Analysis and Design of Planar Phased Array Antenna for 5 GHz Application

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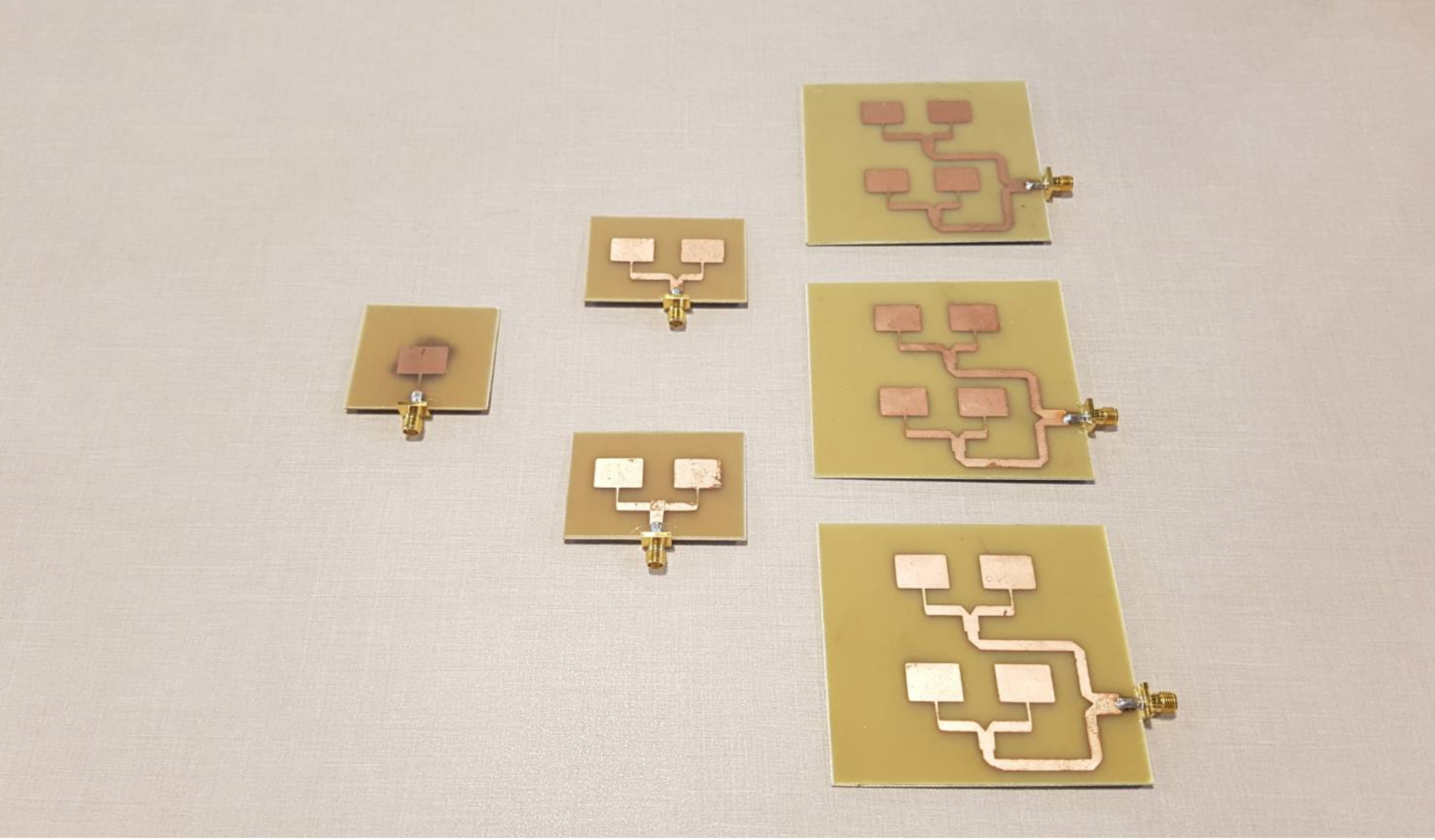
Advisor by Assist. Prof. Tuptim Angkaew



Dedicated Antennas

Fabricated By Norawit Nangsue
at KMUTNB

Outline

- Objective
- Project Plan
- Methodology
  - Microstrip Antenna
  - Array Antenna
  - Phased Array Antenna
- Design & Simulation
- Fabrication Procedure
- Measurement Results

