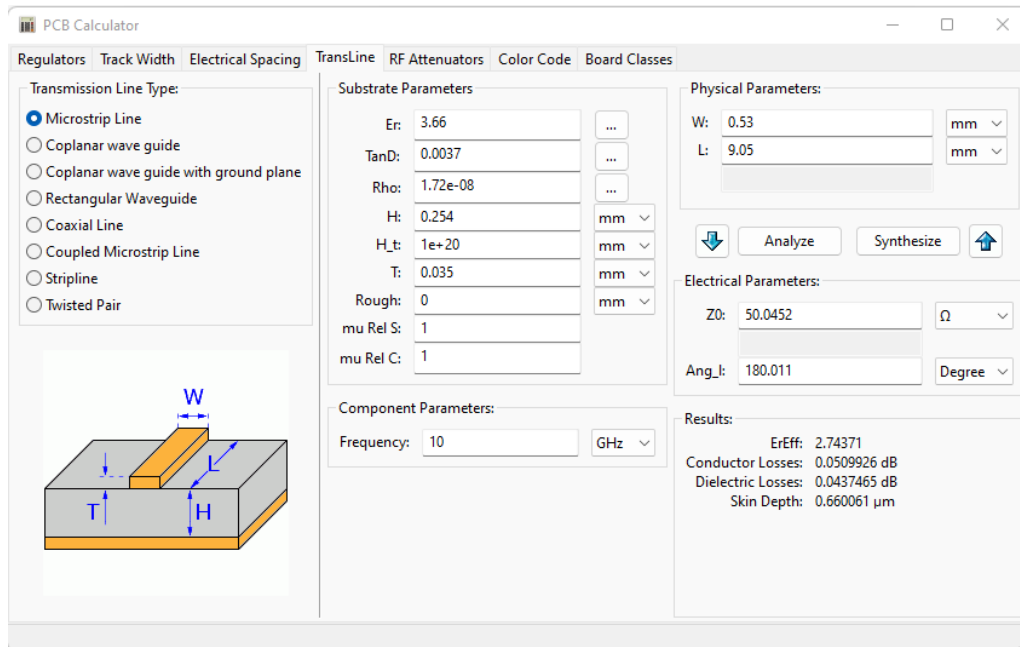


# Phased array patch antenna @10GHz

Objective: “Design a 1D patch phased array of **10 elements** with corporate feeding network for broadside radiation, target **return loss is -10 dB**. **Calculate the radiation pattern analytically and numerically** and compare them. If you want you can select the operating frequency yourself, otherwise use **10 GHz**.”

# Stack-up

- Find an industrialized stack-up so that the design can be fabricated.
- 4-layer stack-up allows having thin substrate, hence thin feeding microstrip line.
- RO4350B chosen for lower dielectric loss



PCB Calculator

Regulators Track Width Electrical Spacing TransLine RF Attenuators Color Code Board Classes

Transmission Line Type:

- ☒ Microstrip Line
- ☐ Coplanar wave guide
- ☐ Coplanar wave guide with ground plane
- ☐ Rectangular Waveguide
- ☐ Coaxial Line
- ☐ Coupled Microstrip Line
- ☐ Stripline
- ☐ Twisted Pair

Substrate Parameters:

Er: 3.66

TanD: 0.0037

Rho: 1.72e-08

H: 0.254 mm

H<sub>t</sub>: 1e+20 mm

T: 0.035 mm

Rough: 0 mm

mu Rel S: 1

mu Rel C: 1

Physical Parameters:

W: 0.53 mm

L: 9.05 mm

Electrical Parameters:

Z0: 50.0452 Ω

Ang\_L: 180.011 Degree

Component Parameters:

Frequency: 10 GHz

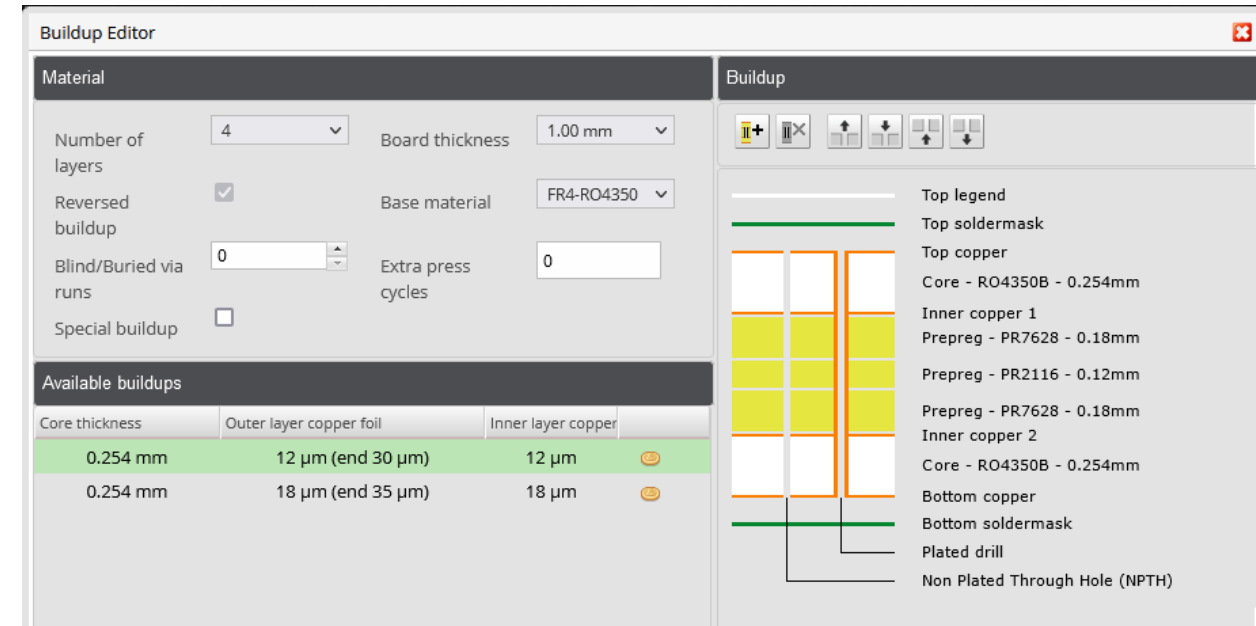
Results:

ErEff: 2.74371

Conductor Losses: 0.0509926 dB

Dielectric Losses: 0.0437465 dB

Skin Depth: 0.660061 μm



Buildup Editor

Material

Number of layers: 4

Board thickness: 1.00 mm

Reversed buildup: ☒

Base material: FR4-RO4350

Blind/Buried via runs: 0

Extra press cycles: 0

Special buildup: ☐

Available builds

Core thickness	Outer layer copper foil	Inner layer copper
0.254 mm	12 μm (end 30 μm)	12 μm
0.254 mm	18 μm (end 35 μm)	18 μm

Buildup

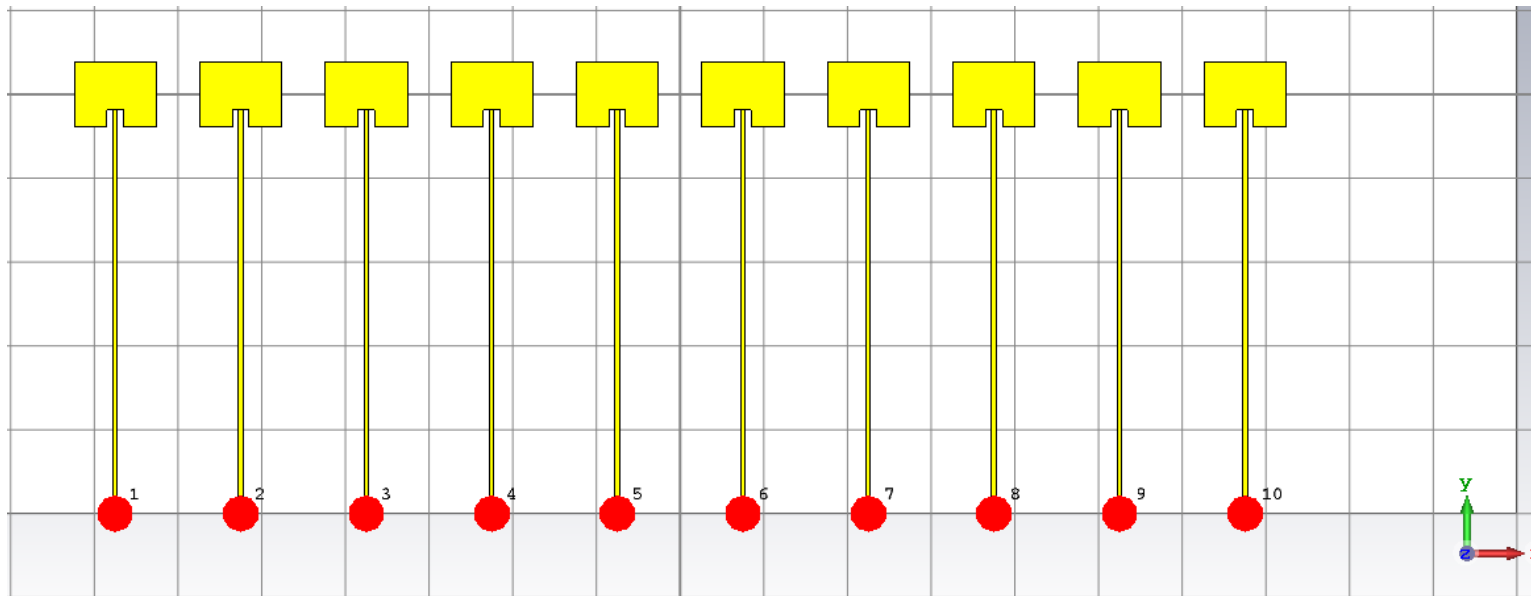
Top legend

- Top soldermask
- Top copper
- Core - RO4350B - 0.254mm
- Inner copper 1
- Prepreg - PR7628 - 0.18mm
- Prepreg - PR2116 - 0.12mm
- Prepreg - PR7628 - 0.18mm
- Inner copper 2
- Core - RO4350B - 0.254mm
- Bottom copper
- Bottom soldermask
- Plated drill
- Non Plated Through Hole (NPTH)

Property	Typical Value		Direction	Units	Condition	Test Method
	RO4003C	RO4350B				
Dielectric Constant, $\epsilon_r$ , Process	3.38 ± 0.05	3.48 ± 0.05	Z	--	10 GHz/23°C	IPC-TM-650 2.5.5.5 Clamped Stripline
<sup>(4)</sup> Dielectric Constant, $\epsilon_r$ , Design	3.55	3.66	Z	--	8 to 40 GHz	Differential Phase Length Method
Dissipation Factor tan, $\delta$	0.0027 0.0021	0.0037 0.0031	Z	--	10 GHz/23°C 2.5 GHz/23°C	IPC-TM-650 2.5.5.5
Thermal Coefficient of $\epsilon_r$	+40	+50	Z	ppm/°C	-50°C to 150°C	IPC-TM-650 2.5.5.5

# Intended design

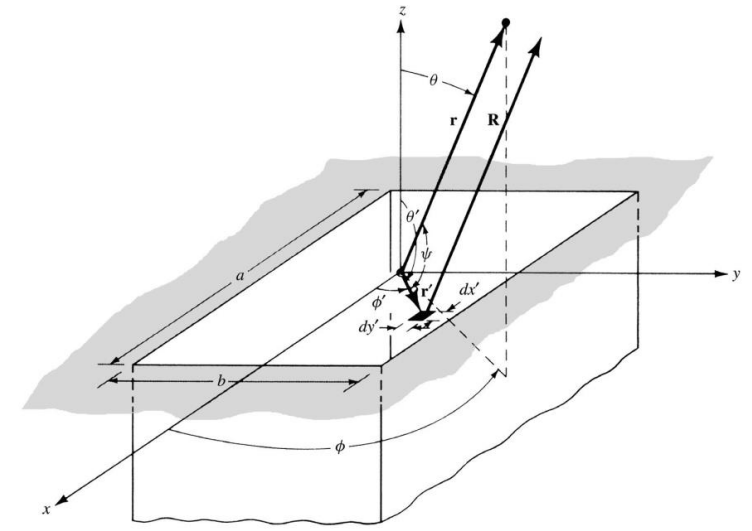
- The patch array antenna is designed as follow:
  - Broadside direction toward +Z
  - Feeding comes from  $-Y$  toward +Y
  - Array's elements placed 1D along X and have distance  $\frac{\lambda_0}{2}$



Analytical estimation of 1x10 patch array

# Analytical analysis of the array

- Cavity model of the element patch antenna
- $TM_{010}$  as dominant mode
- The following is MATLAB calculation from Balanis for the intended design (chapter 14)



## INPUT PARAMETERS

=====

RESONANT FREQUENCY (in GHz) = 10.0000

DIELECTRIC CONSTANT OF THE SUBSTRATE = 3.6600

HEIGHT OF THE SUBSTRATE (in cm) = 0.0254

POSITION OF THE RECESSED FEED POINT (in cm) = 0.2000

## OUTPUT PARAMETERS

=====

PHYSICAL WIDTH OF PATCH (in cm) = 0.9827

EFFECTIVE LENGTH OF PATCH (in cm) = 0.8027

PHYSICAL LENGTH OF PATCH (in cm) = 0.7785

E-PLANE HPBW (in degrees) = **136.0000**

H-PLANE HPBW (in degrees) = **80.0000**

DIRECTIVITY OF RECTANGULAR PATCH (dimensionless) = 4.2200

DIRECTIVITY OF RECTANGULAR PATCH (in dB) = **6.2531**

RESONANT INPUT RESISTANCE AT LEADING RADIATING EDGE ( $y=0$ )  $R_{in0}$  = 293.4669 ohms

RESONANT INPUT RESISTANCE AT RECESSED FEED POINT ( $y=0.2000$  cm)  $R_{INy0}$  = 140.3699 ohms

\*\*\* NOTE:

