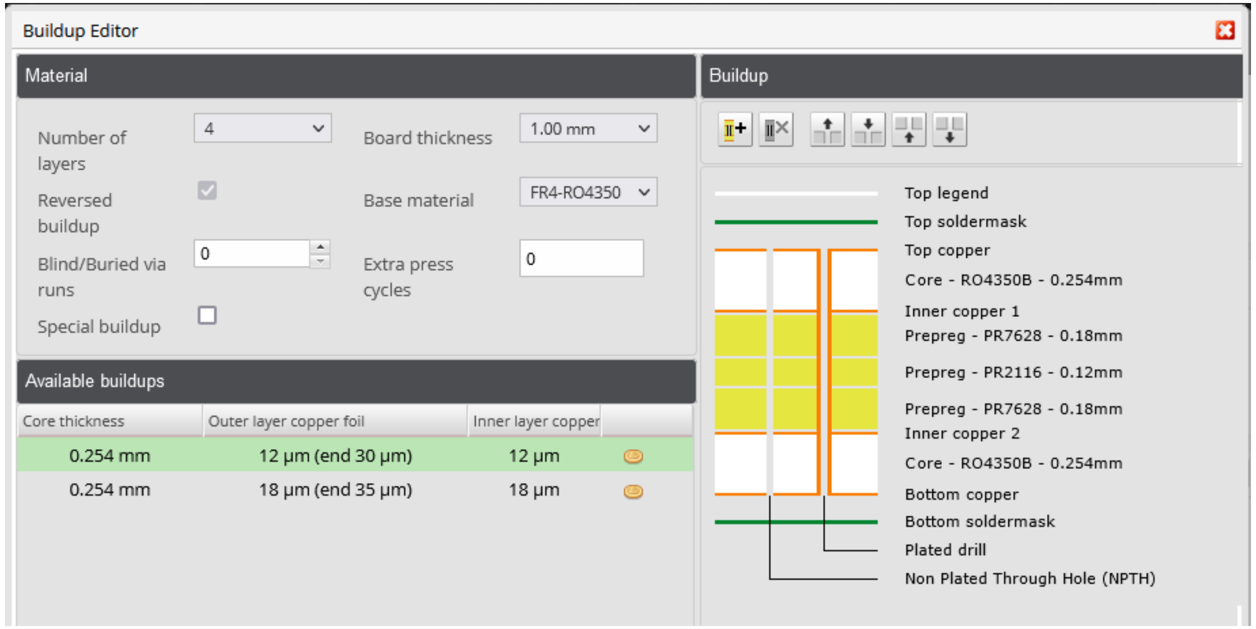
Phased array patch antenna @10GHz

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***."

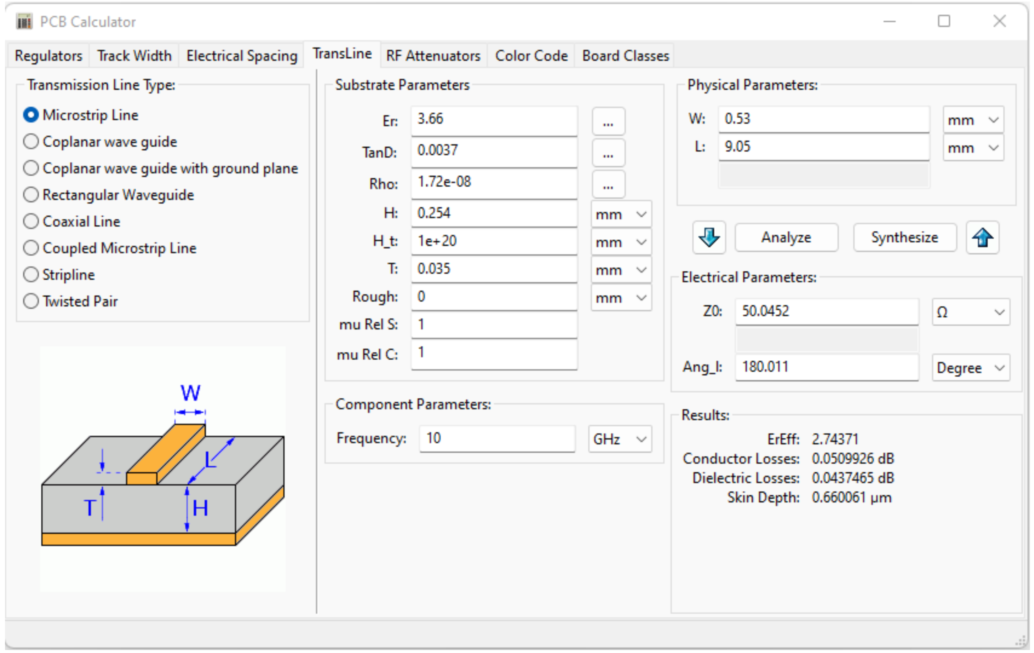
Khai NGUYEN - Oct. 2022

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

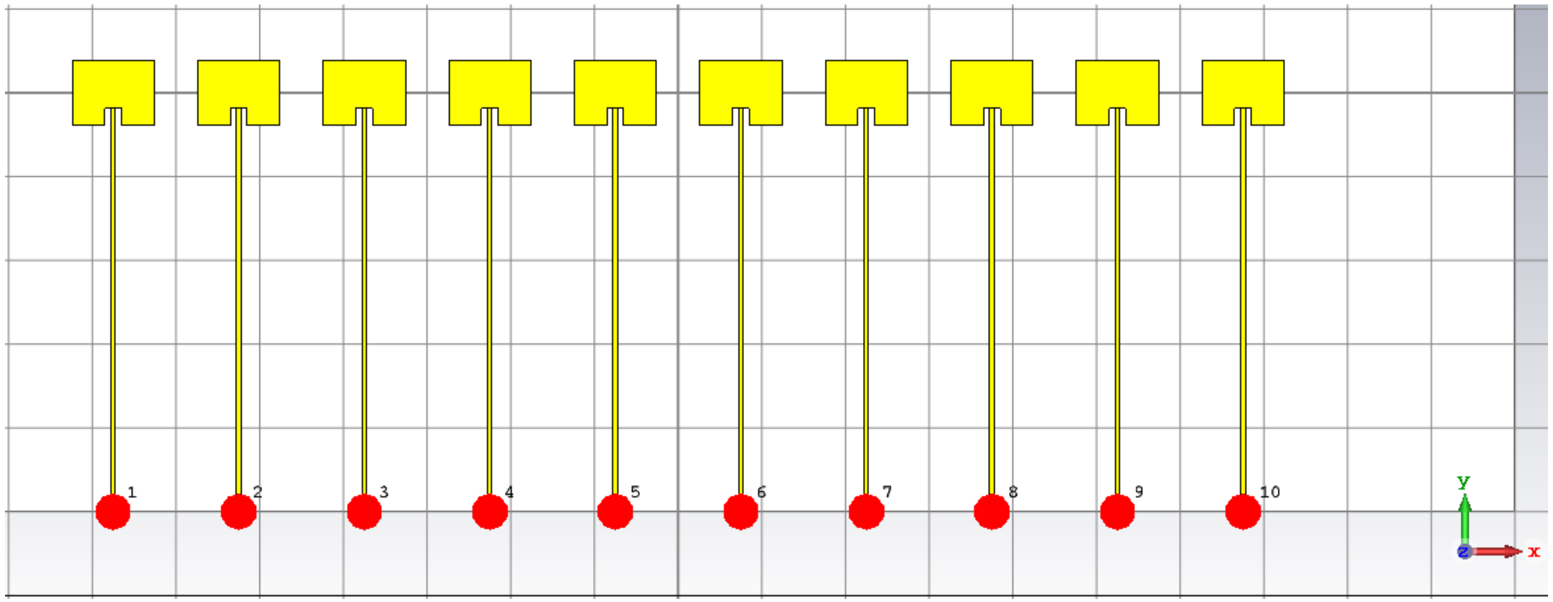


Property	Typical Value RO4003C	Typical Value RO4350B	Direction	Units	Condition	Test Method
Dielectric Constant, ε_r Process	3.38 ± 0.05	3.48 ± 0.05	Z	--	10 GHz/23°C	IPC-TM-650 2.5.5.5 Clamped Stripline
(1) Dielectric Constant, ε_r Design	3.55	3.66	Z	--	8 to 40 GHz	Differential Phase Length Method
Dissipation Factor tan, δ	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 ε_r	+40	+50	Z	ppm/°C	-50°C to 150°C	IPC-TM-650 2.5.5.5



Intended design

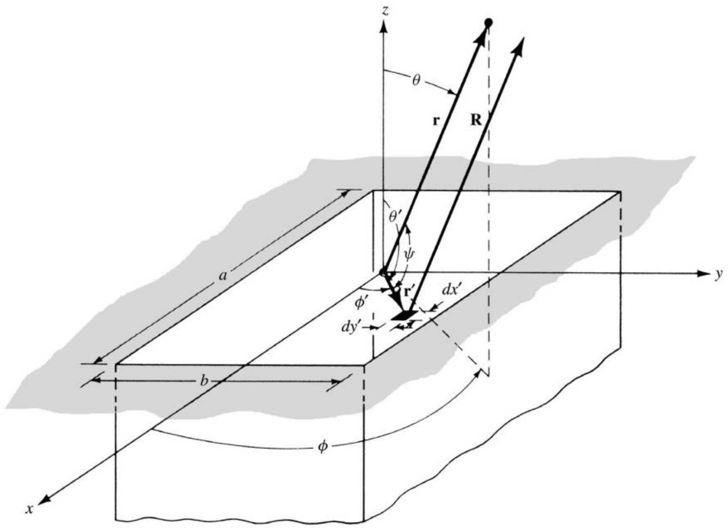
- The patch array antenna is designed as follow:
  - Broadside direction toward +Z
  - Feeding comes from –Y toward +Y
  - Array's elements placed 1D along X and have distance $\frac{\lambda_0}{2}$



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

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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 LENGH OF PATCH (in cm) = 0.8027

PHYSICAL LENGH 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) Rin0= 293.4669 ohms

RESONANT INPUT RESISTANCE AT RECESSED FEED POINT (y=0.2000 cm) RINYo= 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

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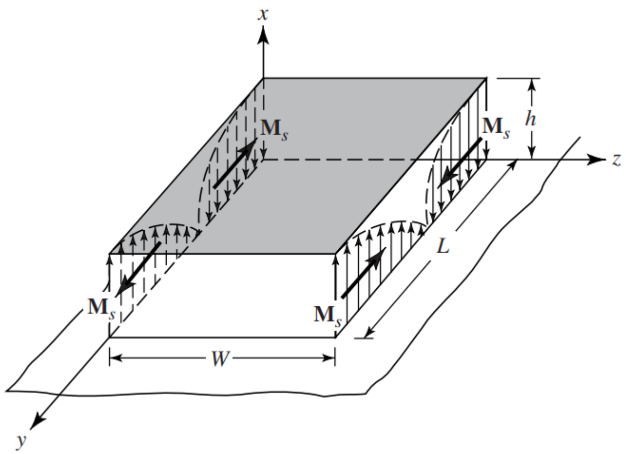
Analytical analysis of the array

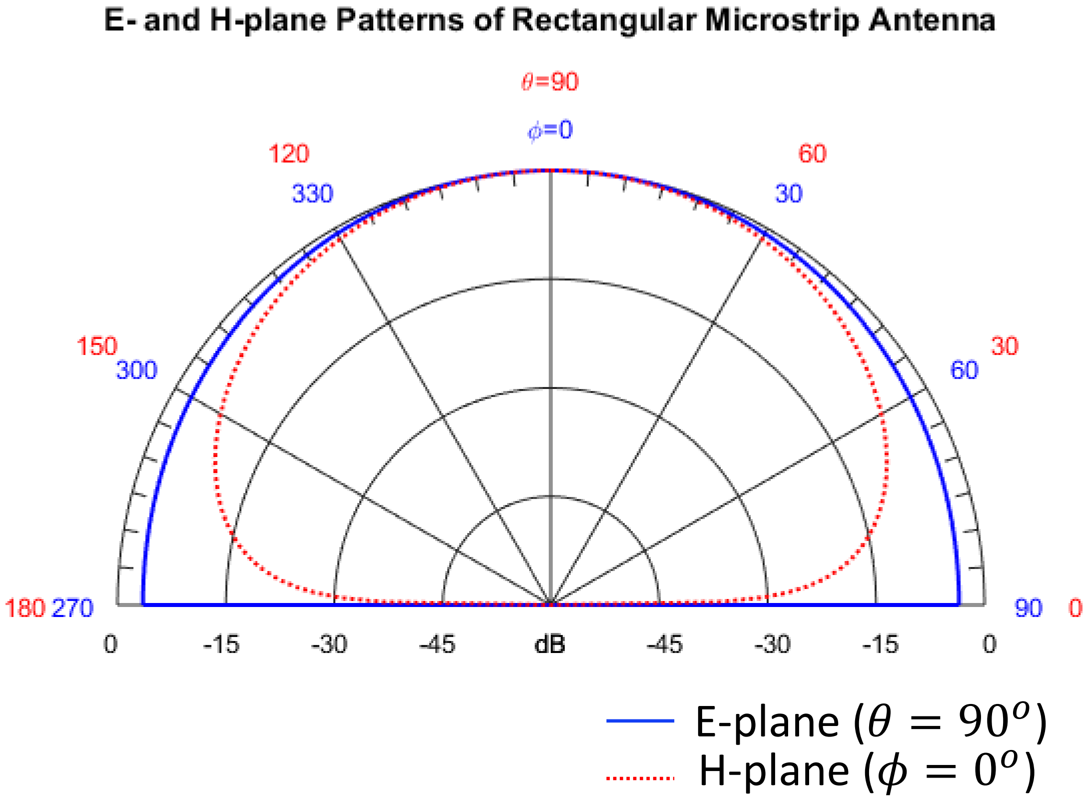


- Analytical pattern calculated by Balanis for X-direction broadside
- E-plane ($\theta = 90^o$)