Objective

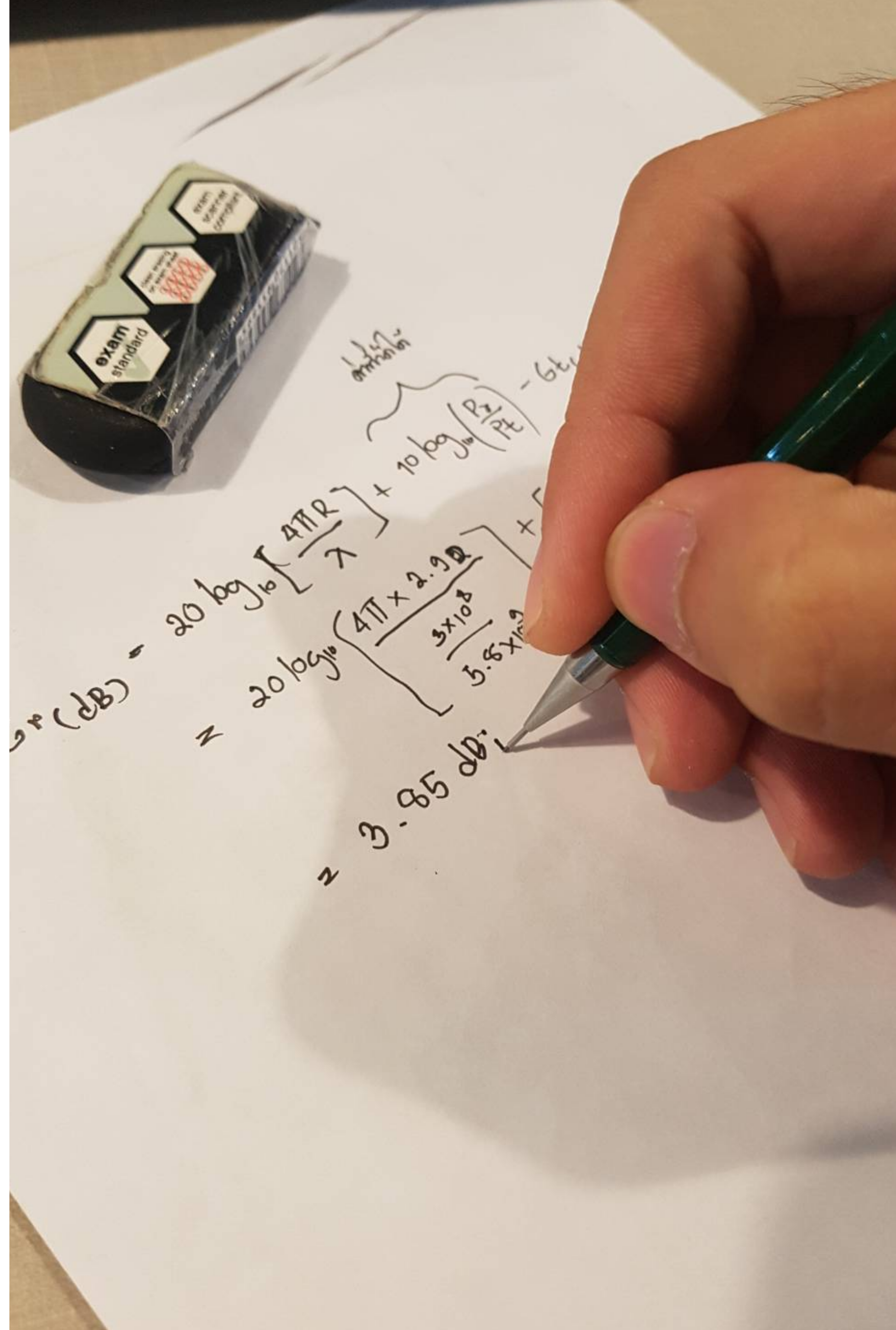
- To study the on how to analyze and design 5.8 GHz of
  - Single Microstrip Patch Antenna
  - 1x2, 2x2 Microstrip Array Antenna which is expected to have more gain than a single patch
  - 1x2, 2x2 Microstrip Phased Array Antenna which beam is expected to be tilted