THE E-PLANE AMPLITUDE PATTERN IS STORED IN Epl-Micr\_m.dat

THE H-PLANE AMPLITUDE PATTERN IS STORED IN Hpl-Micr\_m.dat

=====

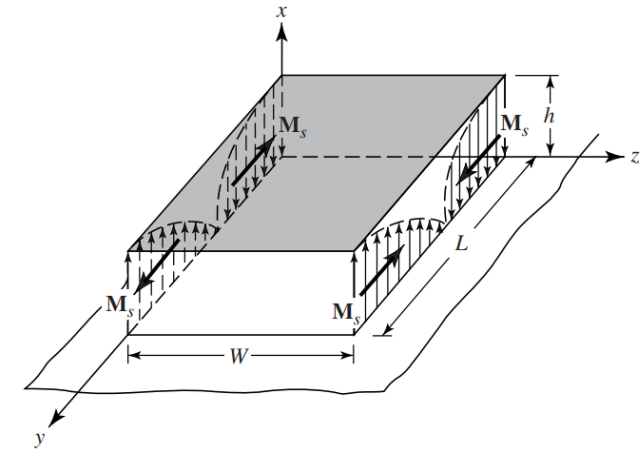
# Analytical analysis of the array

- Analytical pattern calculated by Balanis for X-direction broadside
- E-plane ( $\theta = 90^\circ$ )

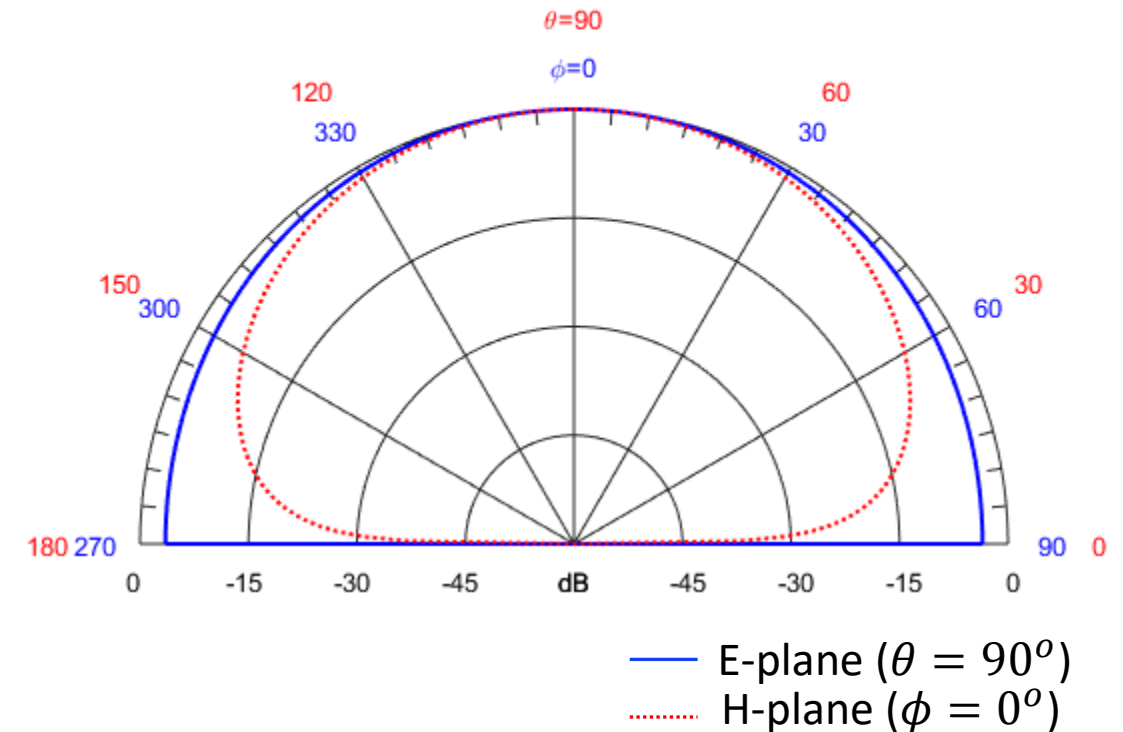
$$E_\phi^t = +j \frac{k_0 W V_0 e^{-jk_0 r}}{\pi r} \left\{ \frac{\sin \left( \frac{k_0 h}{2} \cos \phi \right)}{\frac{k_0 h}{2} \cos \phi} \right\} \cos \left( \frac{k_0 L_e}{2} \sin \phi \right)$$

- H-plane ( $\phi = 0^\circ$ )

$$E_\phi^t \simeq +j \frac{k_0 W V_0 e^{-jk_0 r}}{\pi r} \left\{ \sin \theta \frac{\sin \left( \frac{k_0 h}{2} \sin \theta \right)}{\frac{k_0 h}{2} \sin \theta} \frac{\sin \left( \frac{k_0 W}{2} \cos \theta \right)}{\frac{k_0 W}{2} \cos \theta} \right\}$$

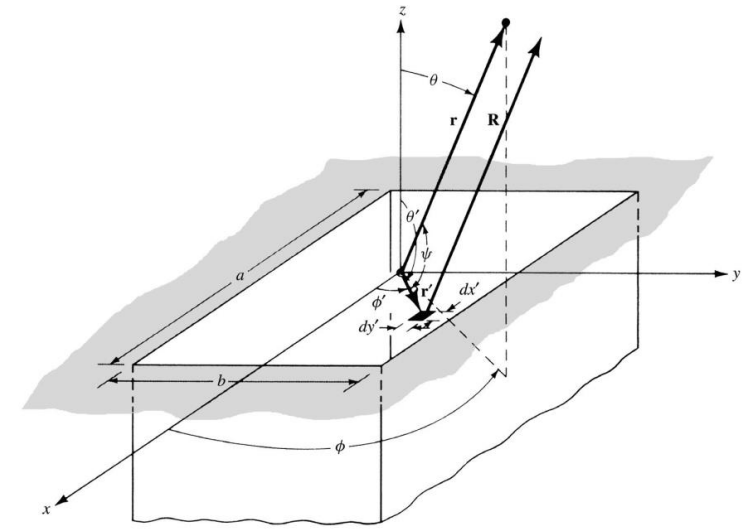


E- and H-plane Patterns of Rectangular Microstrip Antenna

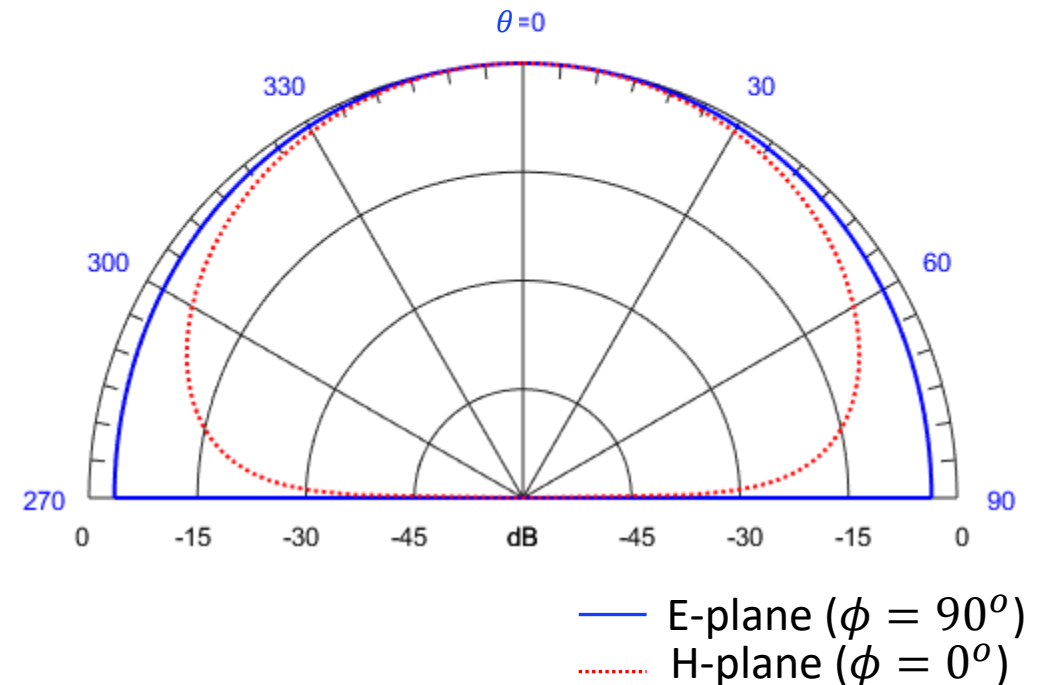


# Analytical analysis of the array

- The symmetry of the antenna allows us to have now
  - E-plane ( $\theta = 90^\circ$ )
  - H-plane ( $\theta = 0^\circ$ )
- Rotating  $90^\circ$  along Y-axis to achieve the intended +Z broadside patch antenna.



E- and H-plane Patterns of Rectangular Microstrip Antenna



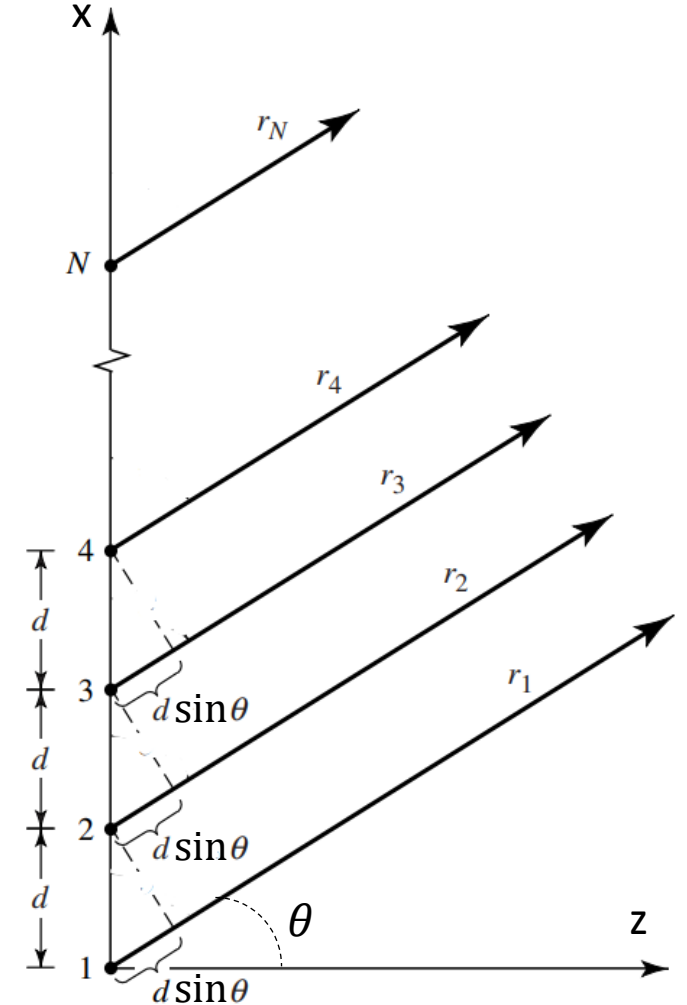
# Analytical analysis of the array

- Array factor of the  $1 \times 10$  patch array along X axis
- Broadside direction is along +Z
- $AF = \frac{1}{N} \left( 1 + e^{j(kd \sin \theta + \beta)} + \dots + e^{+j2(kd \sin \theta + \beta)} + e^{+j9(kd \sin \theta + \beta)} \right) = \frac{1}{N} \left[ \frac{\sin\left(\frac{N}{2}(kd \sin \theta + \beta)\right)}{\sin\left(\frac{(kd \sin \theta + \beta)}{2}\right)} \right]$

with  $N = 10, d = 15\text{mm}, k = \frac{2\pi}{\lambda}$ , and  $\beta$  is phase difference between neighbor elements.

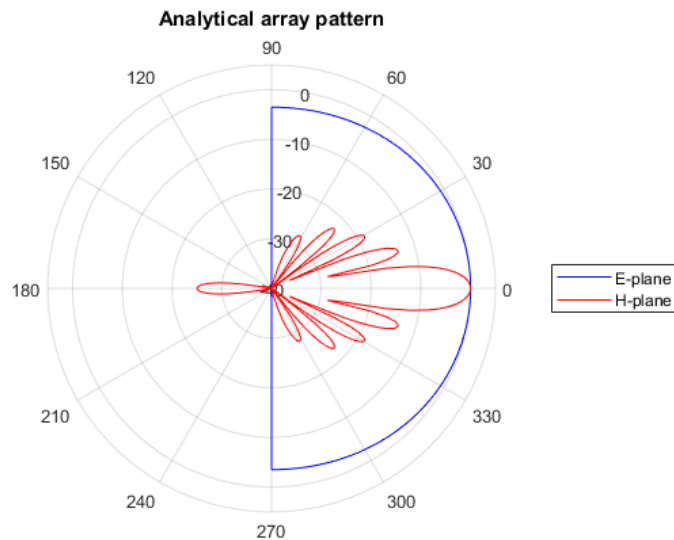
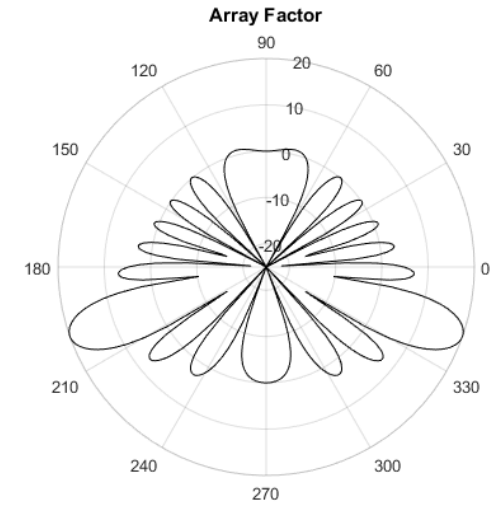
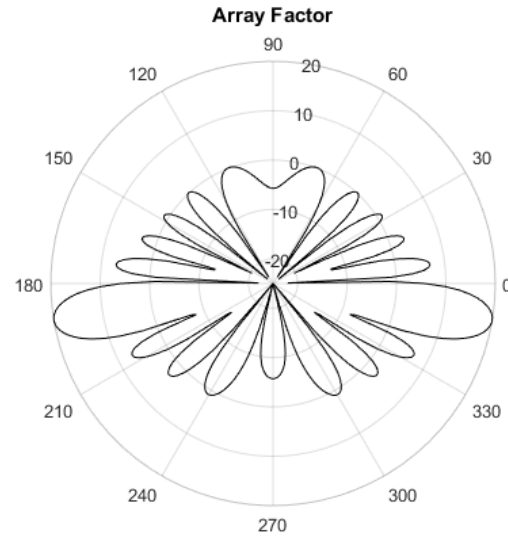
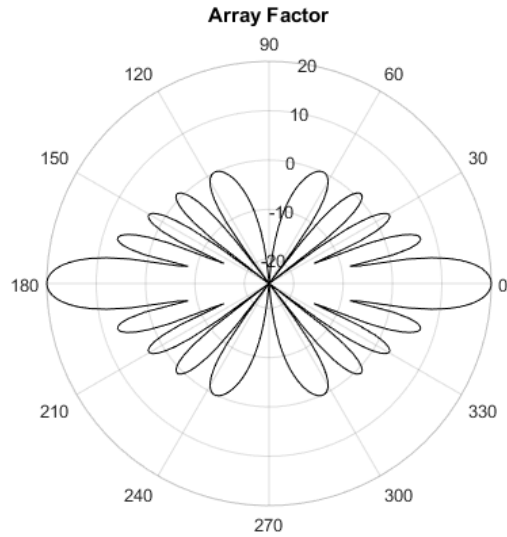
- So