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

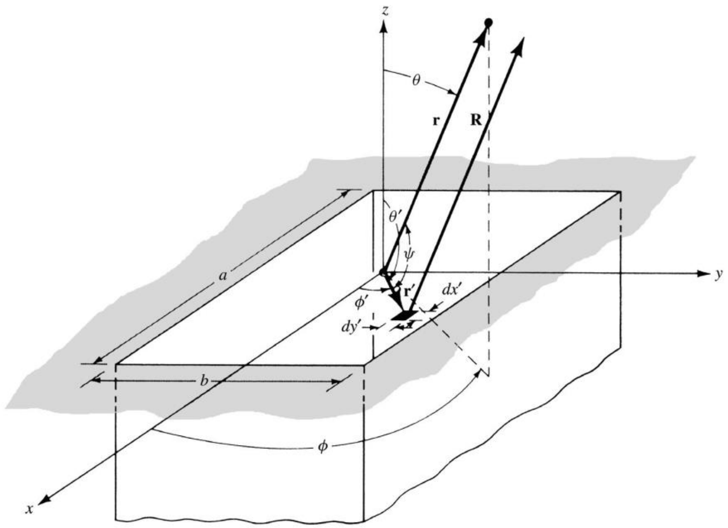
- H-plane($\varphi = 0^o$)

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

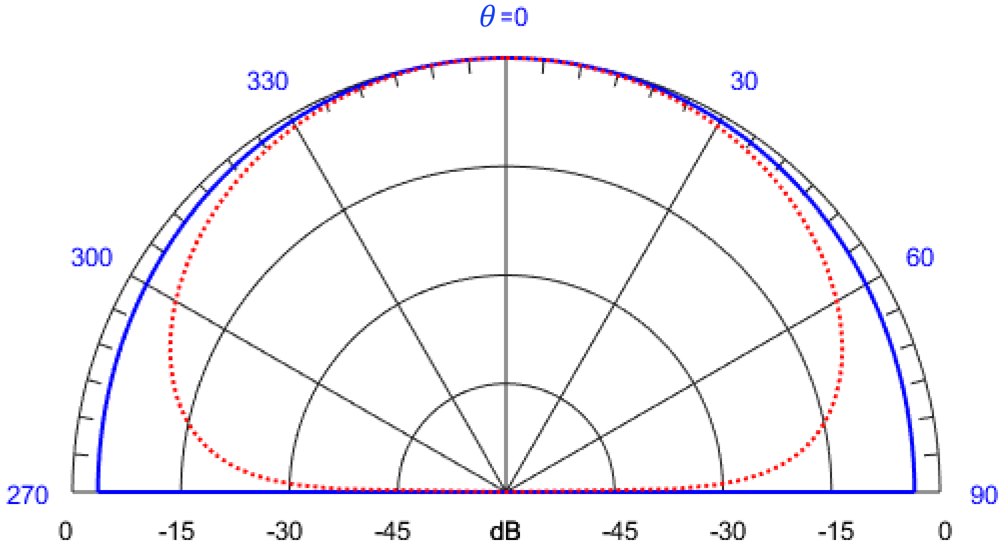


Analytical analysis of the array

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



E- and H-plane Patterns of Rectangular Microstrip Antenna



E-plane ($\phi = 90^o$)
H-plane ($\phi = 0^o$)

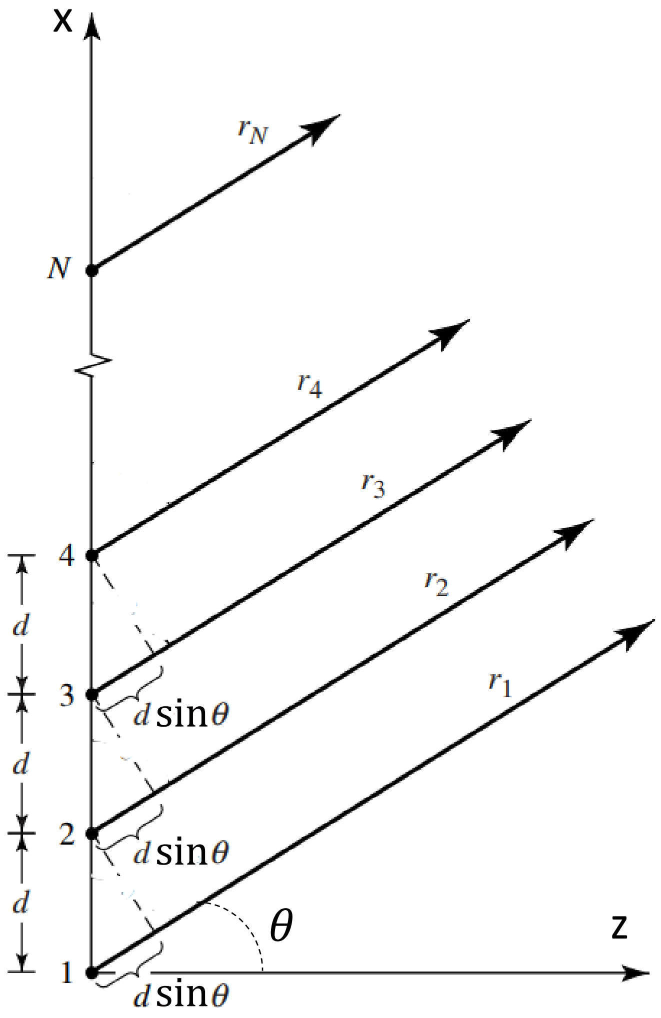
Analytical analysis of the array

- Array factor of the 1×10 patch array along X axis
- Broadside direction is along +Z
- $AF_{H-plane} = \frac{1}{N}\left(1 + e^{j(kdsin\theta+\beta)} + \cdots + e^{+j2(kdsin\theta+\beta)} + e^{+j9(kdsin\theta+\beta)}\right) = \frac{1}{N}\left[\frac{\sin\left(\frac{N}{2}(kdsin\theta+\beta)\right)}{\sin\left(\frac{(kdsin\theta+\beta)}{2}\right)}\right]$

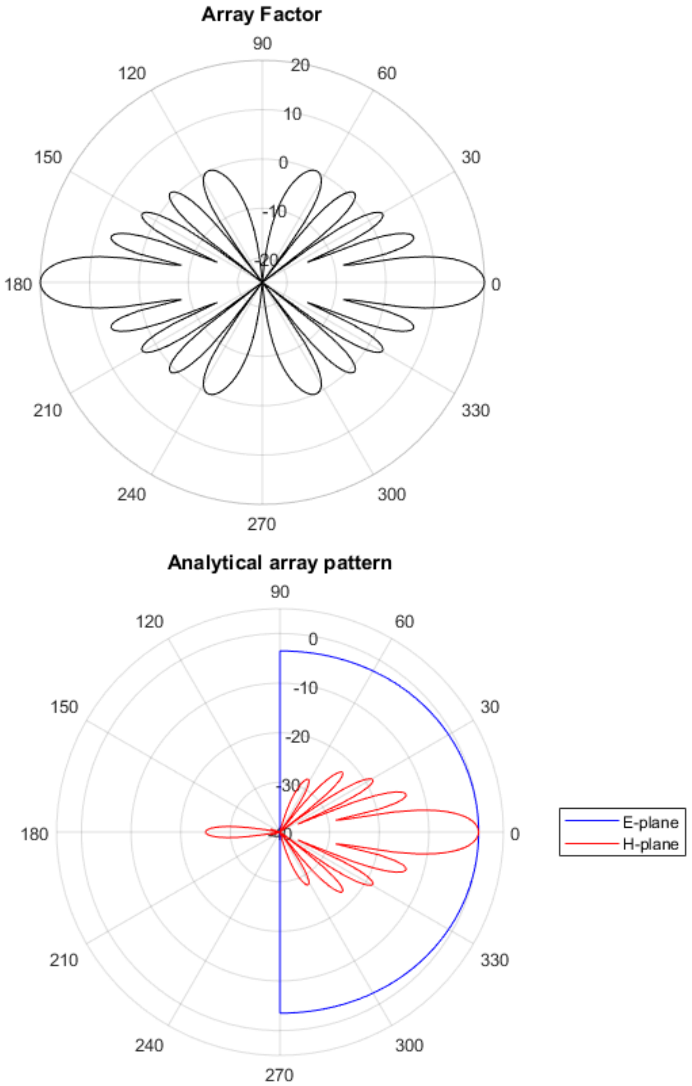
with $N = 10, d = 15mm, k = \frac{2\pi}{\lambda}$, and β is phase difference between neighbor elements.