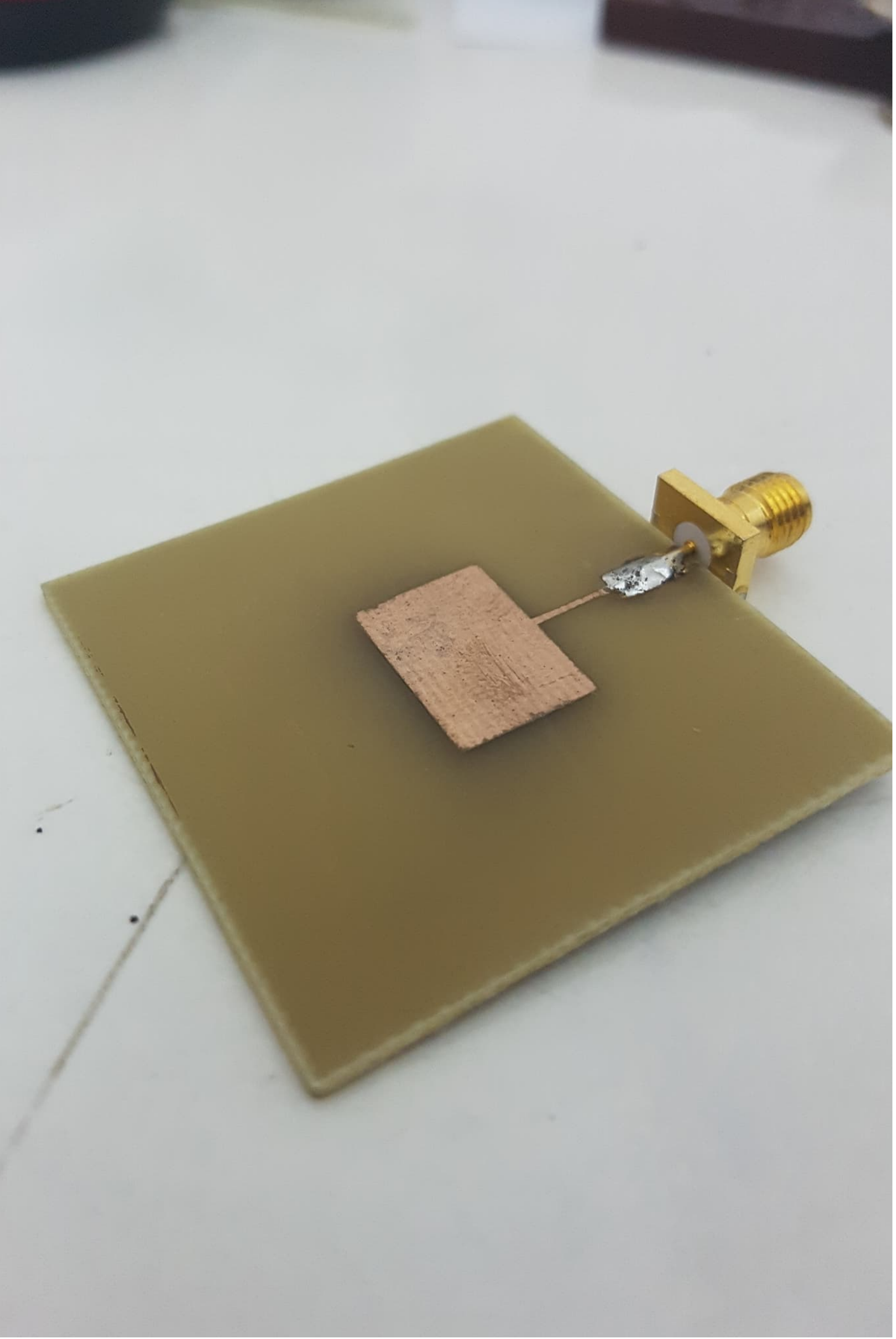
Project Plan

- 1. Design Microstrip Patch Antenna
- 2. Design 50 Ohm Matching Circuit
- 3. Simulate and optimize using CST Software
- 4. Combine together as an array antenna and design power divider with matching circuit
- 5. Shift phase of the array antenna
- 6. Fabricate those antennas
- 7. Measure for results