$$E_{\phi\_arr} = AF \times E_{\phi}$$

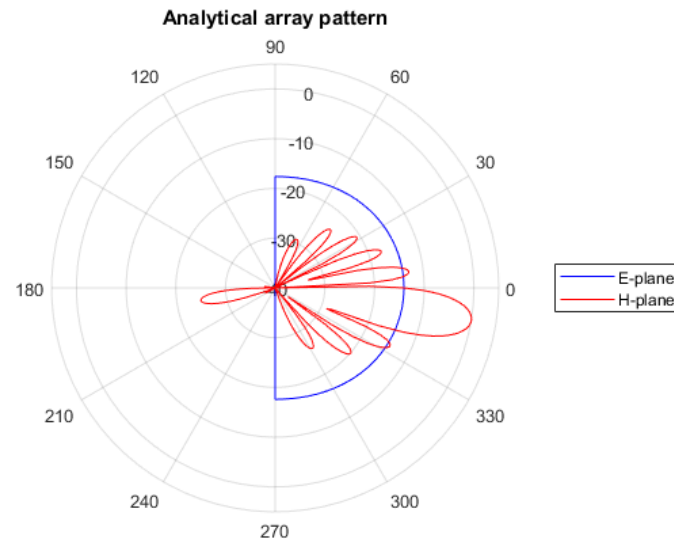




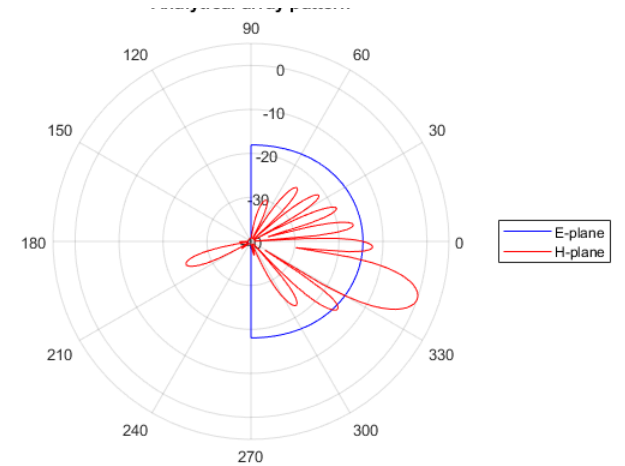
# Analytical analysis of the array



$$\beta = 0^\circ$$



$$\beta = 30^\circ$$




$$\beta = 60^\circ$$

Numerical estimation of  $1 \times 10$  patch array

# Patch array design

- Using online tool to calculate patch dimension.


ALL PRODUCTS
THE CABLE CREATOR™
NEW PRODUCTS
RESOURCE TOOLS
SUPPORT 24/7

Calculation

Dielectric Constant

3.66

Dielectric Height:

0.254

Millimeters

Operation Frequency:

10

GHz

CALCULATE

Result:

Width: 9.820 mm

Length: 7.780 mm

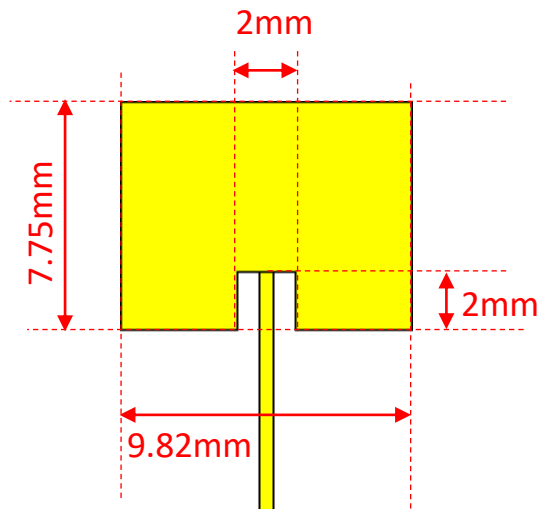
Coaxial Cable Impedance Calculator  
CRA Calculator  
EIRP Calculator  
Free Space Path Loss Calculator  
Friis Transmission Calculator  
IRA Calculator  
Link Budget Calculator  
Microstrip Calculator  
[Microstrip Patch Antenna Calculator](#)  
Noise Figure - Noise Temperature Calculator  
N-Way Power Divider Calculator  
Pi Attenuator Calculator  
Power Added Efficiency Calculator  
Power Density Calculator  
Reflection Attenuator Calculator  
RF Power Conversion Calculator  
Radar Maximum Range Calculator  
RF Power Ratio Conversion Calculator  
Skin Depth Calculator  
Stripline Impedance Calculator  
Tank Circuit Resonance Calculator  
Tee Attenuator Calculator  
Temperature Converter  
Torque Conversion Calculator  
Unit Conversion Calculator  
VSWR / Return Loss Calculator  
Waveguide Calculator (Circular)  
Waveguide Calculator (Rectangular)  
Wavelength (TEM) Calculator

$$Width = \frac{c}{2f_0\sqrt{\frac{\epsilon_R+1}{2}}}; \quad \epsilon_{eff} = \frac{\epsilon_R+1}{2} + \frac{\epsilon_R-1}{2} \left[ \frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}} \right]$$

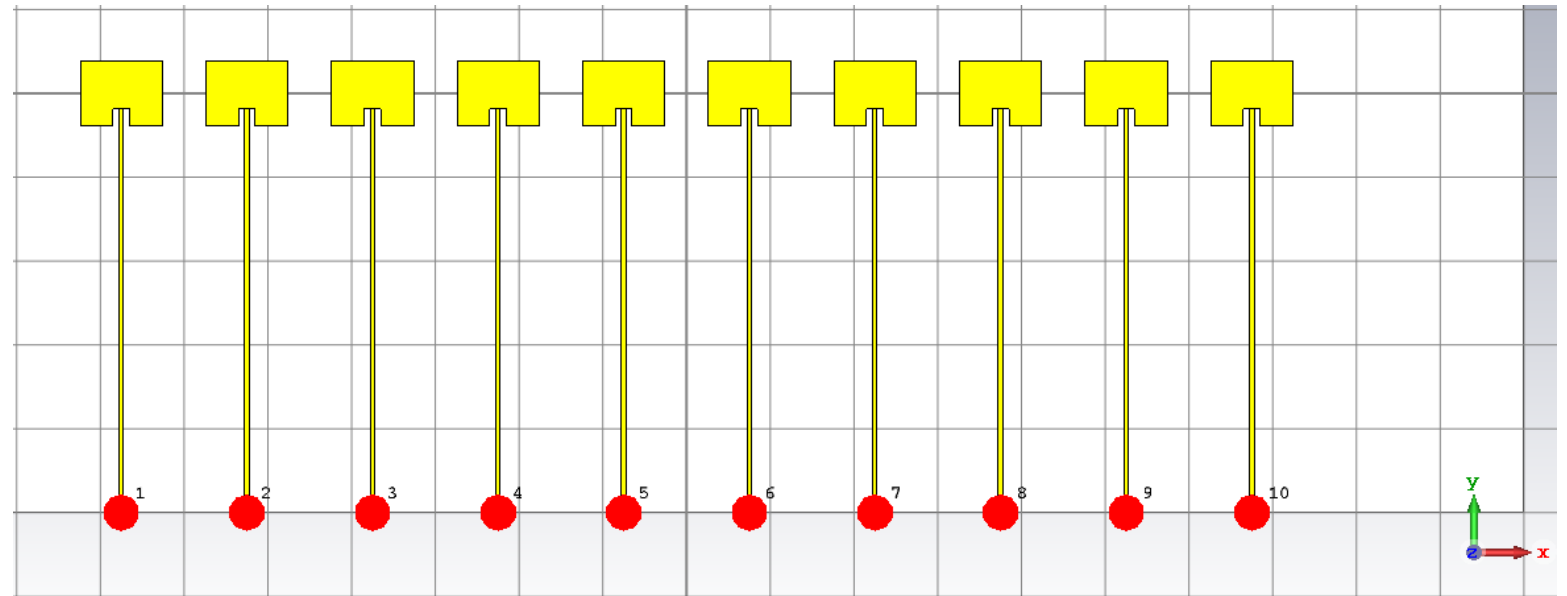
$$Length = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} - 0.824h \left( \frac{(\epsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\epsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \right)$$

# Numerical simulation CST

- Recessed microstrip-line feed point to have a better impedance matching
- Making array with distance  $\lambda_{air}/2 = 15\text{mm}$  and with separate ports
- Phase excitation is controlled by simulator
- Microstrip line width is 0.53mm