- So

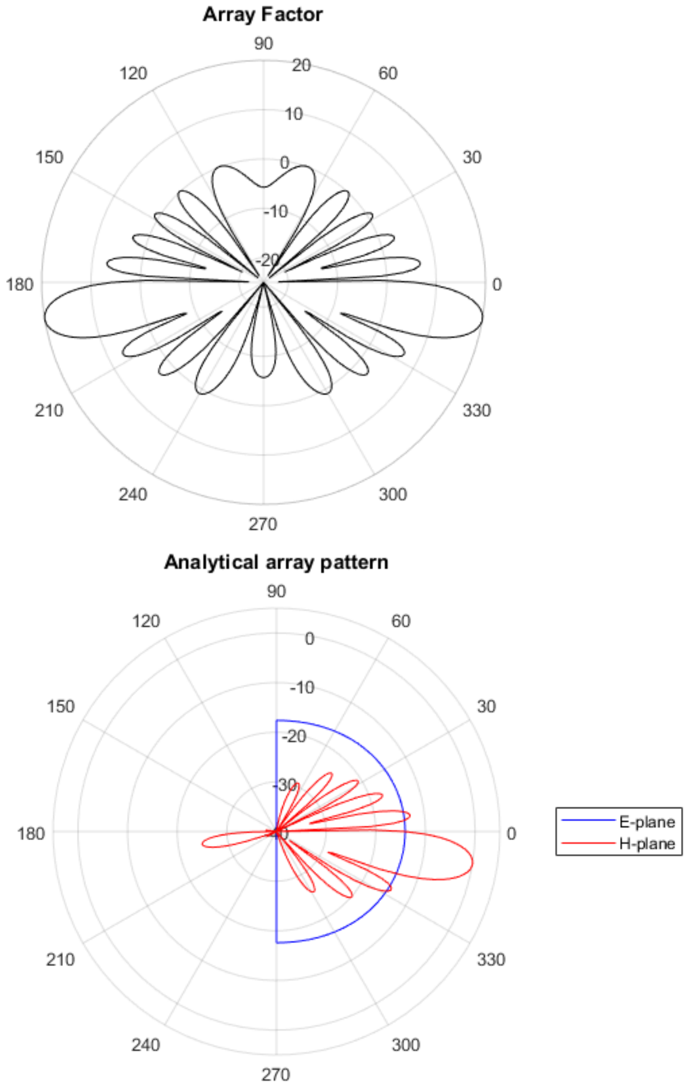
$$E_{arr} = AF \times E_{element}$$



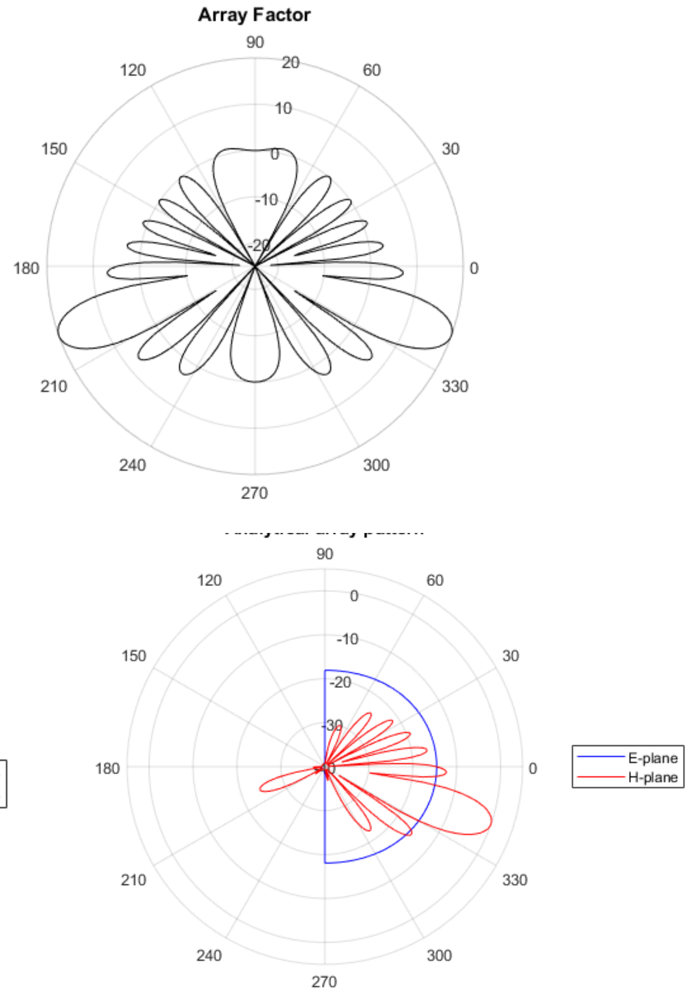
Analytical analysis of the array



$\beta = 0^o$



$\beta = 30^o$

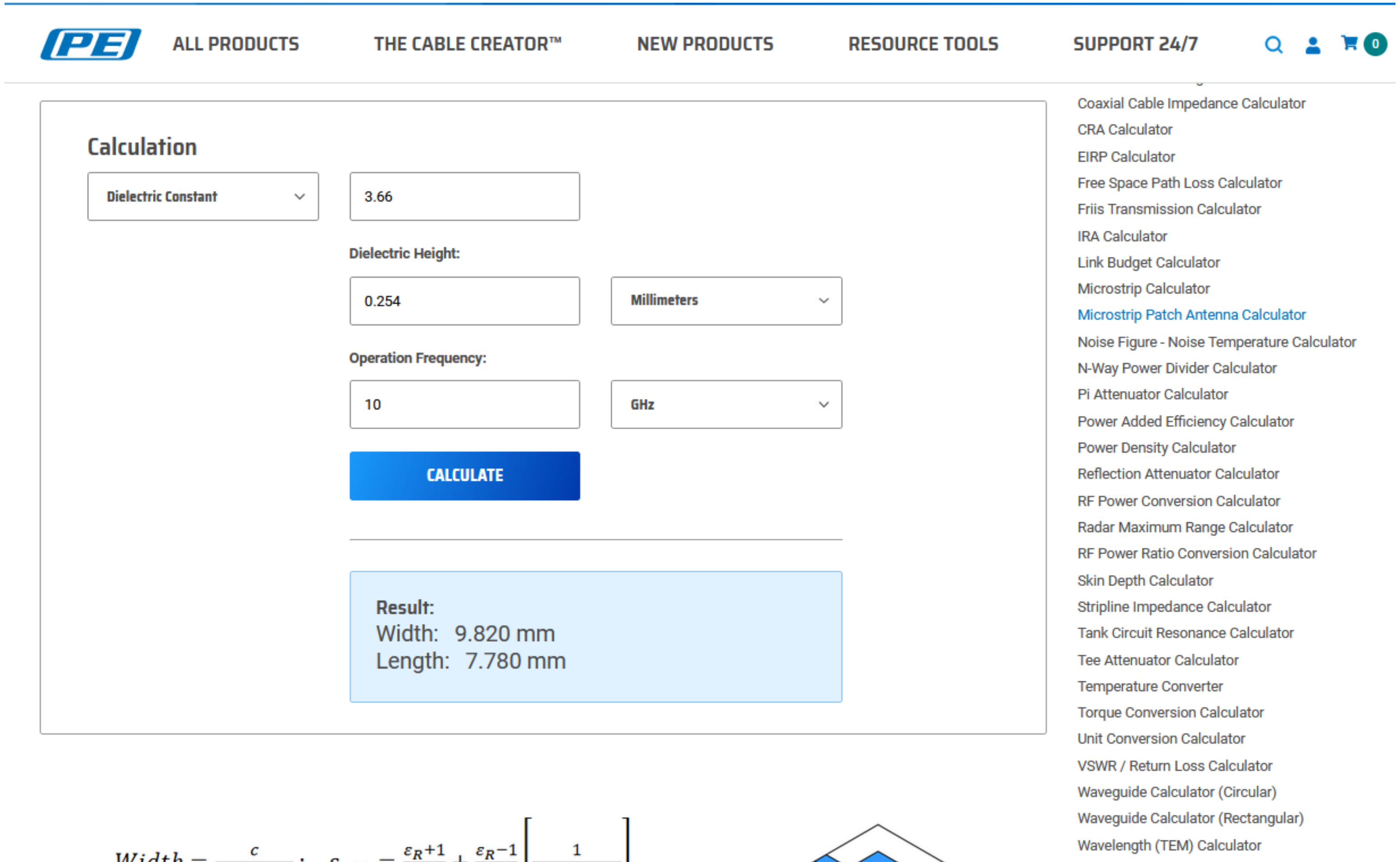


$\beta = 60^o$

Numerical estimation of 1x10 patch array

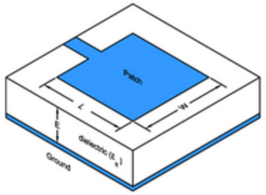
Patch array design

- Using online tool to calculate patch dimension.



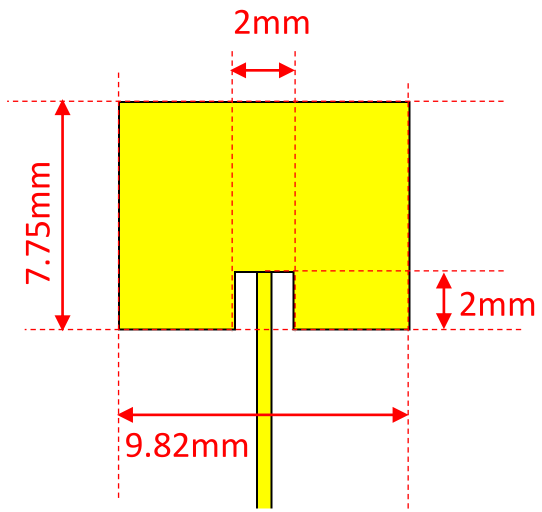
$$Width = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}}; \quad \varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