Methodology

Theories and calculation



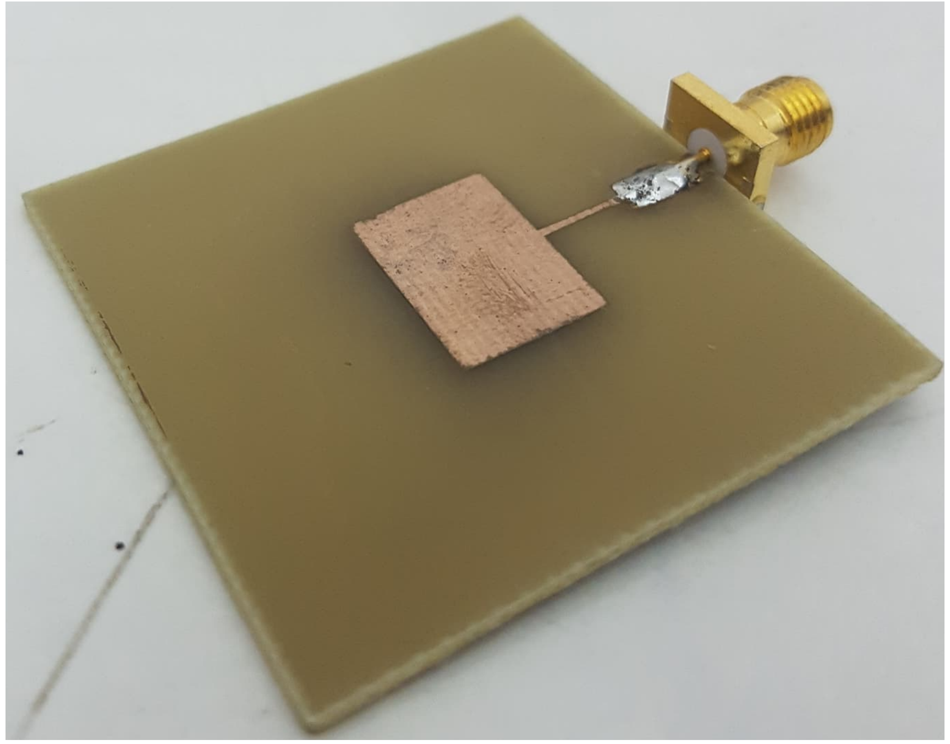


Microstrip Antenna

What's microstrip patch antenna?
Why using microstrip patch?
Transmission Line Model
Fringing Effect
Preliminary Design
Radiation Pattern
Design Procedure

What's microstrip patch antenna

- A patch over ground plane
- Resonant cavity with open slot
- In this project, it is built on FR-4 substrate