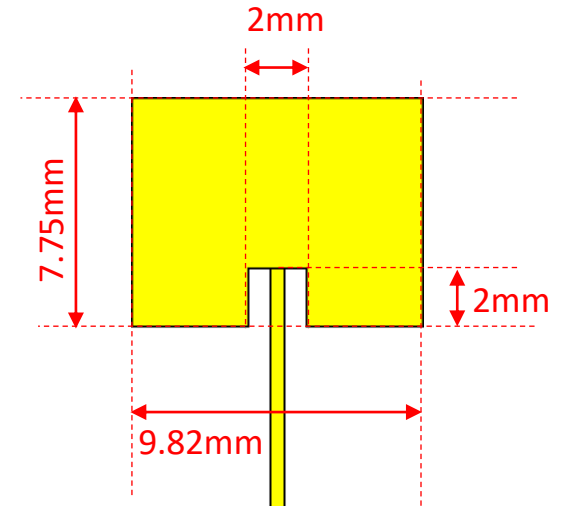
Single patch design



1x10 patch array design

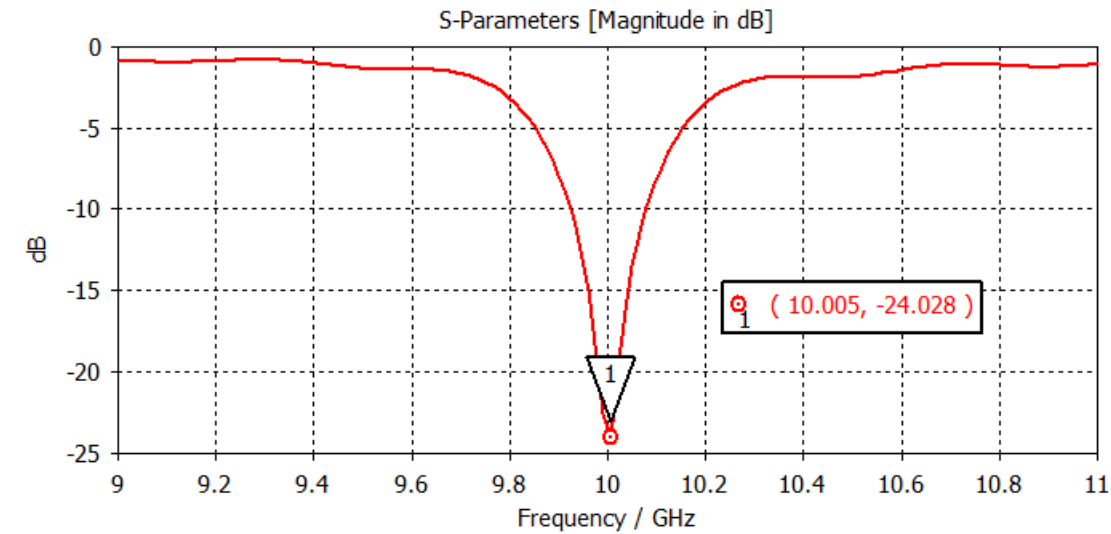
# Numerical simulation CST

- Simulation of single patch

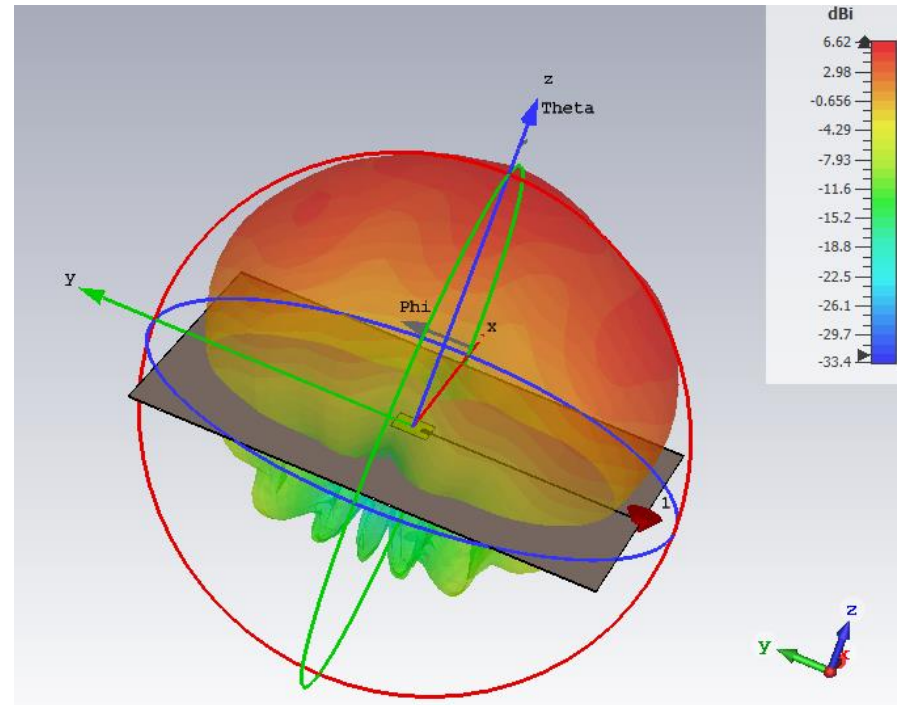


3D radiation pattern of single patch

Single patch design

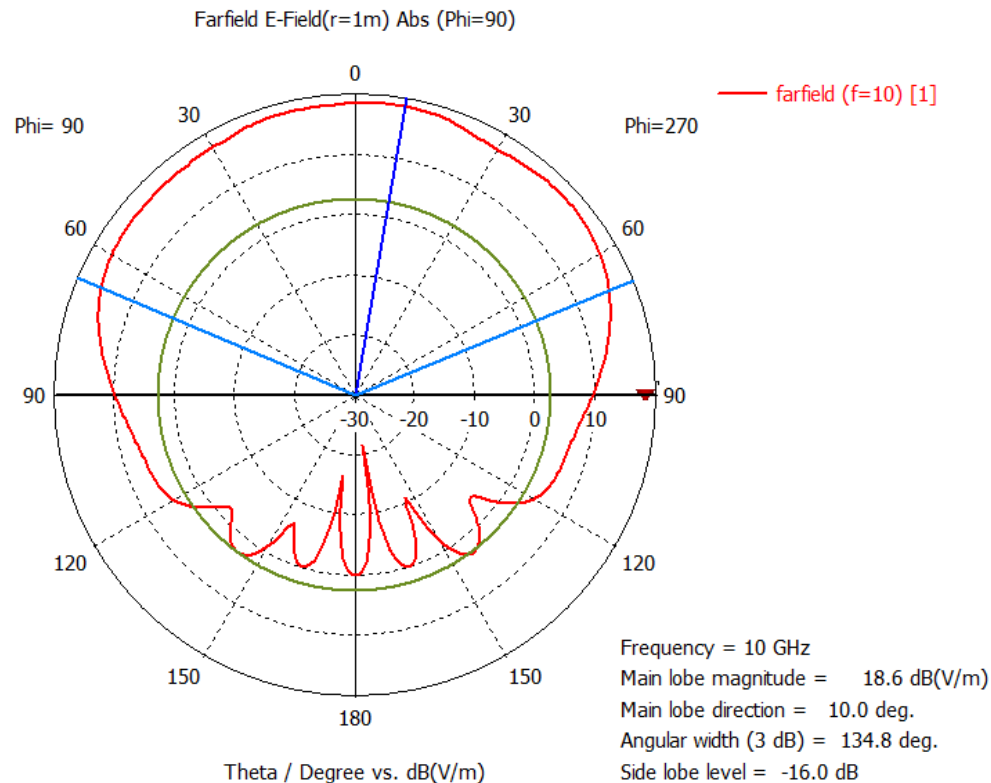
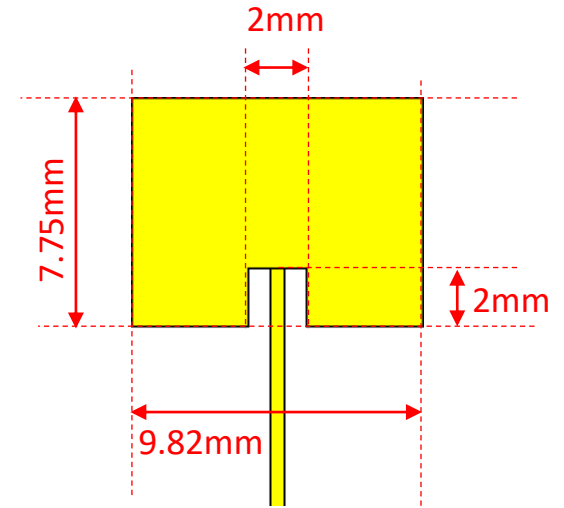


Impedance matching of single patch

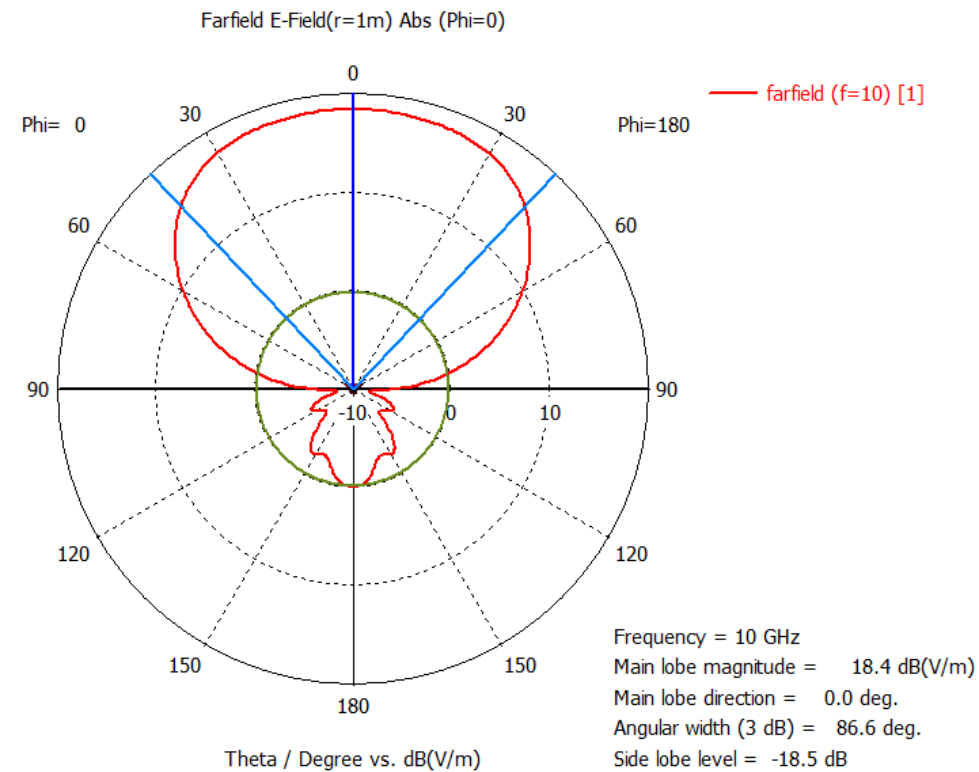


# Numerical simulation CST

- Simulation of single patch



E-plane

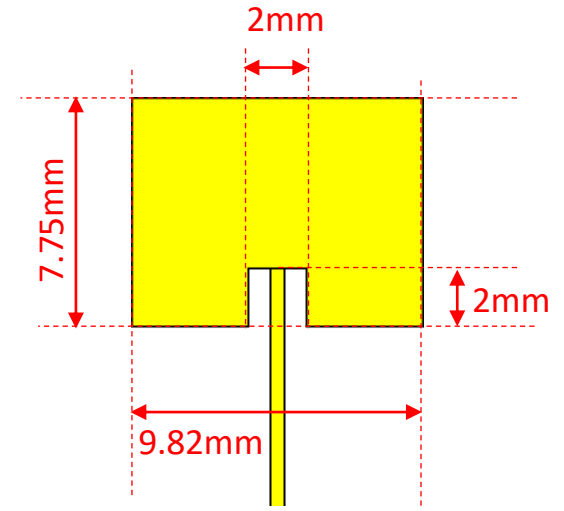


H-plane

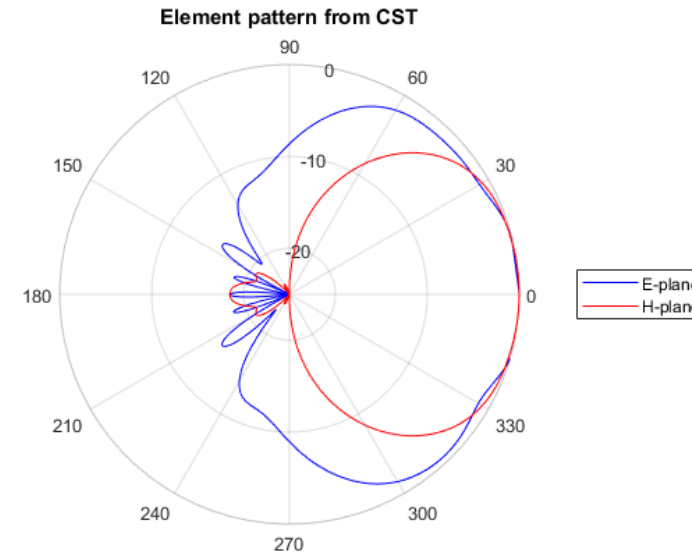
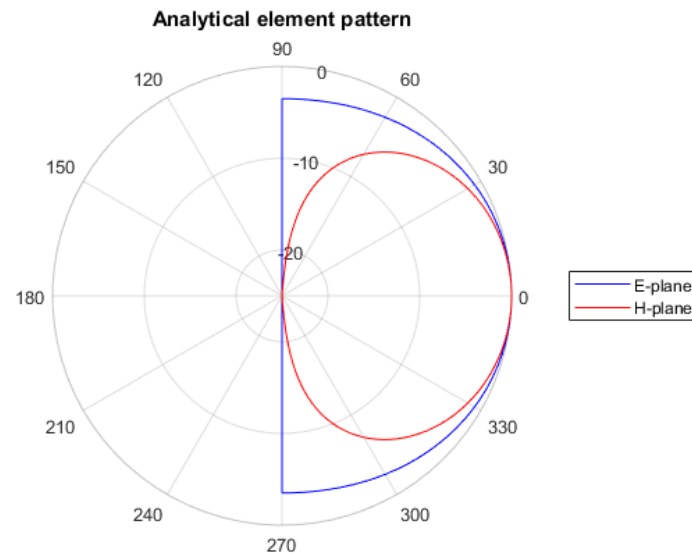
Single patch design

# Numerical simulation CST

- Simulation of single patch versus analytical results
  - Directivity = **6.62 dBi** (versus **6.25 dBi** of analytical result)
  - E-plane HPBW = **134.8°** (versus **136°** of analytical result)
  - H-plane HPBW = **86.6°** (versus **80°** of analytical result)



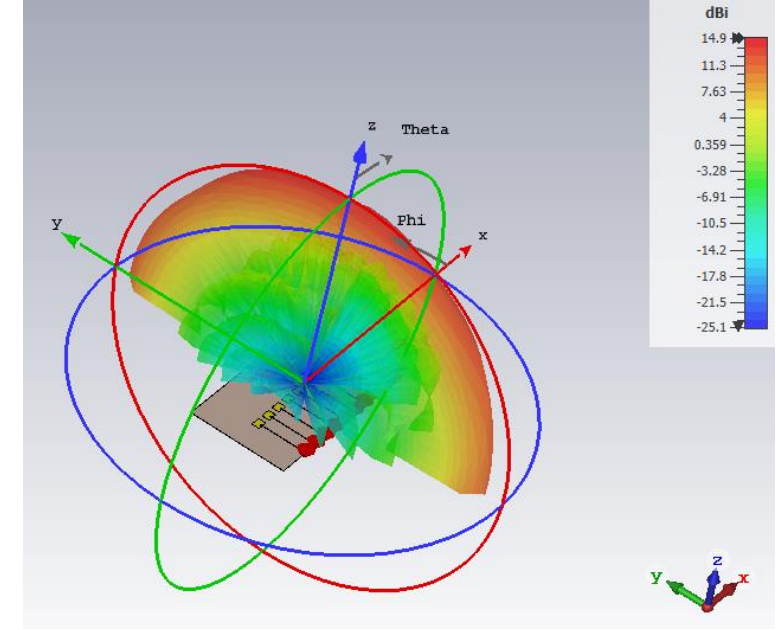
Single patch design



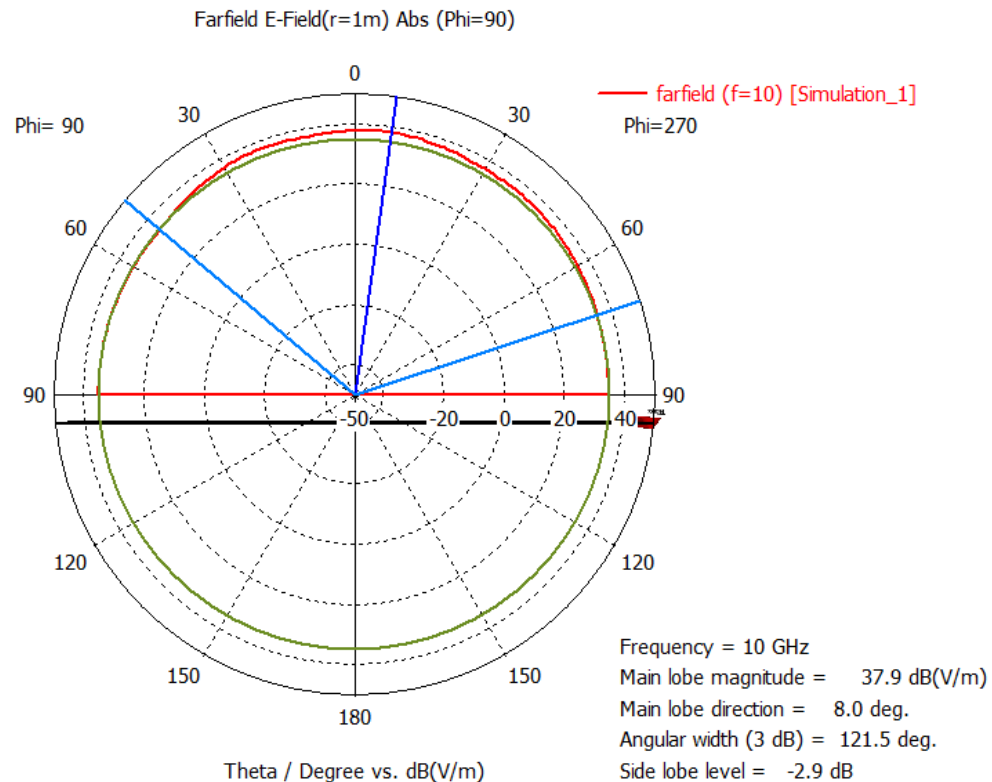
\*back radiation due to finite ground plane