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

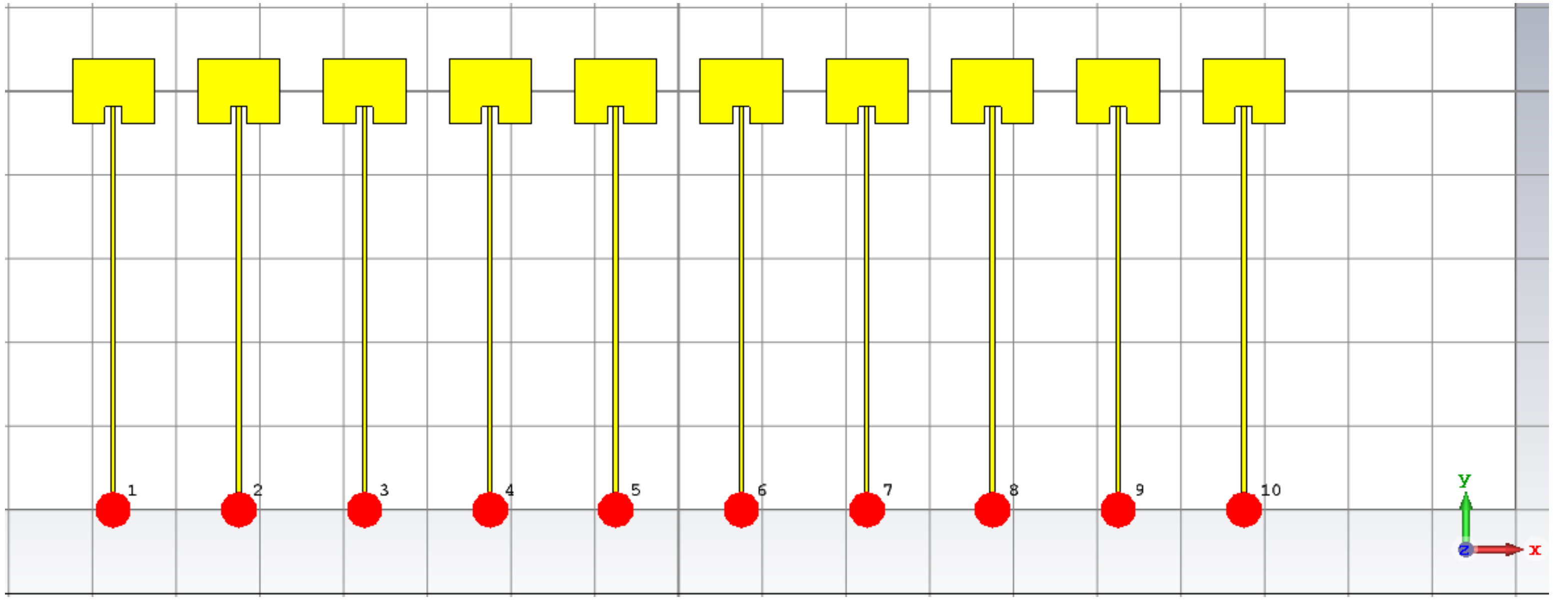


Numerical simulation CST

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



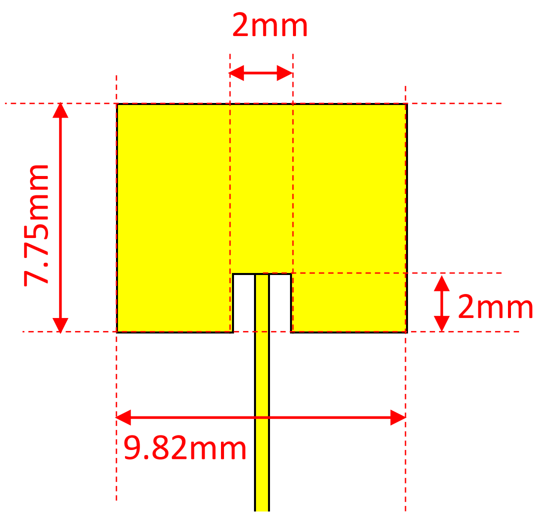
Single patch design



1x10 patch array design

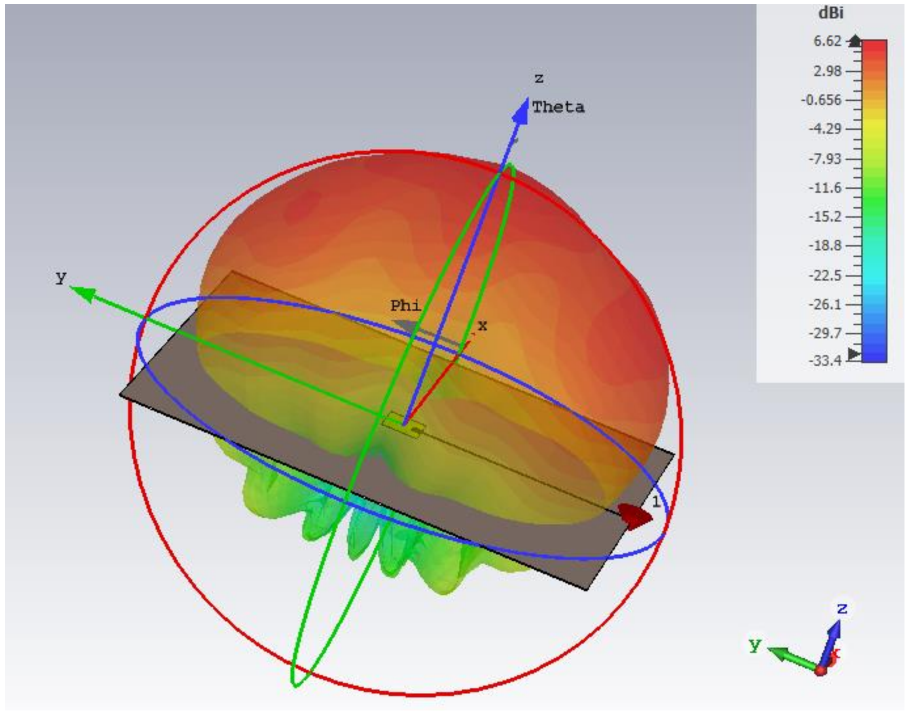
Numerical simulation CST

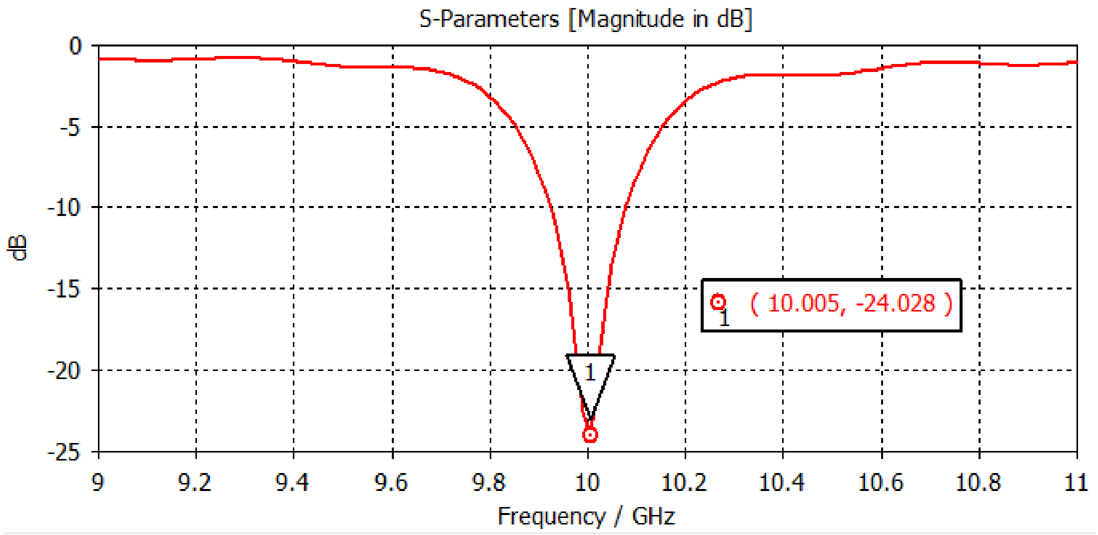
- Simulation of single patch



Single patch design

3D radiation pattern of single patch

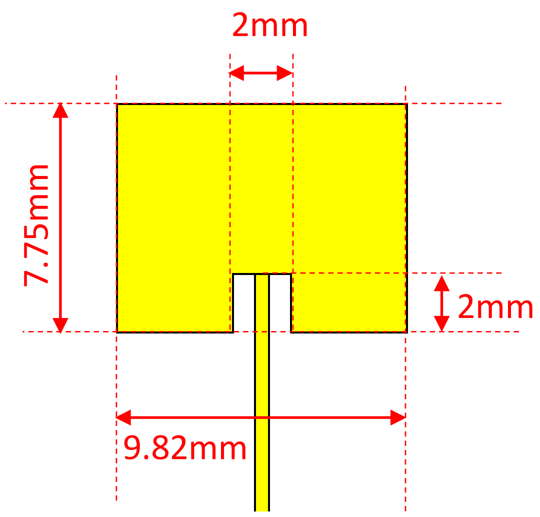




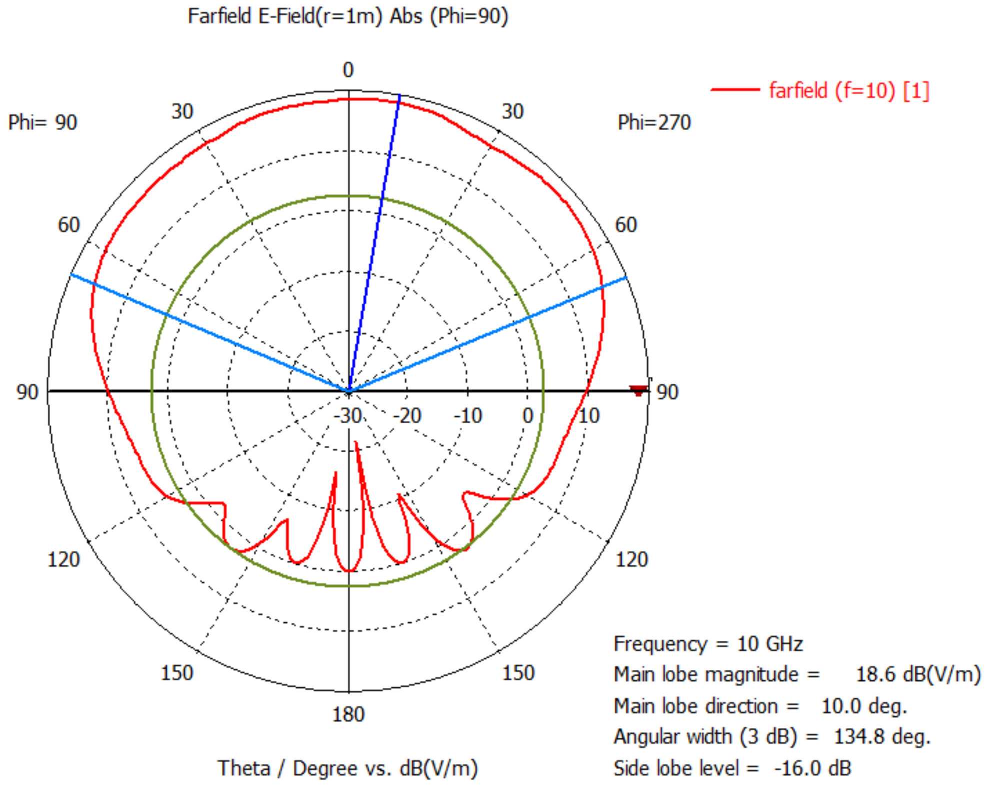
Impedance matching of single patch

Numerical simulation CST

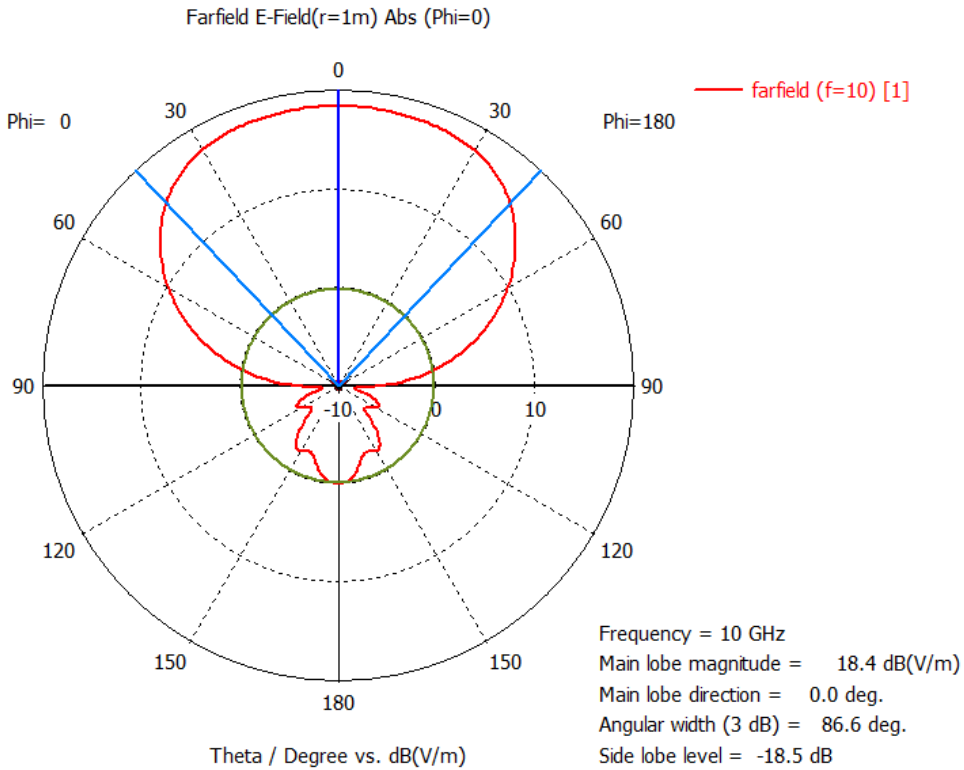
- Simulation of single patch



gle patch design



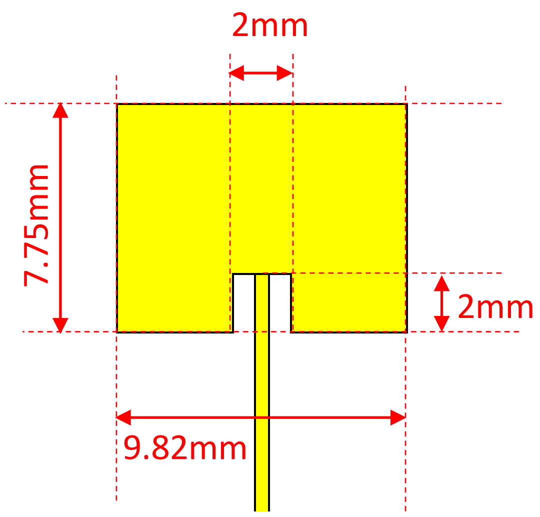
E-plane



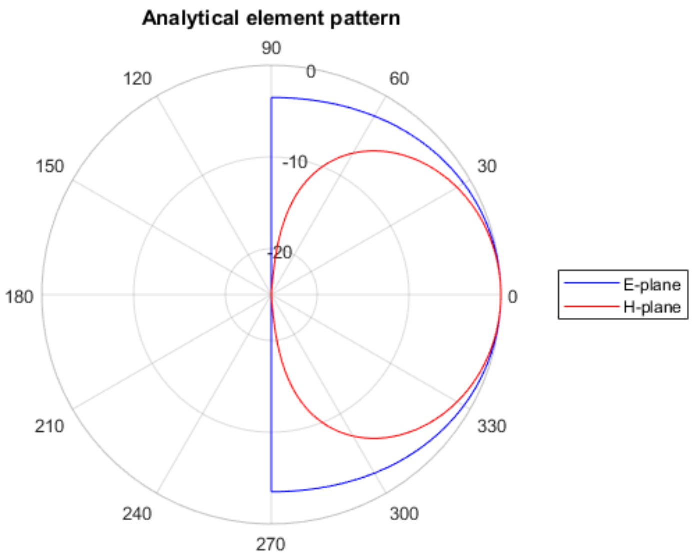
H-plane

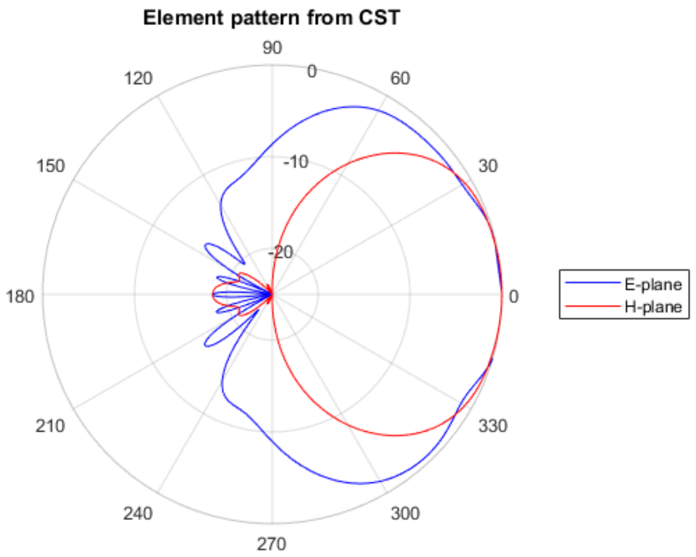
Numerical simulation CST

- 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

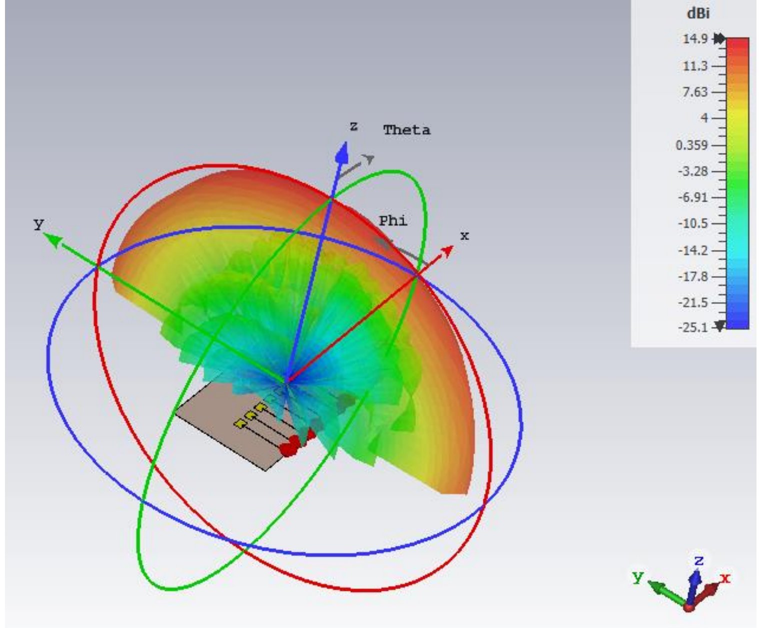




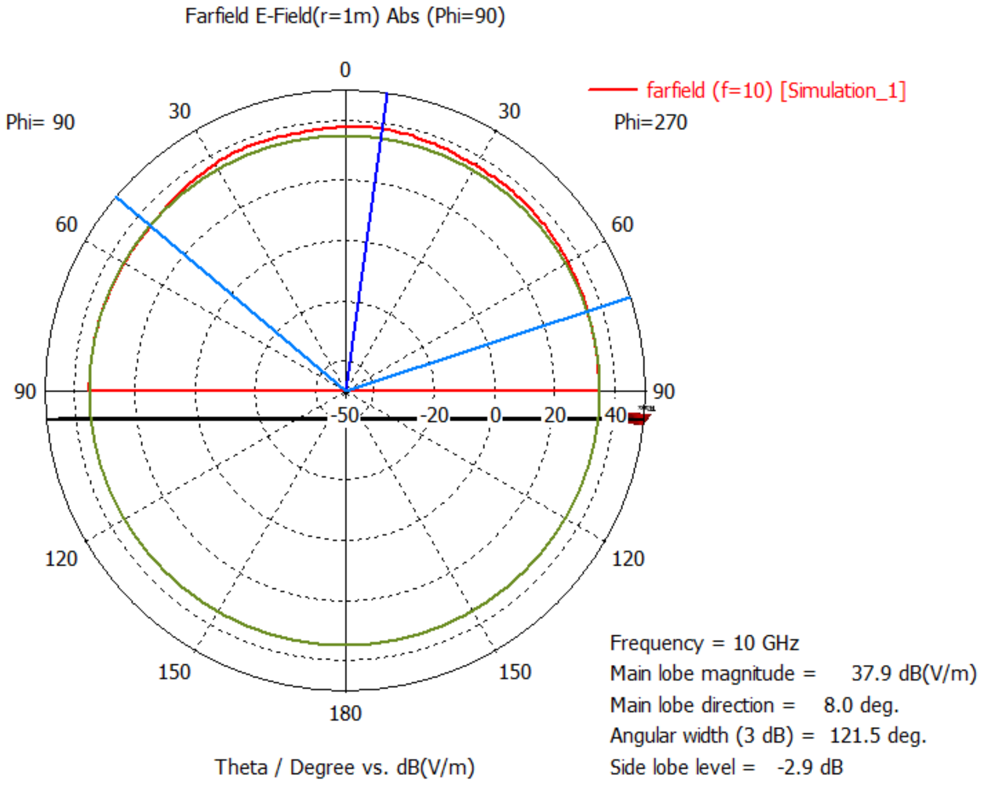
*back radiation due to finite ground plane