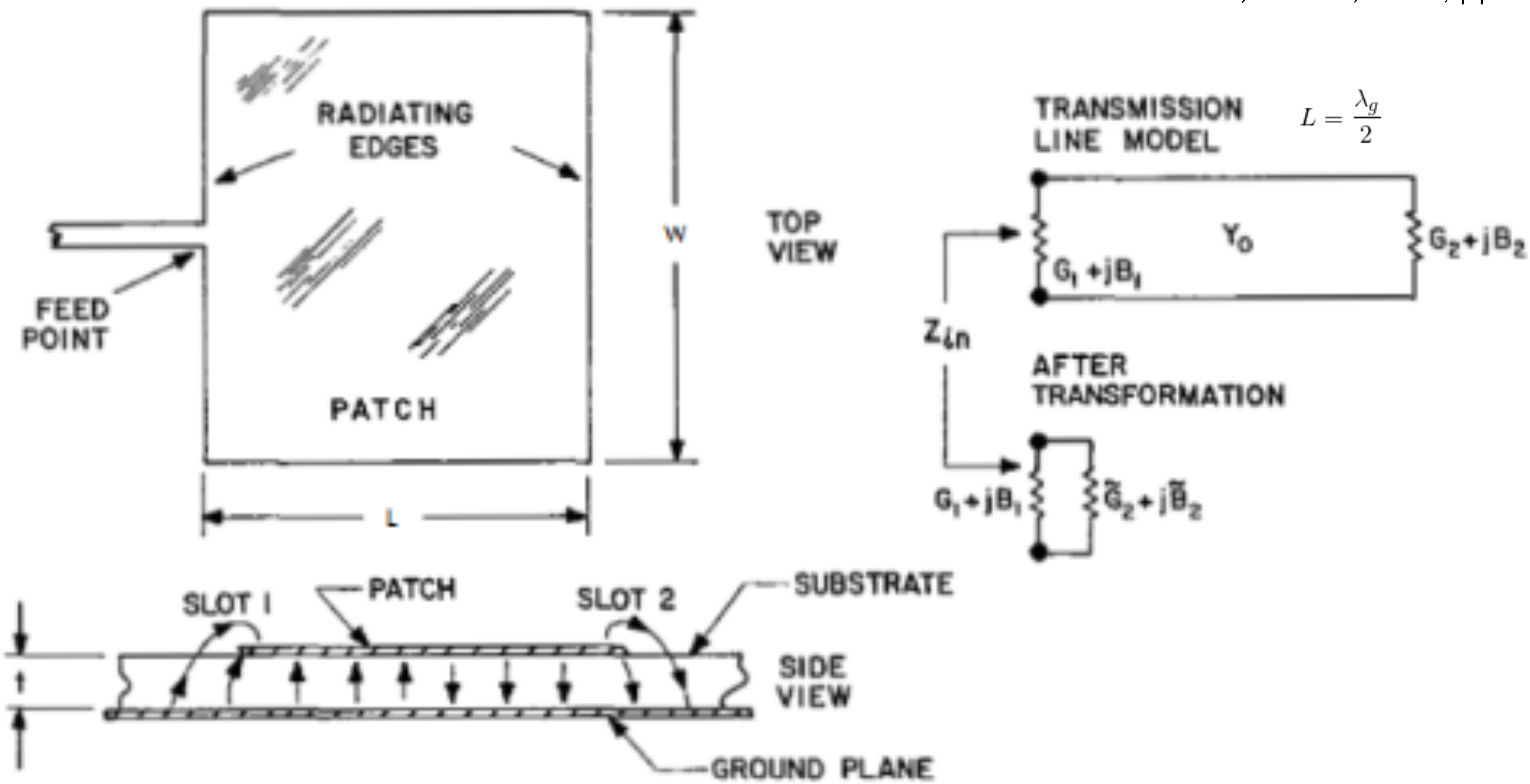


Why using microstrip patch antenna?

- It's low profile
- It's lightweight
- It's easy to fabricate
- It's cost effective

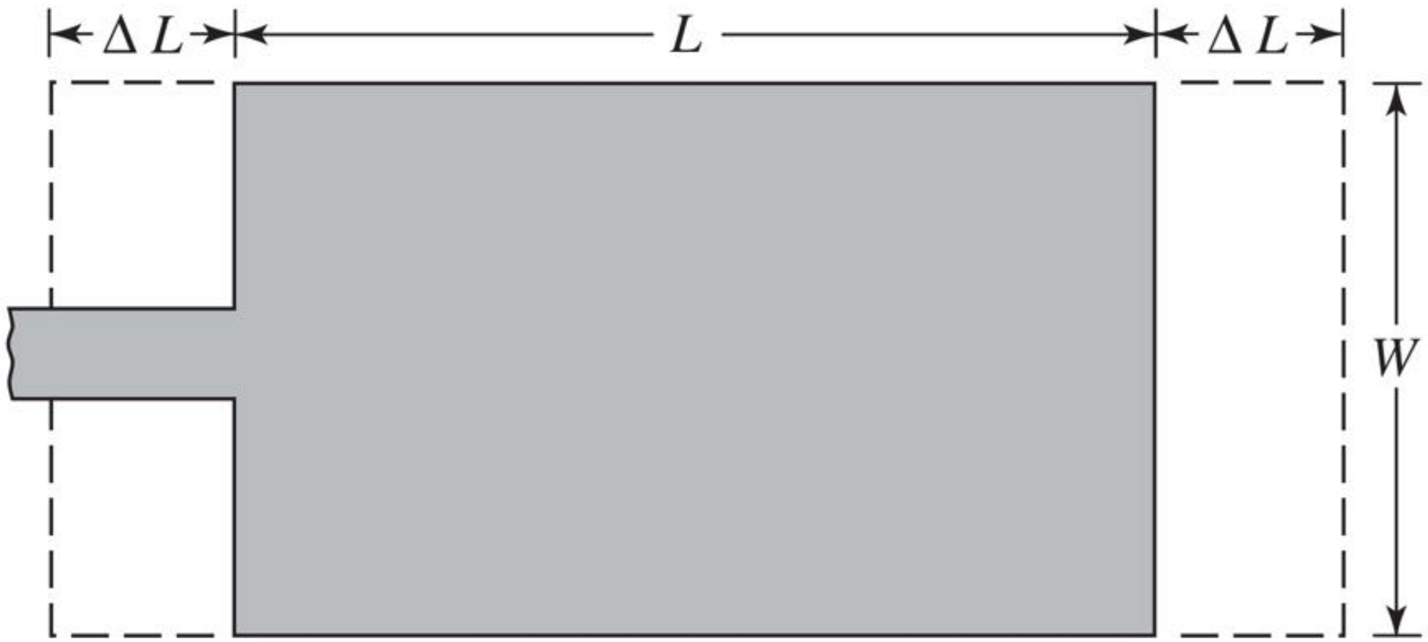
Microstrip Antenna - Transmission Line Model

K. Carver and J. Mink, "Microstrip antenna technology," in IEEE Transactions on Antennas and Propagation, vol. 29, no. 1, pp. 2-24, Jan 1981.