# Numerical simulation CST

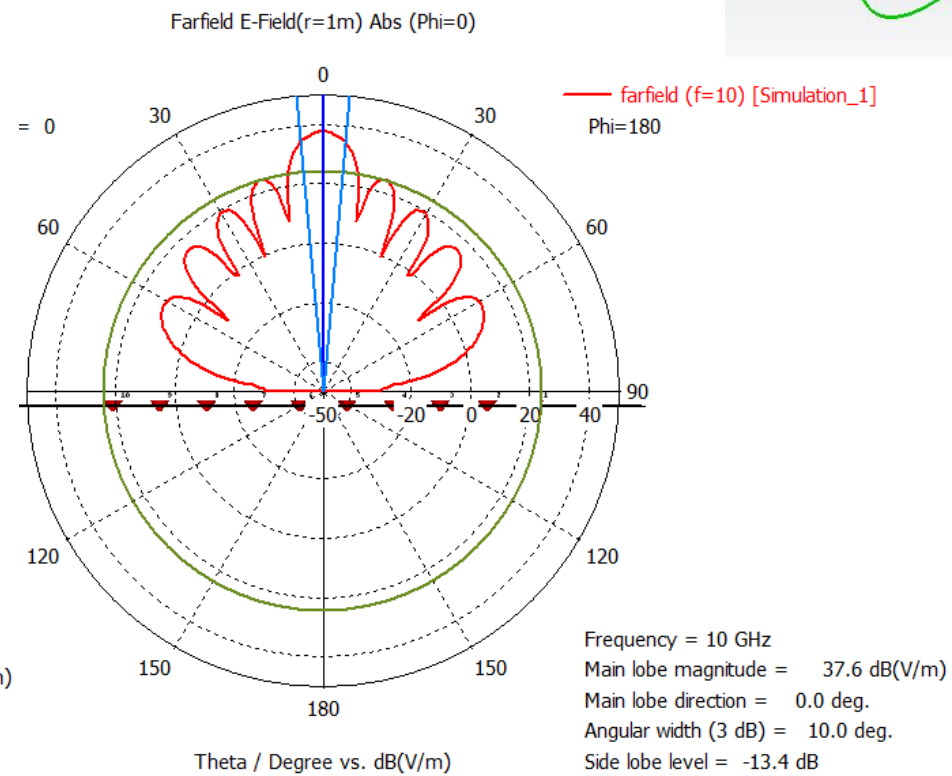
- Simulation of 1x10 patch array ( $\beta = 0^\circ$ )



Array directivity



E-plane

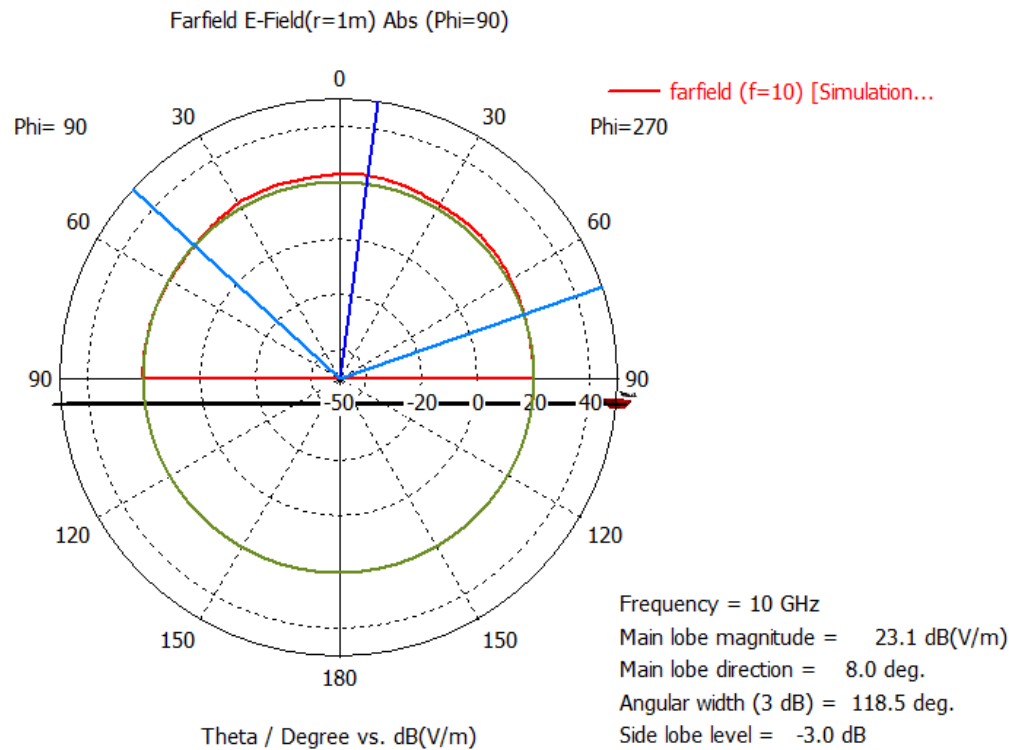
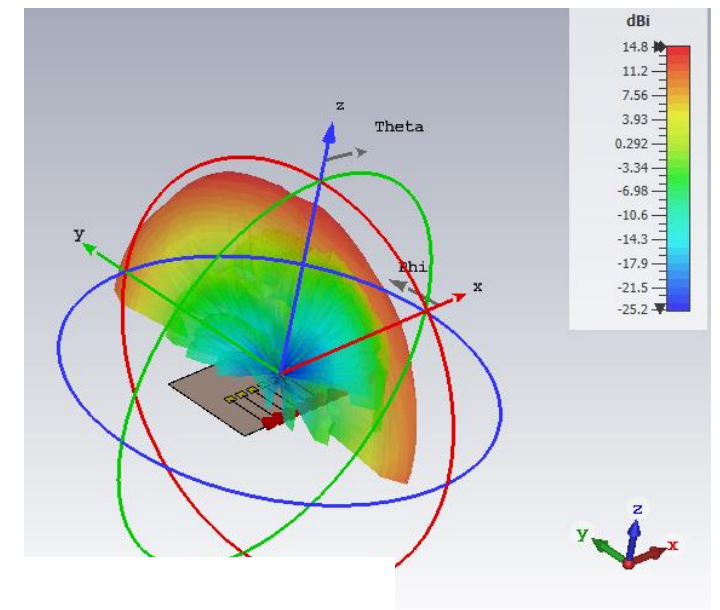


H-plane

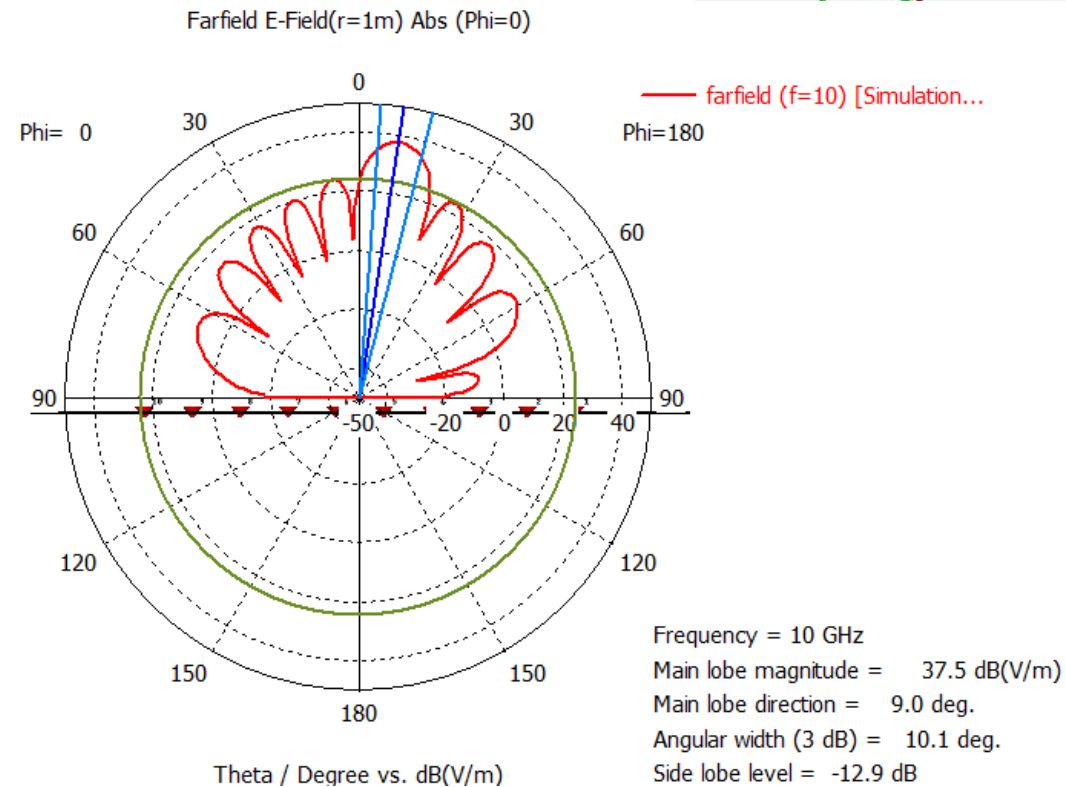


# Numerical simulation CST

- Simulation of 1x10 patch array ( $\beta = 30^\circ$ )



E-plane

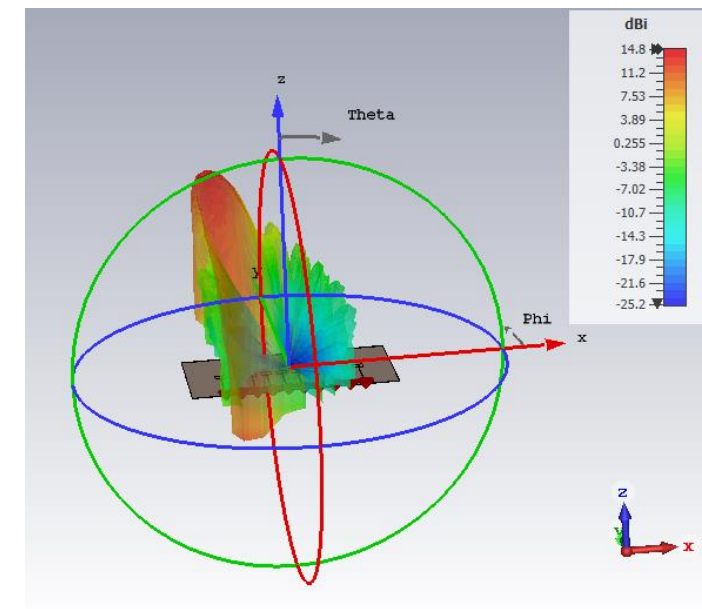


H-plane

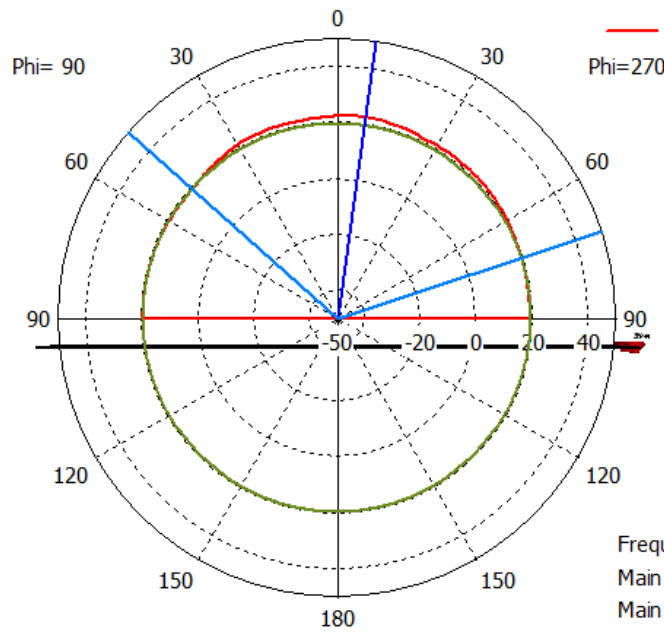
activity

# Numerical simulation CST

- Simulation of 1x10 patch array ( $\beta = 60^\circ$ )



Farfield E-Field(r=1m) Abs (Phi=90)

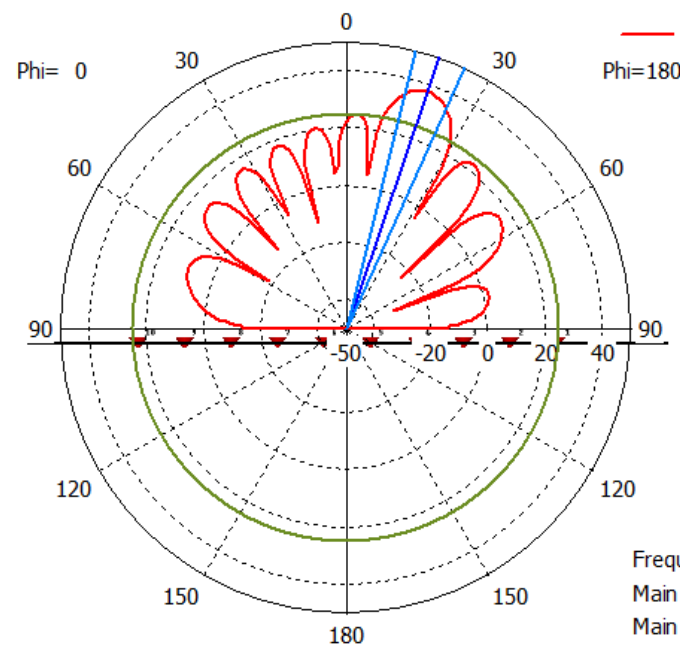


Theta / Degree vs. dB(V/m)