Numerical simulation CST

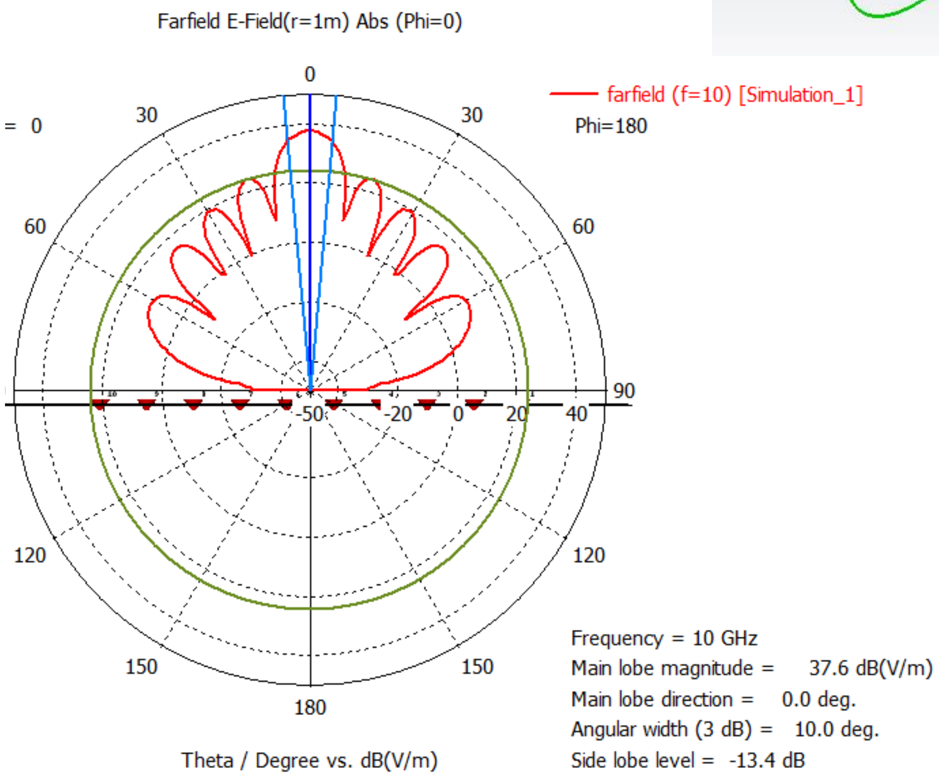
- Simulation of 1x10 patch array ($\boldsymbol{\beta = 0^o}$)



Array directivity



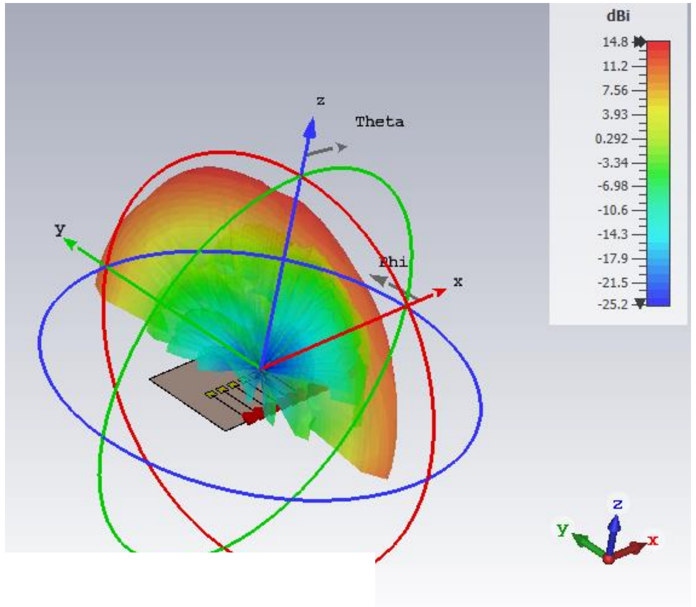
E-plane



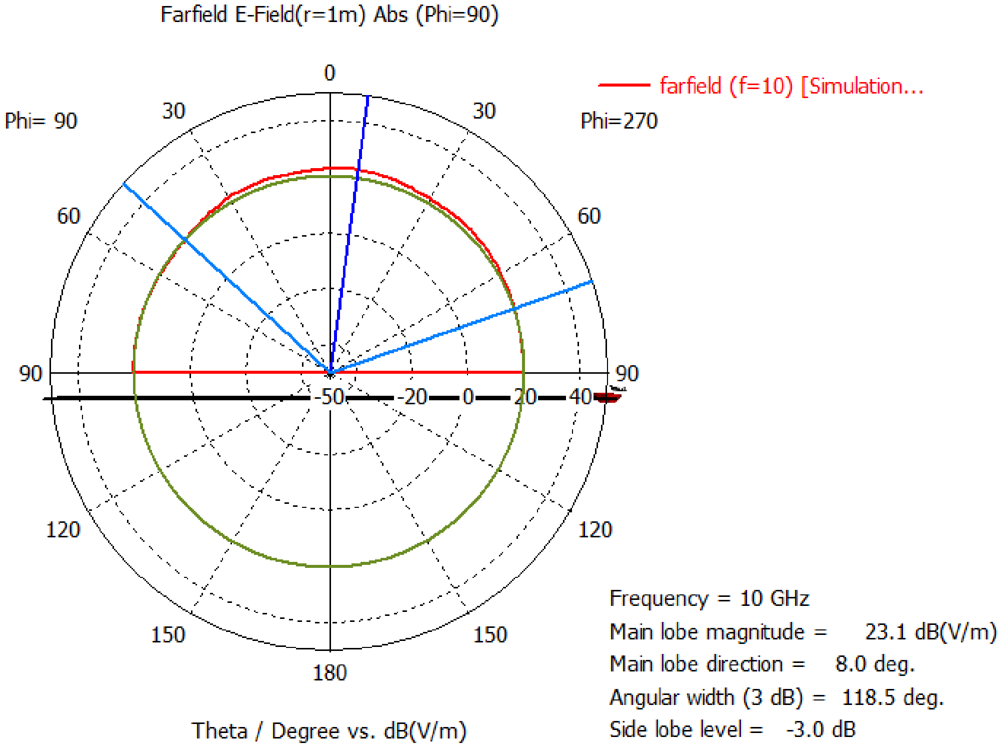
H-plane

Numerical simulation CST

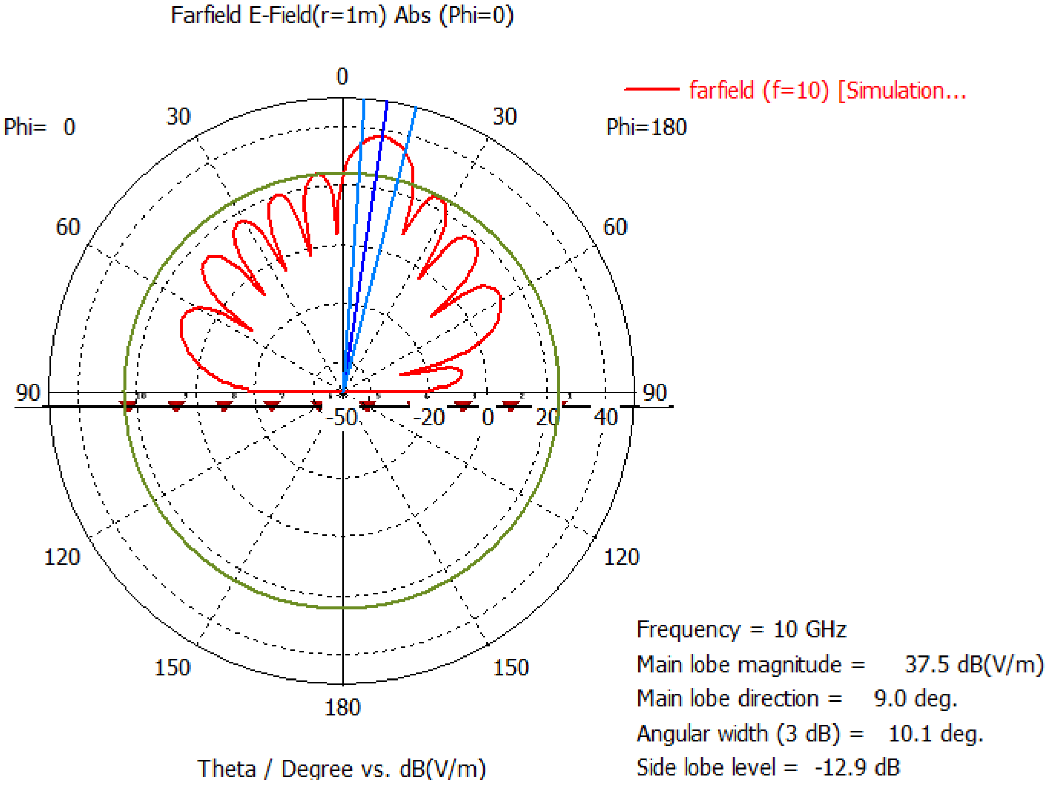
- Simulation of 1x10 patch array ($\boldsymbol{\beta = 30^o}$)