E-plane

Frequency = 10 GHz  
Main lobe magnitude = 22.5 dB(V/m)  
Main lobe direction = 8.0 deg.  
Angular width (3 dB) = 120.2 deg.  
Side lobe level = -3.0 dB

Farfield E-Field(r=1m) Abs (Phi=0)

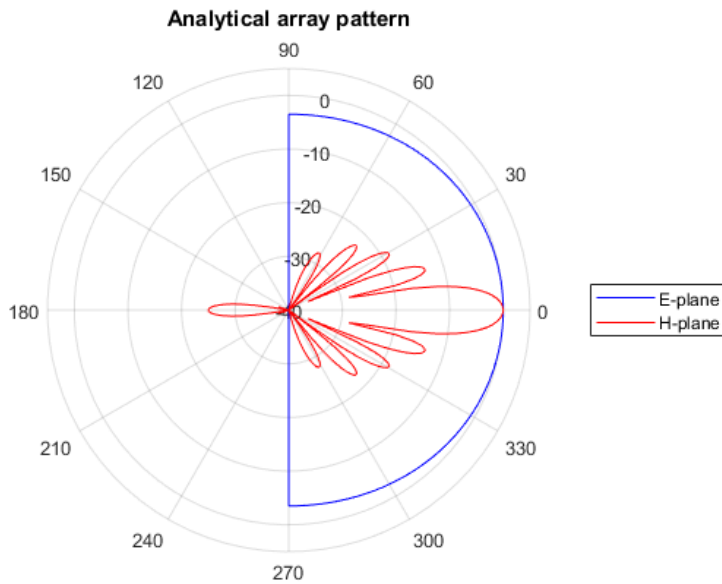


Theta / Degree vs. dB(V/m)

H-plane

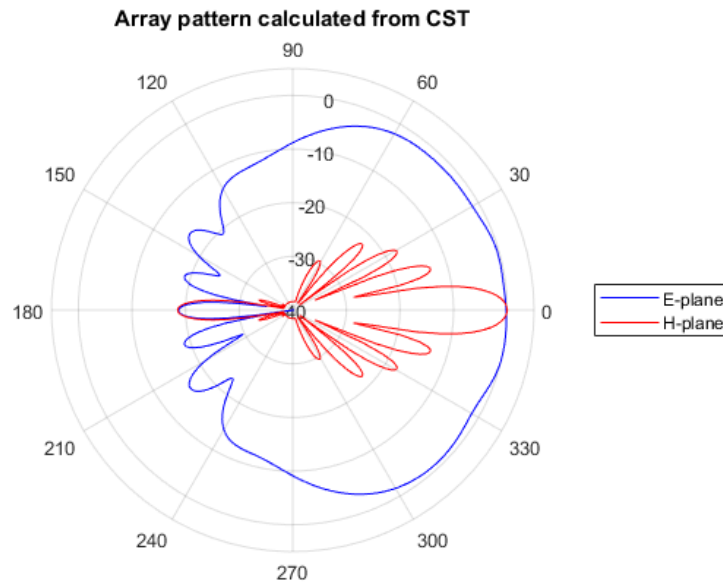
Frequency = 10 GHz  
Main lobe magnitude = 37.3 dB(V/m)  
Main lobe direction = 19.0 deg.  
Angular width (3 dB) = 10.6 deg.  
Side lobe level = -12.5 dB

# Comparison $\beta = 0^\circ$



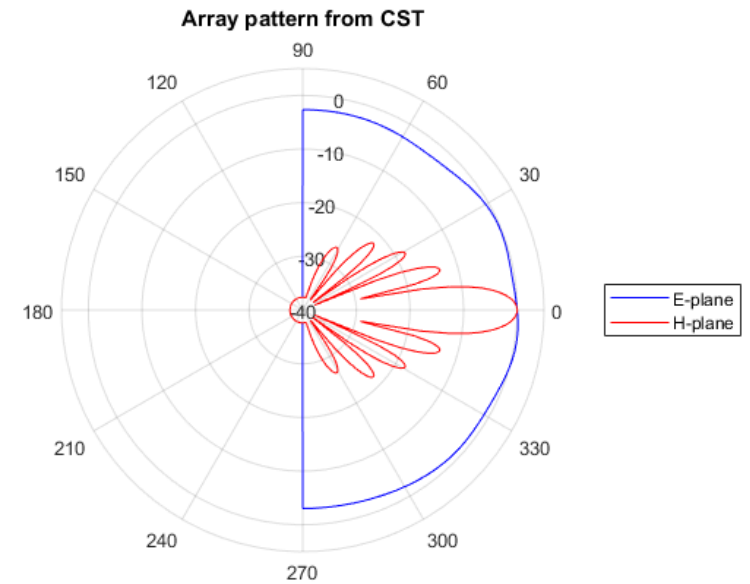
Full analytical result from MATLAB calculations of patch pattern and array factor

- Main lobe at  $0^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 16.2 dBi



Partially analytical result from numerical patch pattern and MATLAB calculation array factor

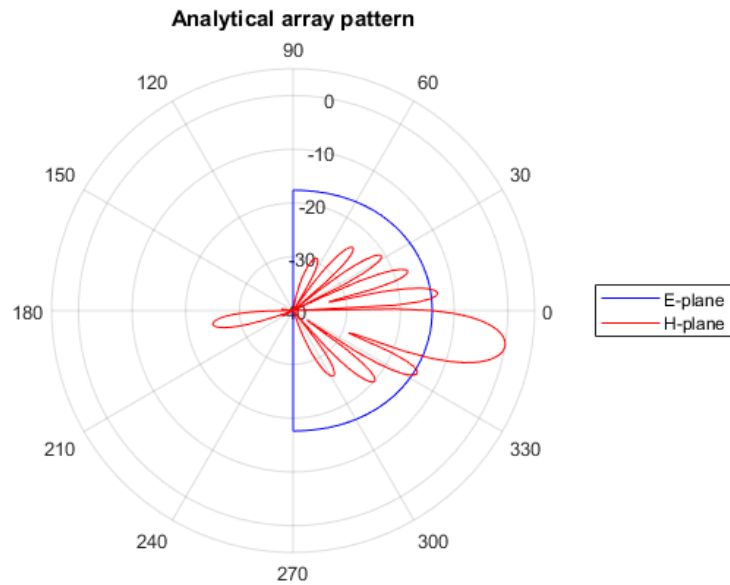
- Close to full analytical results



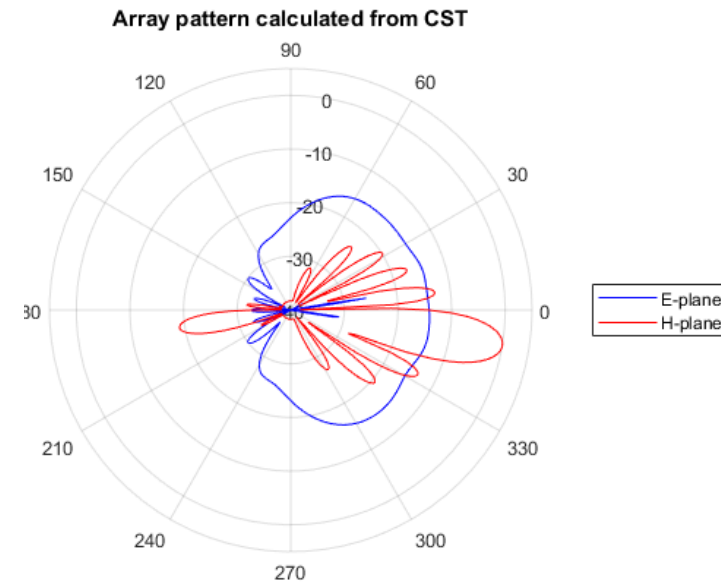
Full numerical result of the array. Electric boundary is used as ground so there is no back radiation

- Main lobe at  $0^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 14.8 dBi

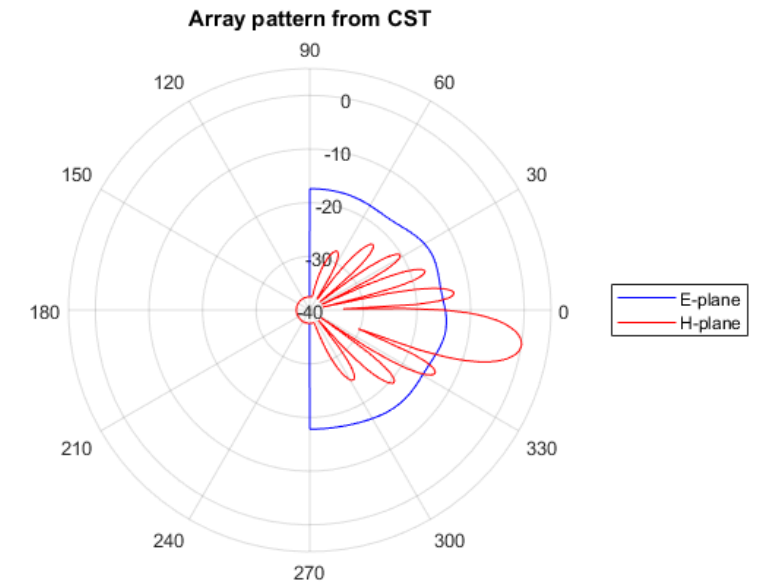
# Comparison $\beta = 30^\circ$



- Full analytical result
- Main lobe at  $10^\circ$
  - Beamwidth  $\sim 10^\circ$
  - Directivity 16.2 dBi

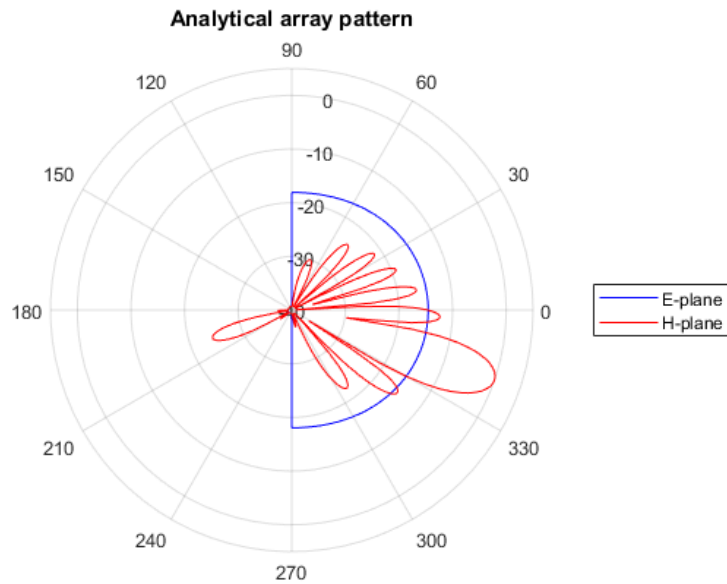


- Partially analytical result
- Close to full analytical results



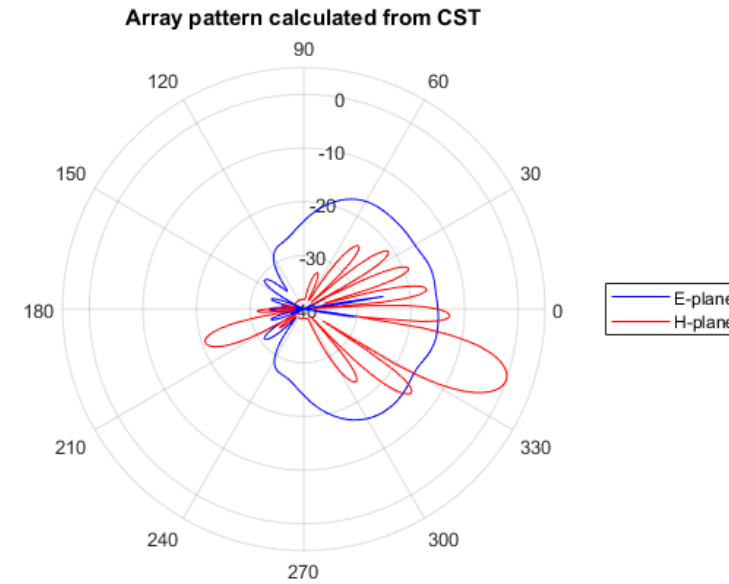
- Full numerical result
- Main lobe at  $9^\circ$
  - Beamwidth  $\sim 10^\circ$
  - Directivity 14.7 dBi

# Comparison $\beta = 60^\circ$



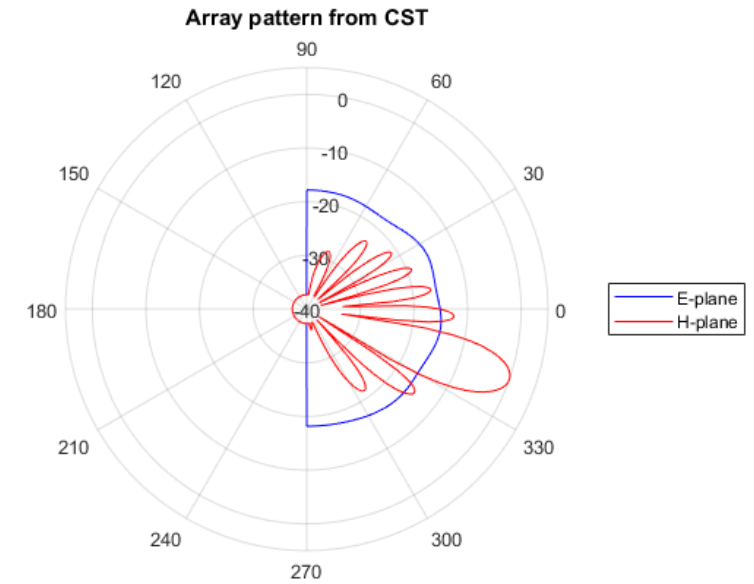
Full analytical result

- Main lobe at  $20^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 16.2 dBi



Partially analytical result

- Close to full analytical results



Full numerical result

- Main lobe at  $19^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 14.8 dBi

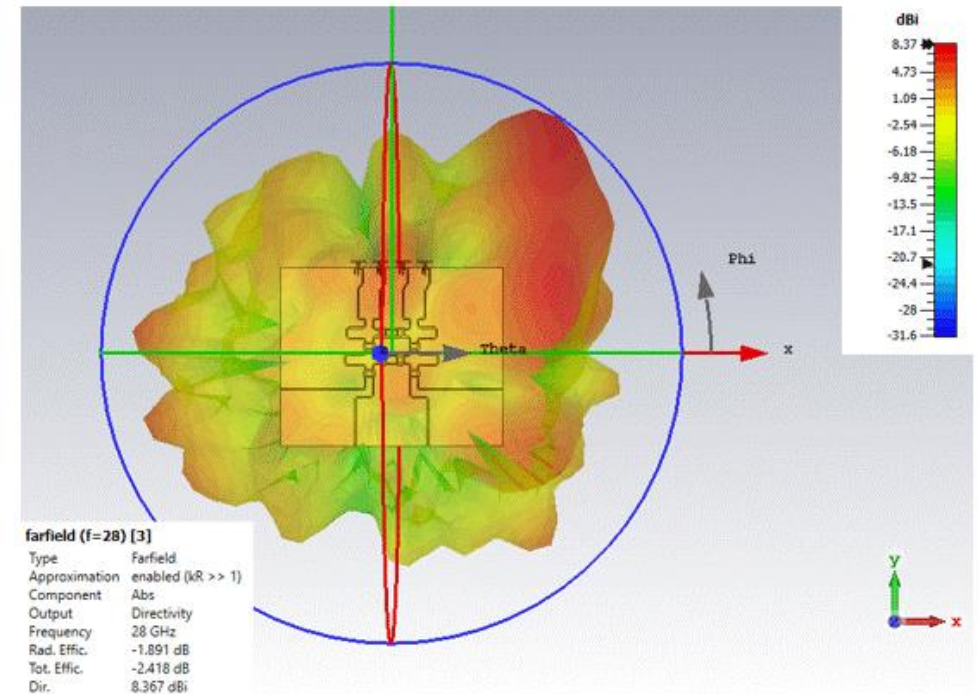
# Conclusion

- The numerical results of separating-element array are quite close to either full or partial analytical results if we ignore the back radiation (depends on ground plane side), in terms of
  - Direction of main lobe
  - Direction and number of nulls
  - Beamwidth
  - Directivity
- The asymmetry of the feed, the finite dimension of the ground in simulation can introduce some differences in the single element pattern and hence array pattern.

# Design of feeding network

# Feeding network

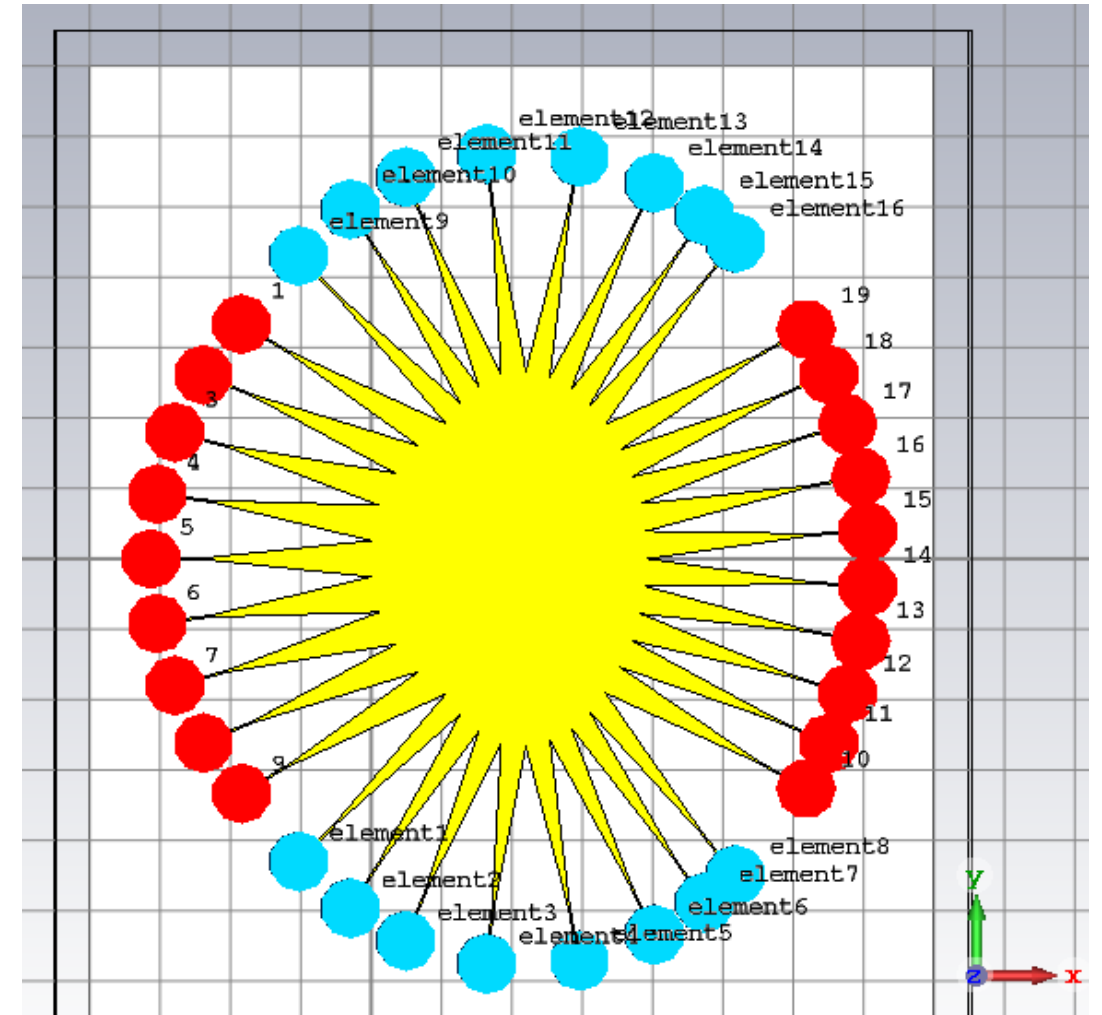
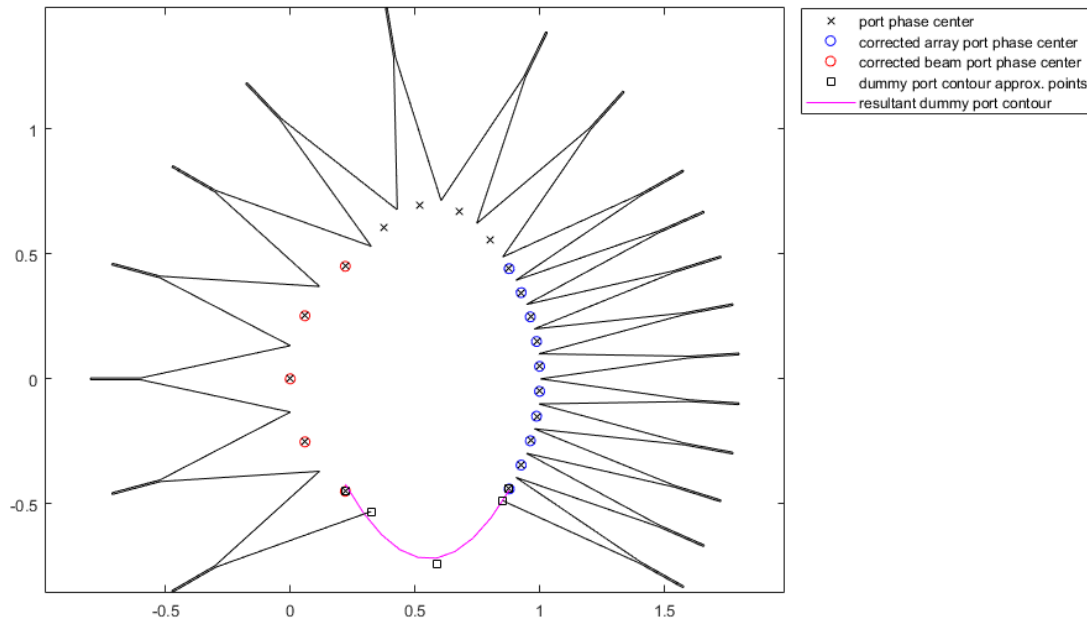
- To produce the difference in phase excitation of each element of the array we can
  - Use some active components, such as phase-shifter.
    - Normally requires complicated control.
    - Need to design a DC part that doesn't couple with RF part
  - Passive feeding network, like
    - Butler matrix, need power-two ( $2^x$ ) number of input and output
    - **Rotman lens** allows have any number of antenna port.





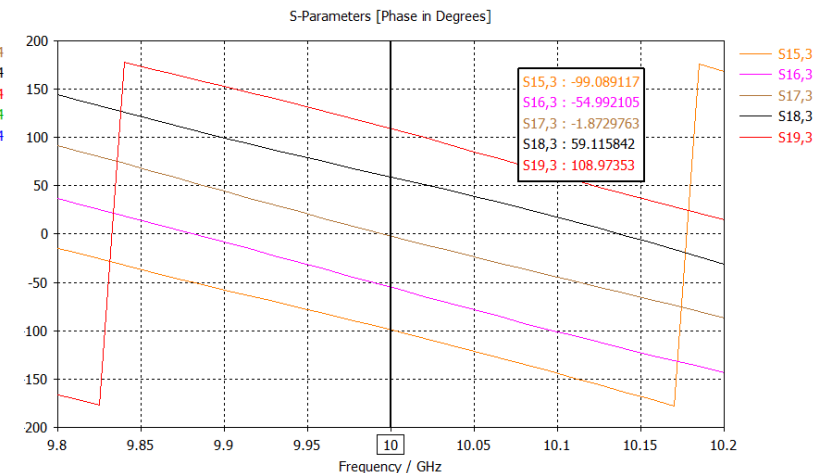
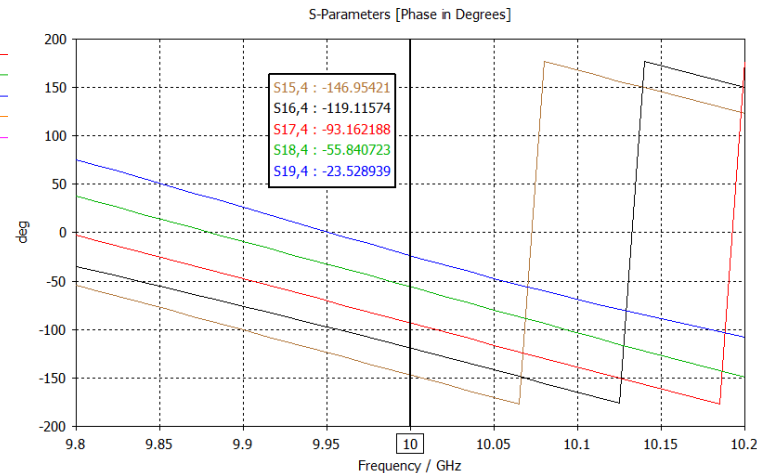
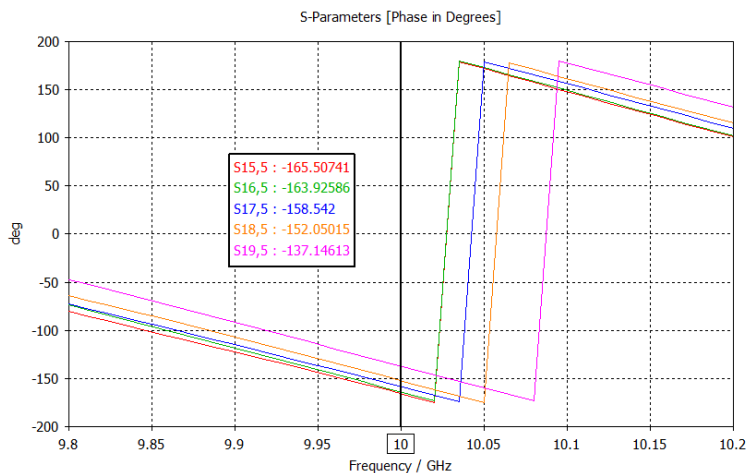
# Rotman lens for feeding network

- 10 array ports (connect to antennas)
- 9 beam ports (excitation ports)
- 8 dummy ports ( $50\Omega$  loads)
- $30^\circ$  phase shift