ectivity



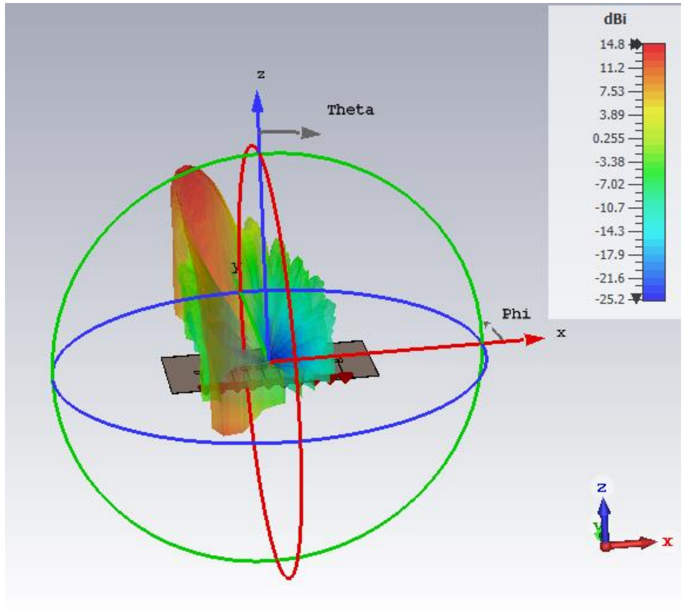
E-plane

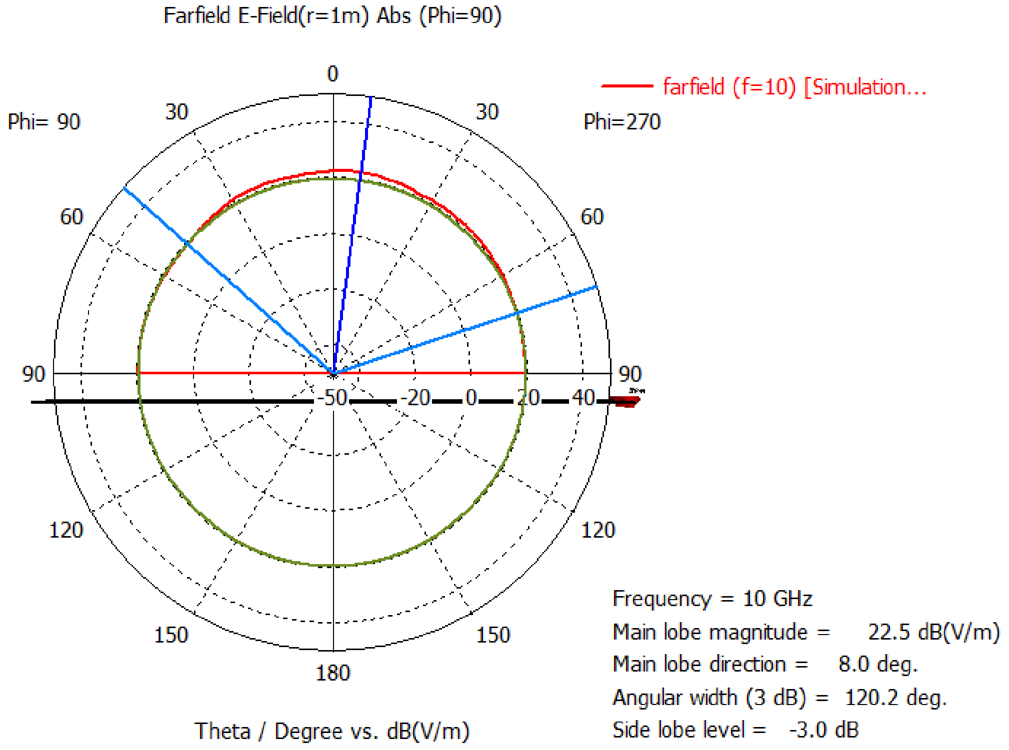


H-plane

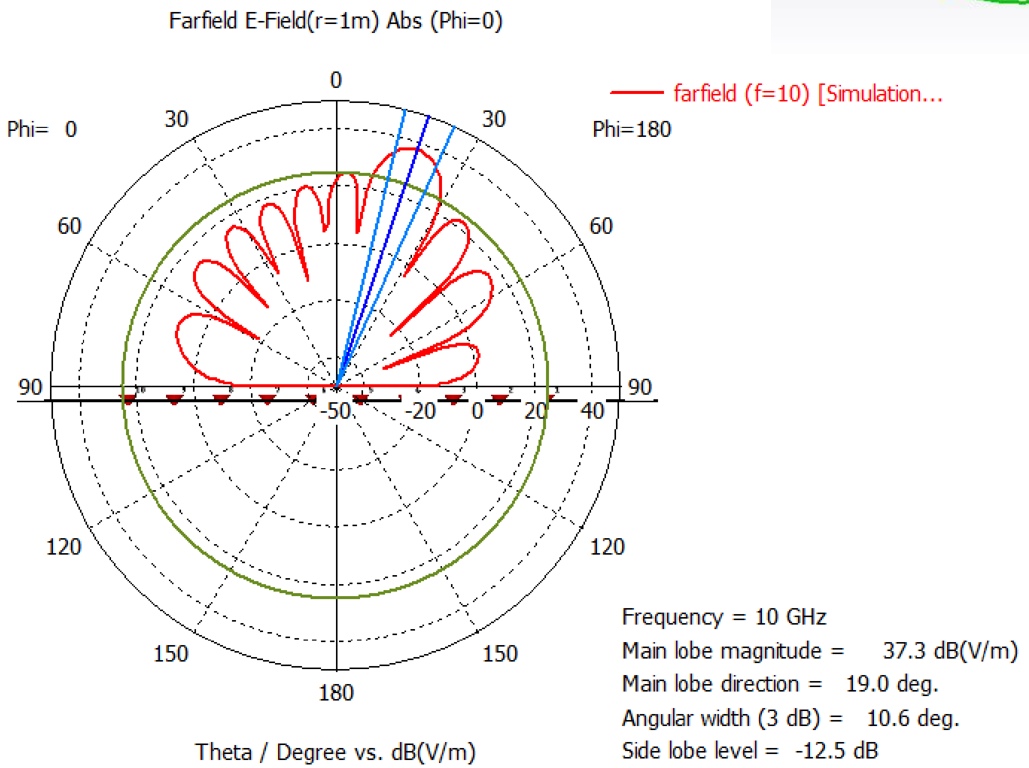
Numerical simulation CST

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



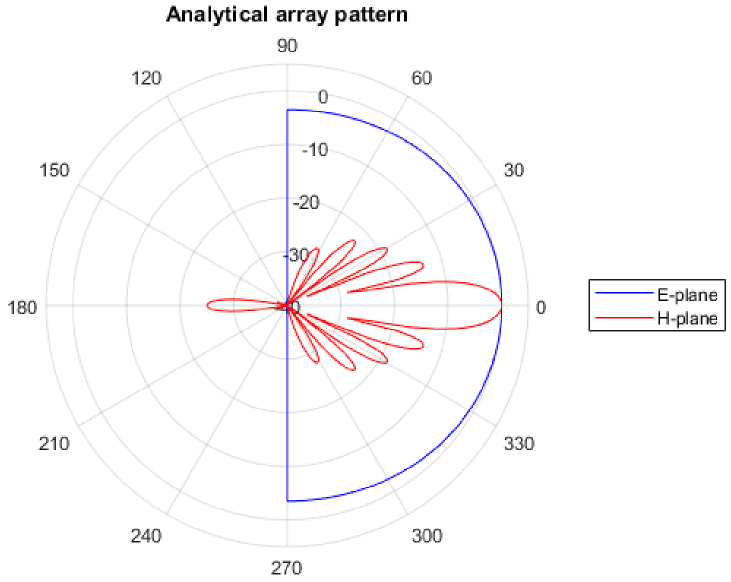


E-plane



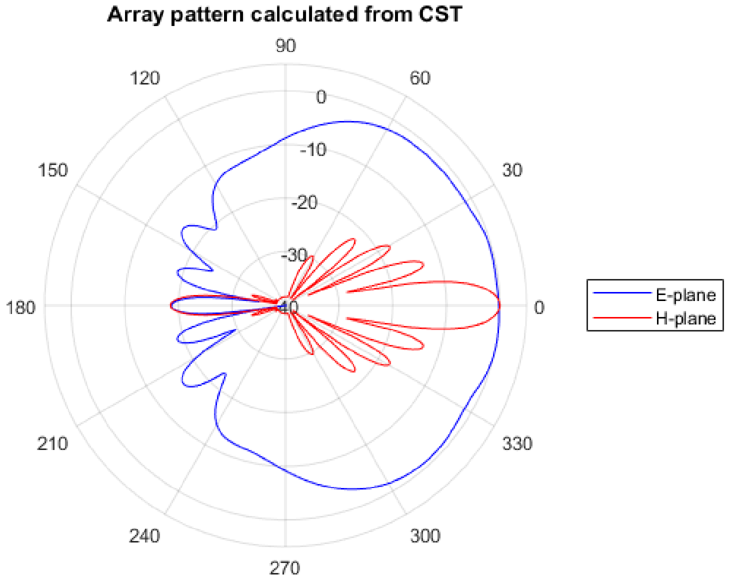
H-plane

Comparison $\beta = 0^o$



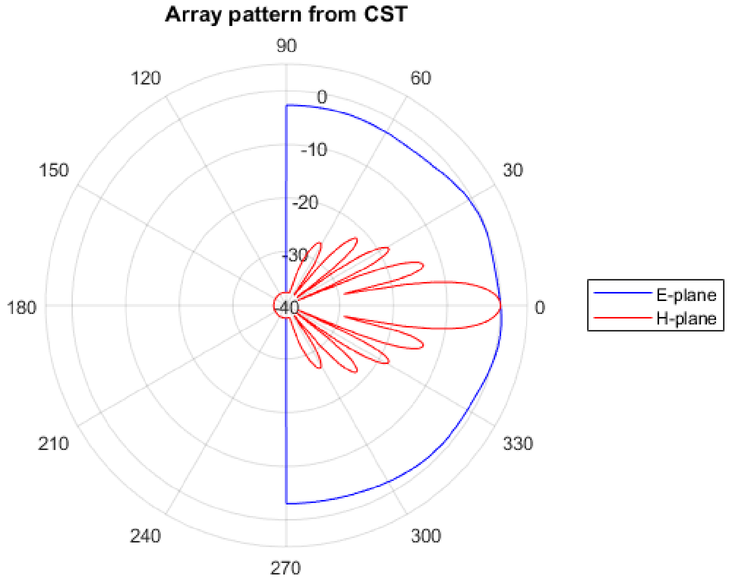
Full analytical result from MATLAB calculations of patch pattern and array factor

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



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

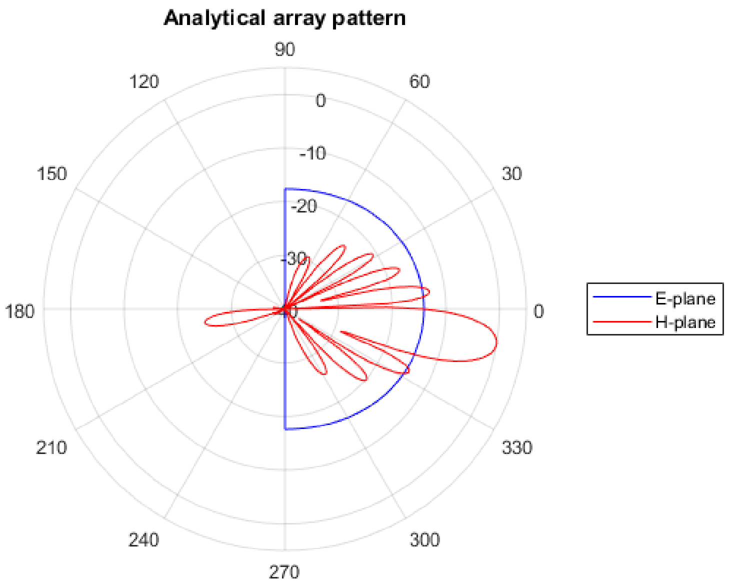
- Close to full analytical results



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

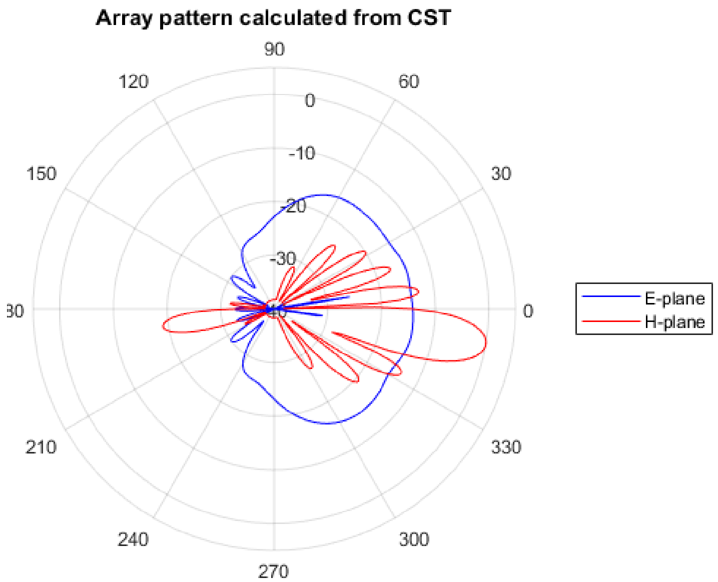
- Main lobe at 0^o
- Beamwidth $\sim 10^o$
- Directivity 14.8 dBi

Comparison $\beta = 30^o$



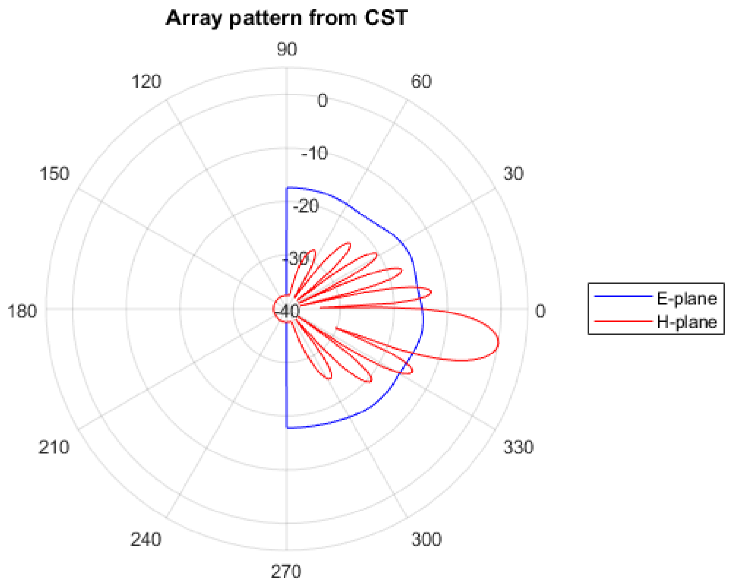
Full analytical result

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



Partially analytical result

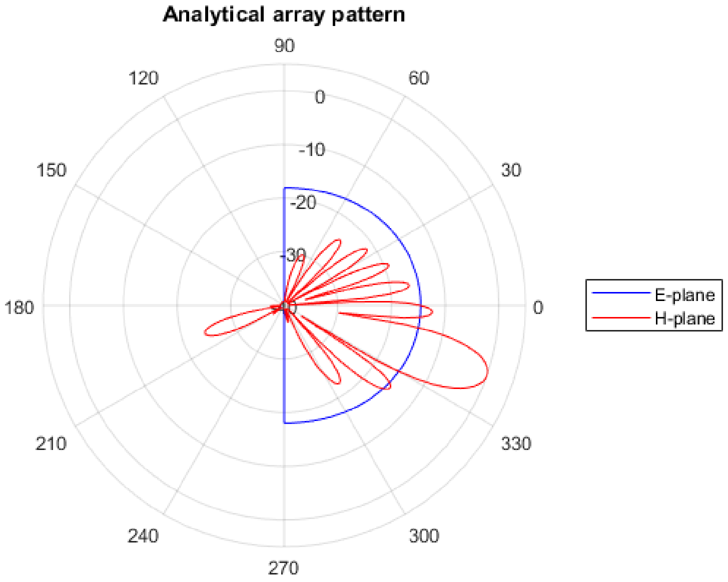
- Close to full analytical results

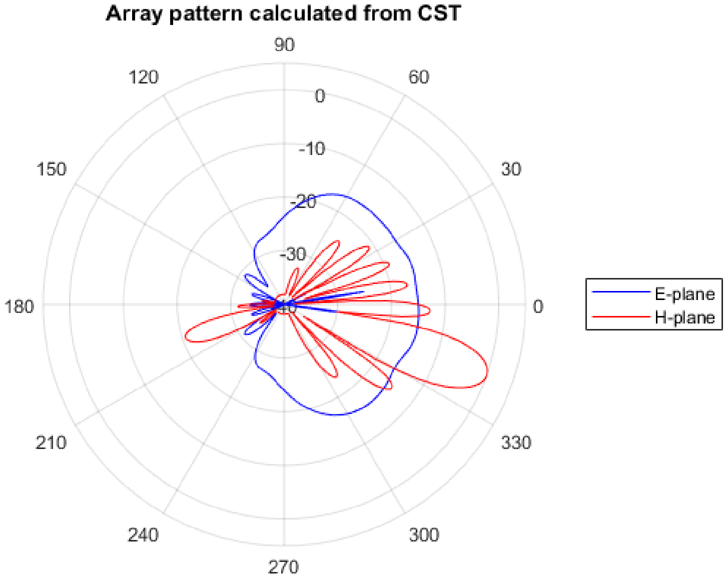


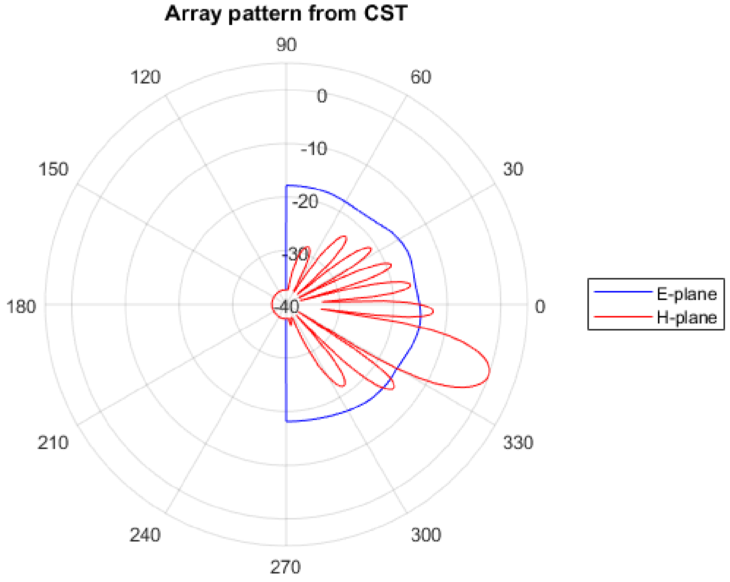
Full numerical result

- Main lobe at 9^o
- Beamwidth $\sim 10^o$
- Directivity 14.7 dBi

Comparison $\beta = 60^o$







Full analytical result

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

Partially analytical result

- Close to full analytical results

Full numerical result

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

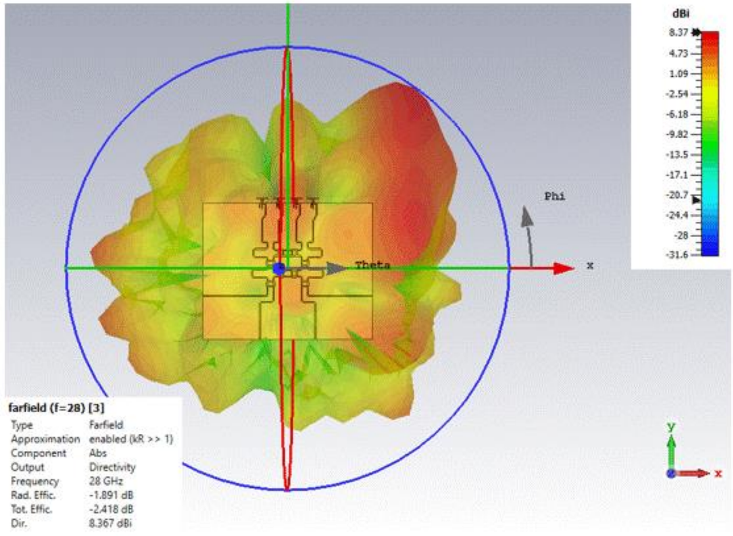
Conclusion

- 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
  - Sidelobe level
- 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