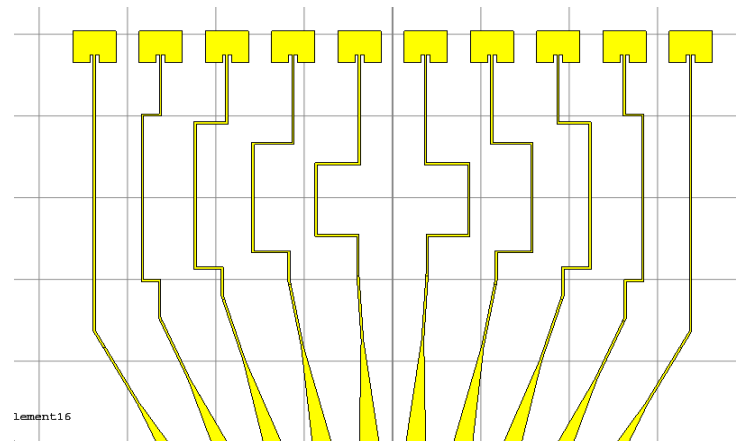
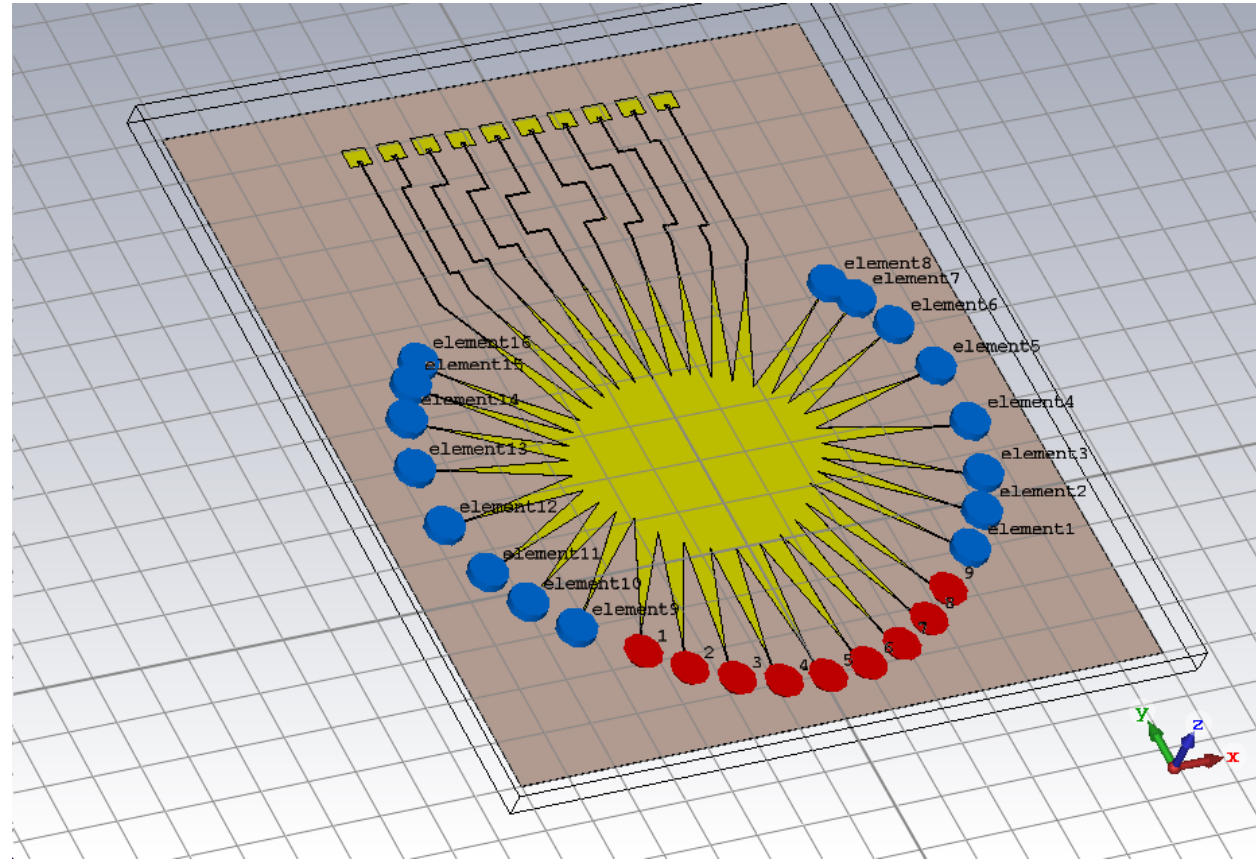
# ROTMAN import CST

- Phase differences are not perfectly produced as intended by the Rotman lens
  - Excitation of port 5:  $\sim 0^\circ$
  - Excitation of port 4 and 6:  $\sim 30^\circ$
  - Excitation of port 3 and 7:  $\sim 50^\circ$
  - ...
- All ports have better Return Loss than -12dB
- Expecting up to 6dB loss due to the Rotman lens



# Final design

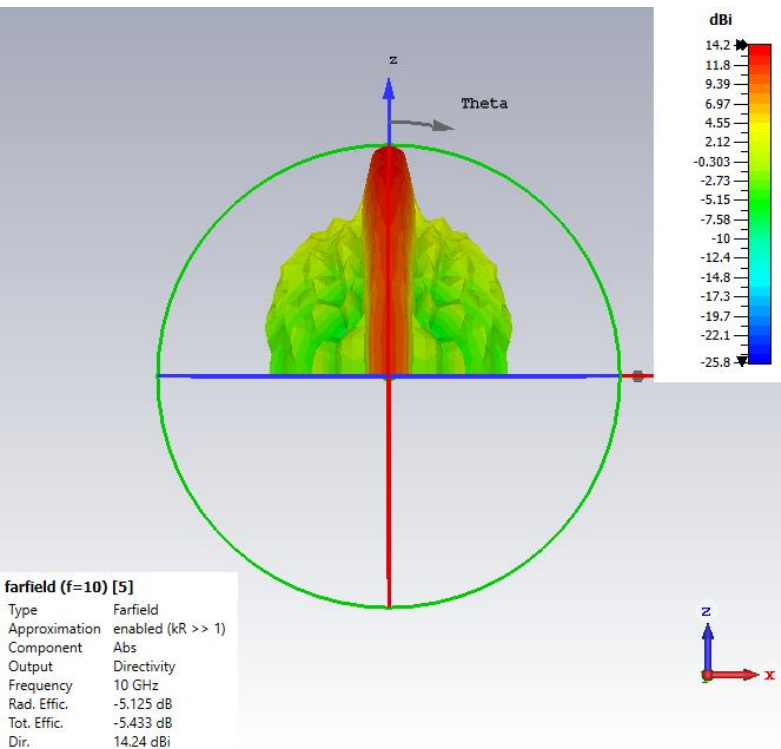
- Some microstrip line phase-shifters are introduced and optimized to produce a phase balance at every antenna port.
- Simulation takes long time on a 16Gb RAM laptop and cannot run very fine meshes.



# Results

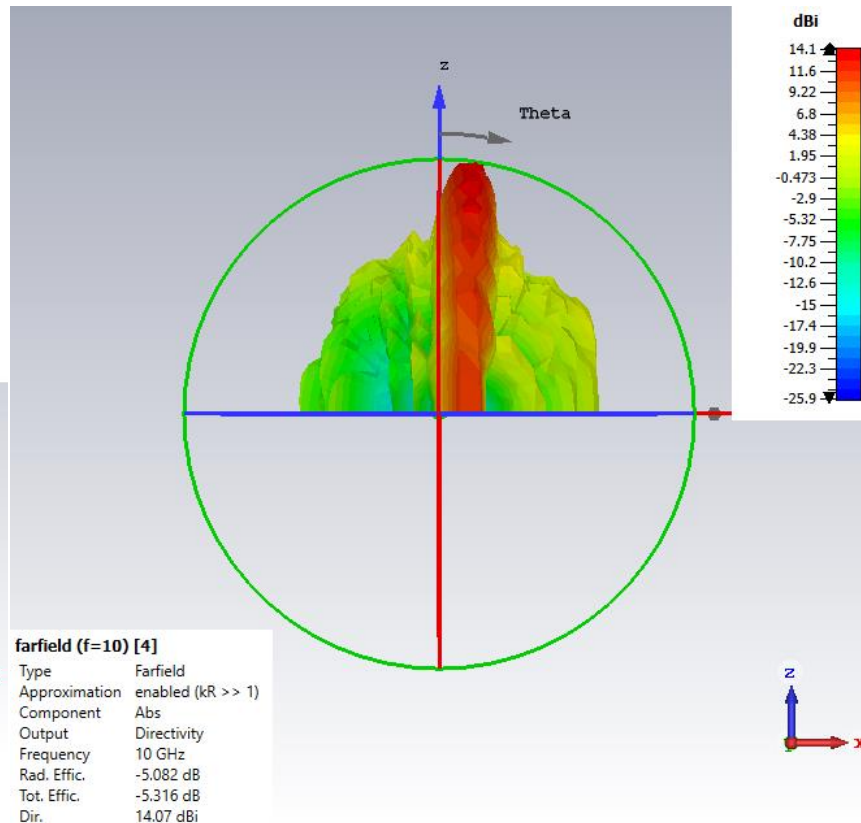
## Excitation to Port 5 (in the middle)

- Main lobe at  $0^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 14.24 dBi



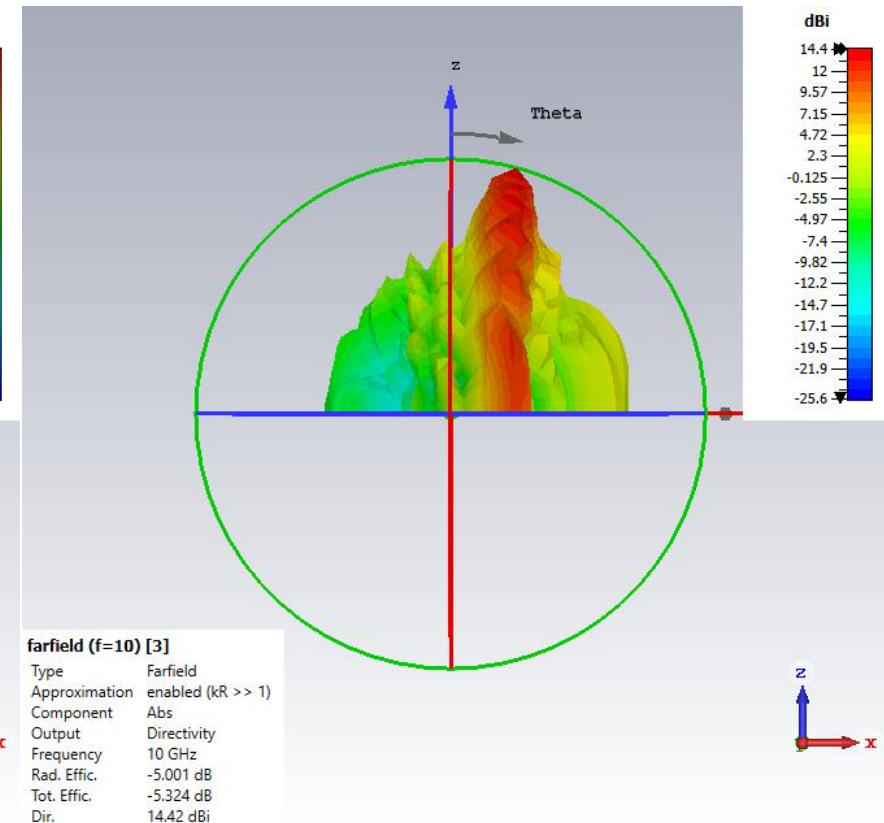
## Excitation to Port 4

- Main lobe at  $7^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 14.07 dBi



## Excitation to Port 3

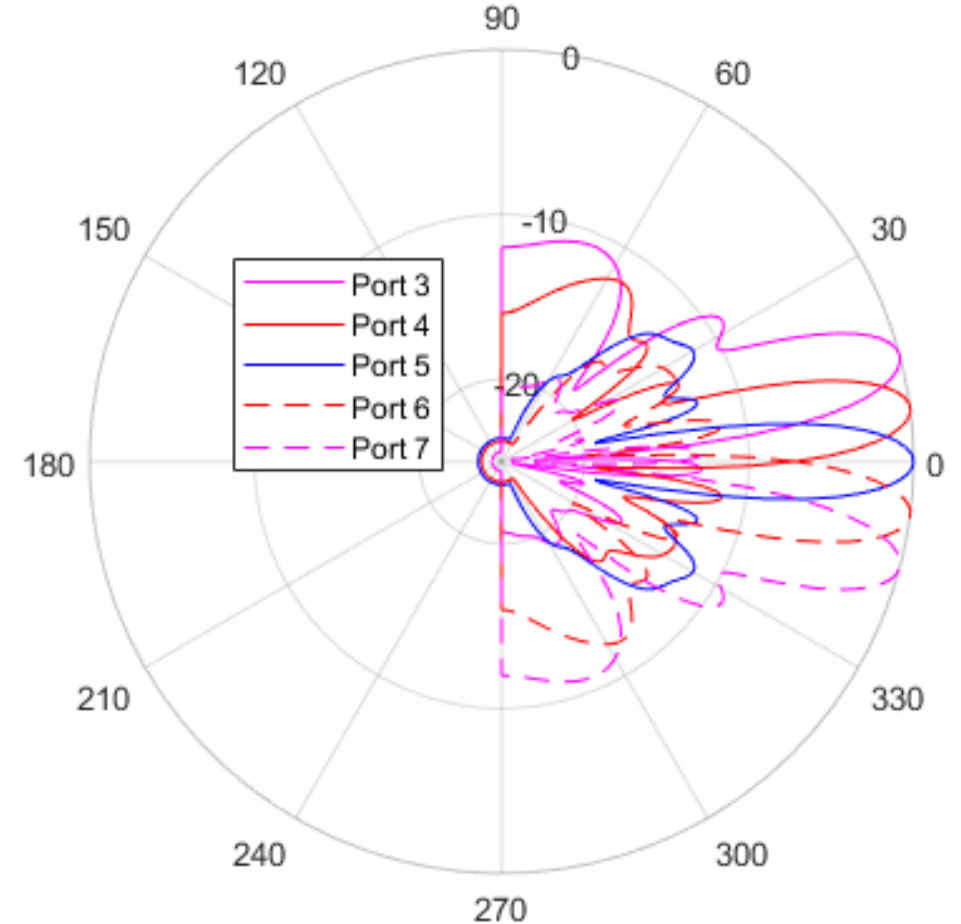
- Main lobe at  $15^\circ$
- Beamwidth  $\sim 10^\circ$
- Directivity 14.42 dBi



# Results

- Directivity and HPBW of the final design are similar to that of analytical and separating element design.
- Phase difference is smaller and varying making the angle of the main lobe smaller.
- Because the feeding network is not perfect, the pattern is not clean as the analytical synthesis or numerical result in which there is no feeding network.

Patterns of phased array with Rotman lens feeding from CST



# Perspective

- This is a preliminary design, refinements are required on
  - Fine mesh simulations
  - Optimizing the Rotman lens to obtain  $\Delta 30^\circ$  step
  - Optimizing the microstrip phase-shifters
  - Finalize the feeding ports to SMA

# References

- 1) Eurocircuits site: <https://www.eurocircuits.com/>
- 2) Balanis, "Antenna Theory: Analysis and Design," 4th edition, MATLAB code: <https://fr.mathworks.com/academia/books/antenna-theory-balanis.html>
- 3) Rotman lens design using MATLAB: [https://fr.mathworks.com/matlabcentral/fileexchange/50490-rotman-lens-design-with-hfss-link?s\\_tid=mwa\\_osa\\_a](https://fr.mathworks.com/matlabcentral/fileexchange/50490-rotman-lens-design-with-hfss-link?s_tid=mwa_osa_a)
- 4) Patch dimension calculator: <https://www.pasternack.com/t-calculator-microstrip-ant.aspx>
- 5) Microstrip line calculator: <https://www.pasternack.com/t-calculator-microstrip.aspx>