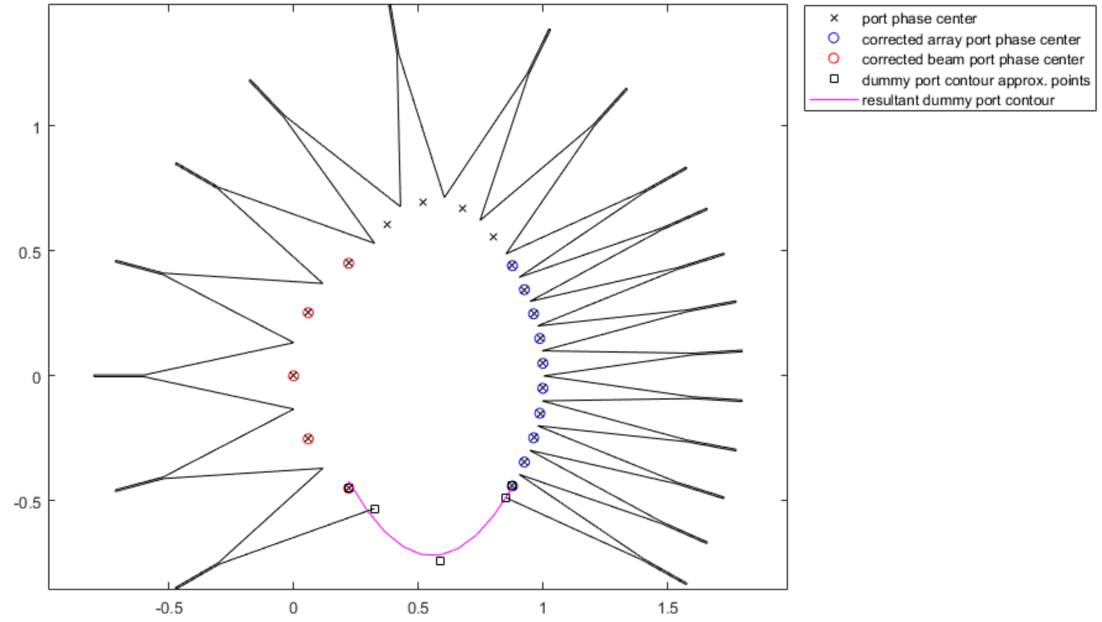
Feeding network

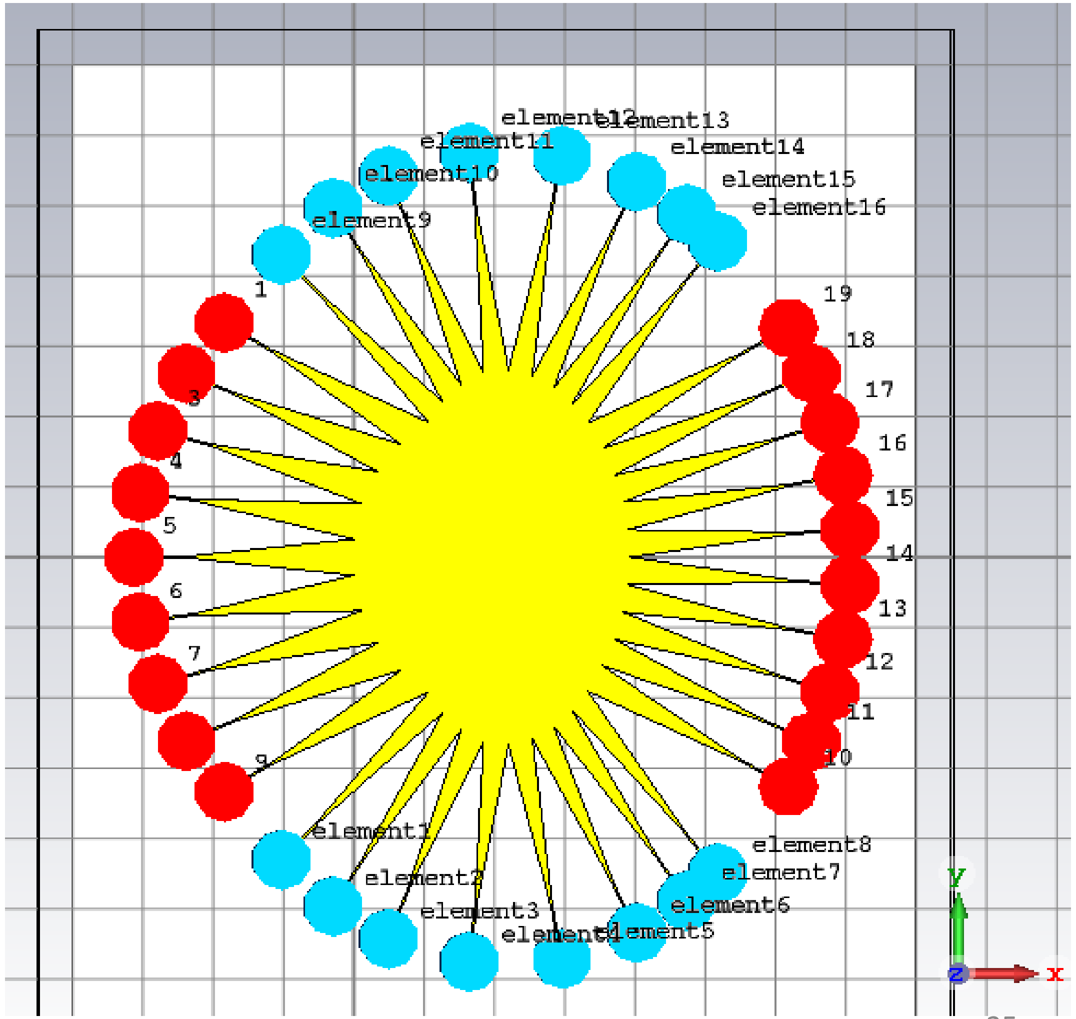
- To produce the difference in phase excitation of each element of the array we can
  - Use some active components, such as phase-shifter.
    - Normally requires complicated control.
    - Need to design a DC part that doesn't couple with RF part
  - Passive feeding network, like
    - Butler matrix,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



Rotman lens for feeding network

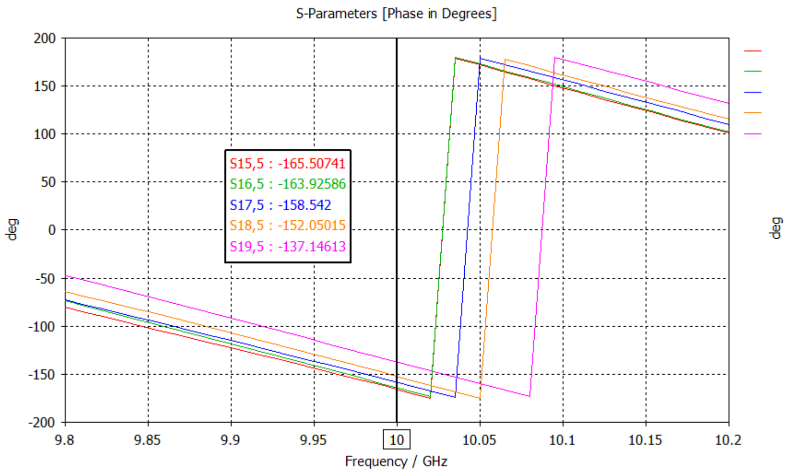
- 10 array ports (connect to antennas)
- 9 beam ports (excitation ports)
- 8 dummy ports (50Ω loads)
- 30° phase shift to cover $\pm 40^o$

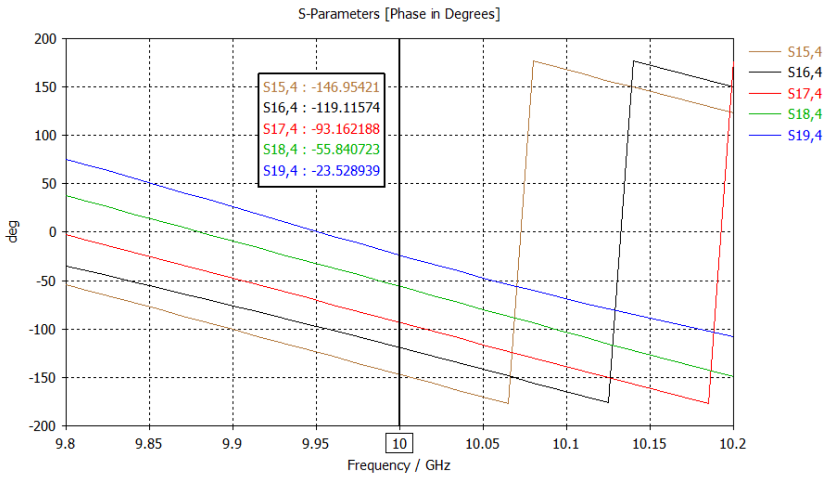


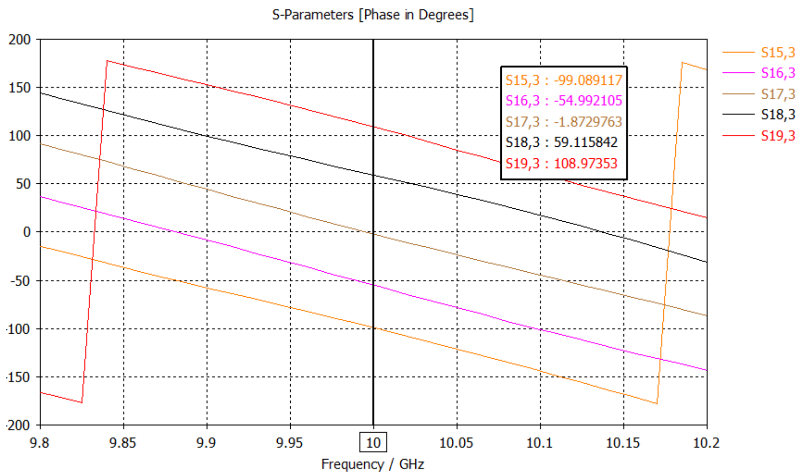


ROTMAN import CST

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

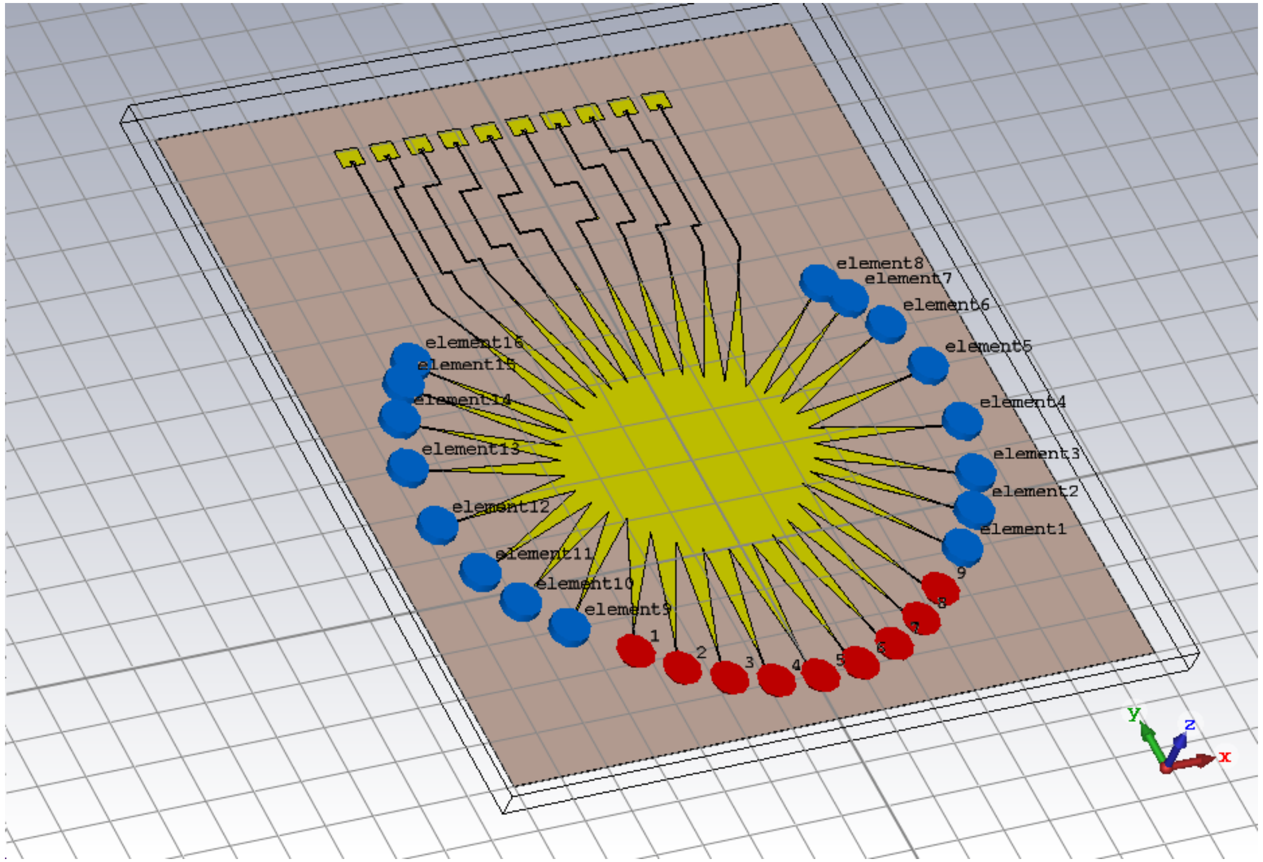


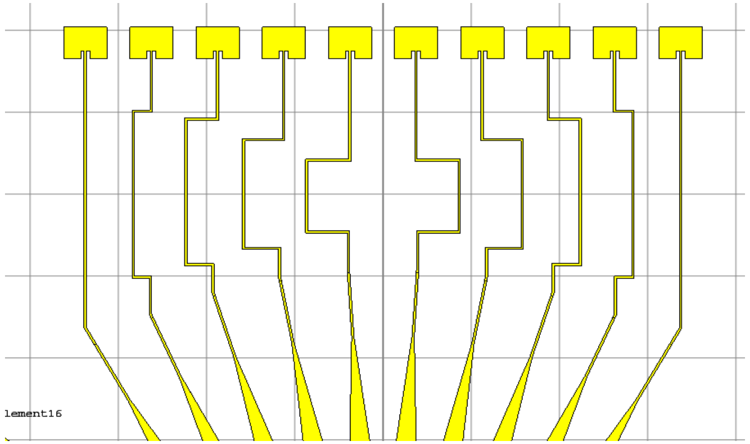




Final design

- 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.





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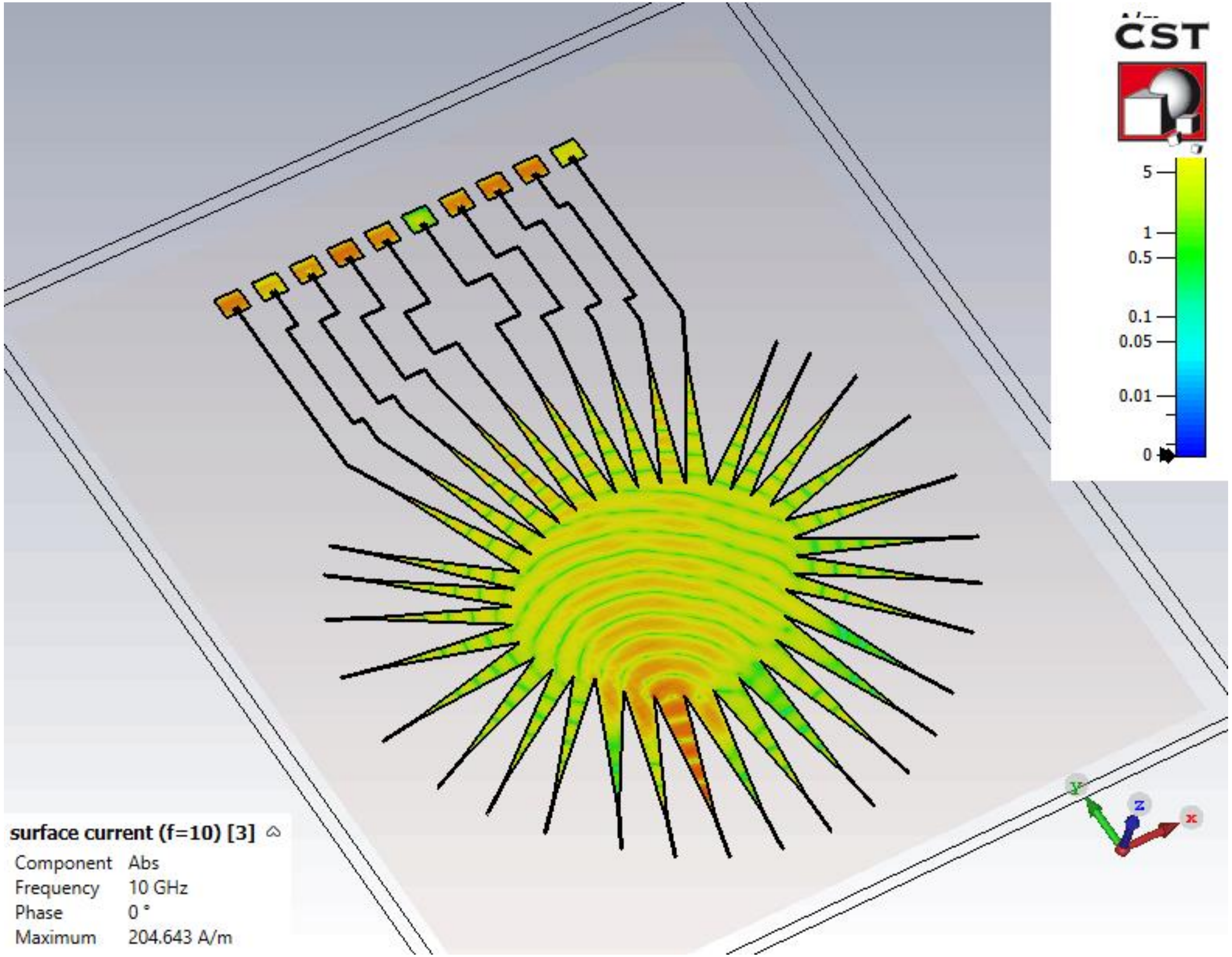
- Some microstrip line phase-shifters are introduced and optimized to produce a phase balance at every antenna port.
- Simulation takes long time on a 16Gb RAM laptop and cannot run very fine meshes.



Results

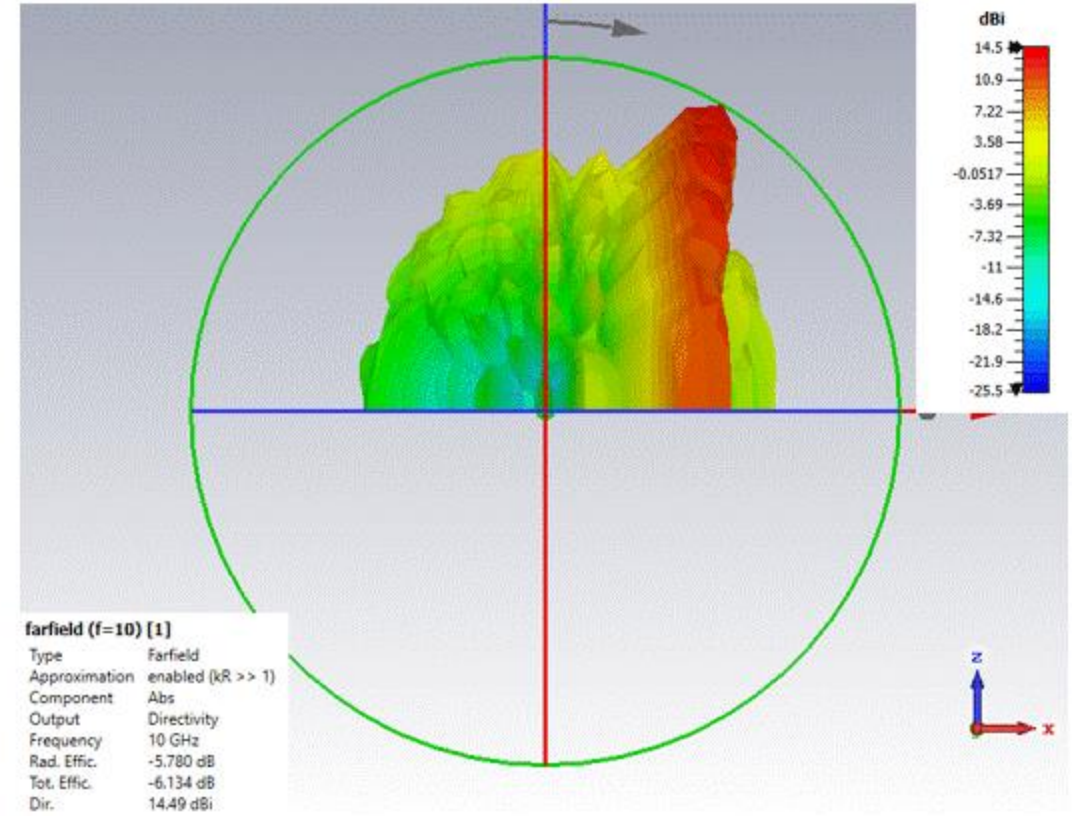
Excitation to Port 1
- Main lobe at 30^o
- 3dB beamwidth 11.6^o
- Directivity 14.2 dBi

Excitation to Port 2
- Main lobe at 22^o
- 3dB beamwidth 11.4^o
- Directivity 14.1 dBi

Excitation to Port 3
- Main lobe at 15^o
- 3dB beamwidth 11.1^o
- Directivity 14.42 dBi

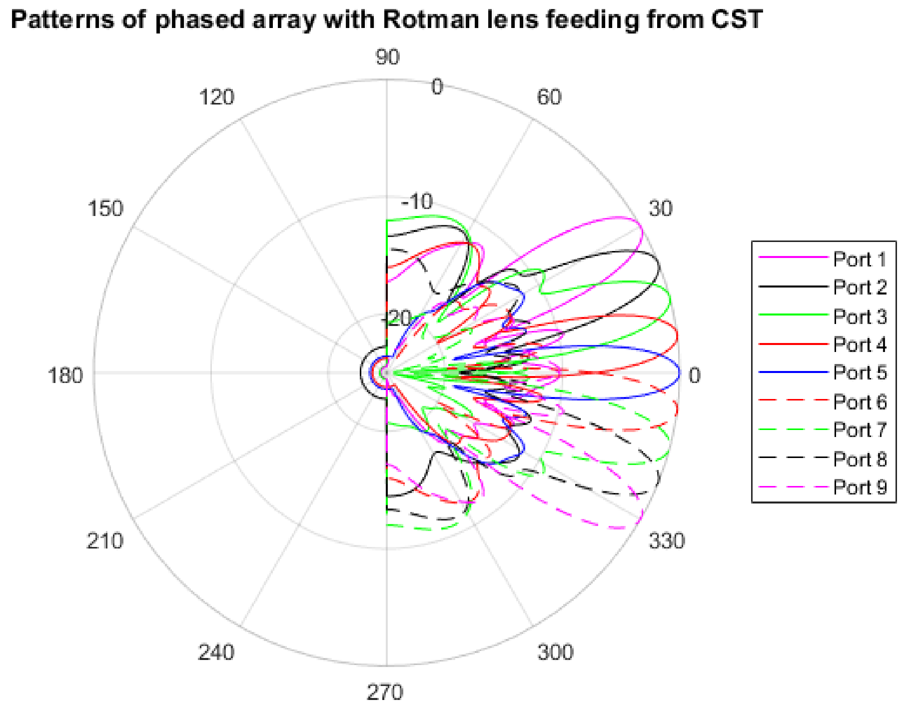
Excitation to Port 4
- Main lobe at 7^o
- 3dB beamwidth 10.3^o
- Directivity 14.07 dBi

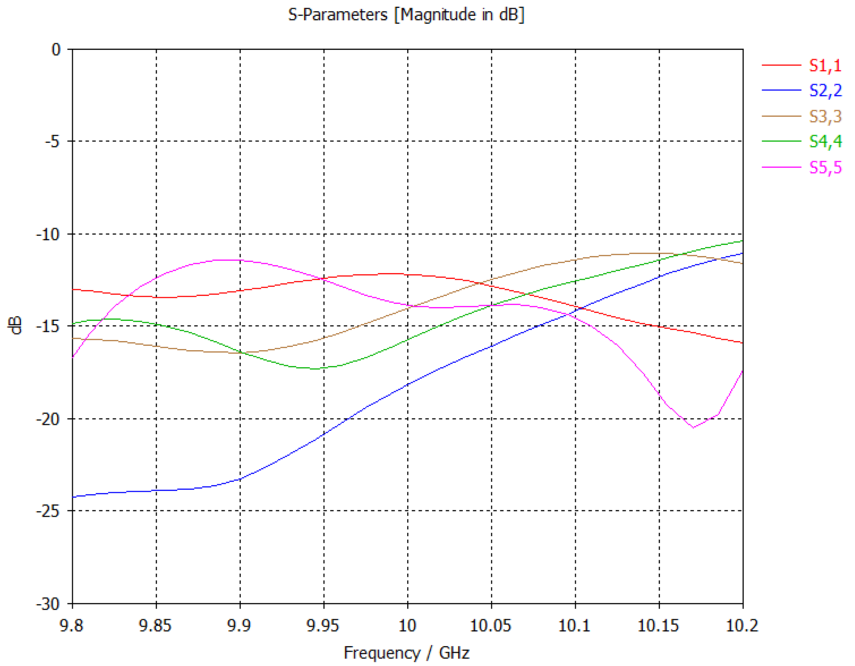
Excitation to Port 5
- Main lobe at 0^o
- 3dB beamwidth 10^o
- Directivity 14.24 dBi



Results

- All ports have better matching than -10dB
- The antenna can scan 60° broadside with around 14 dBi of directivity and with better than 5.5 dB total loss.
- Directivity and HPBW of each beam in the final design are similar to that of analytical and separating element design.
- Phase difference is smaller and varying making the scanning range 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.





Perspective

- This is a preliminary design, refinements are required on
  - Fine mesh simulations
  - Optimizing the Rotman lens to obtain $\Delta 30^{o}$ 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
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

Annex: Analytical analysis of the array

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

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

- So

$$E_{arr} = AF \times E_{element}$$