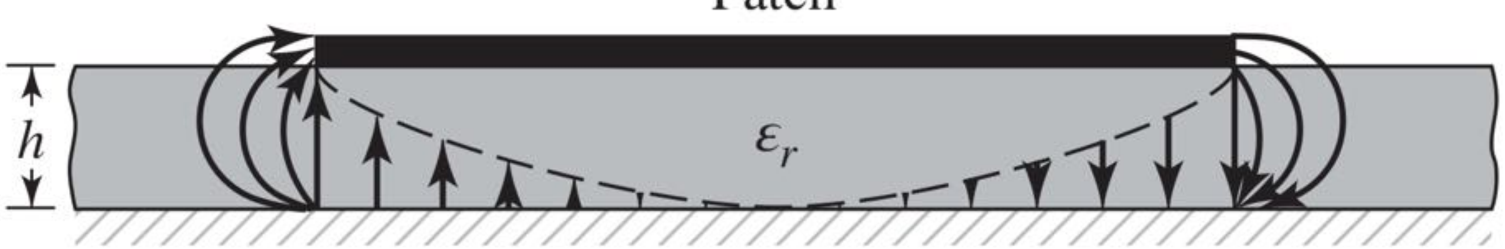
$$G_1 + jB_1 \simeq \frac{\pi W}{\lambda_0 \eta_0}\left[1 + j\left(1 - 0.636 \ln\left(k_0 h\right)\right)\right] \qquad Y_0 = \frac{W\sqrt{\epsilon_r}}{h\eta_0}$$

Microstrip Antenna -
Fringing Effect & Preliminary Design



(a) Top view

Patch



(b) Side view

Extra fringing length

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{r(eff)} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{r(eff)} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

Length with fringing effect compensation

$$L = \frac{c}{2f_r\sqrt{\epsilon_r\mu_r}} - 2\Delta L$$

For best radiation efficiency

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}}$$

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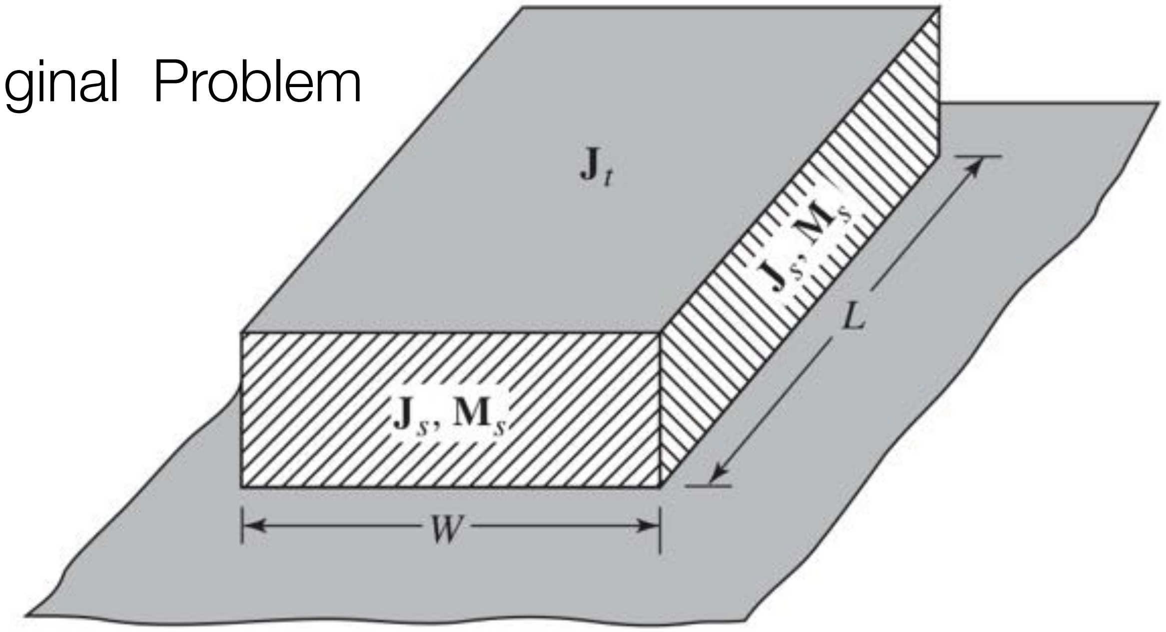
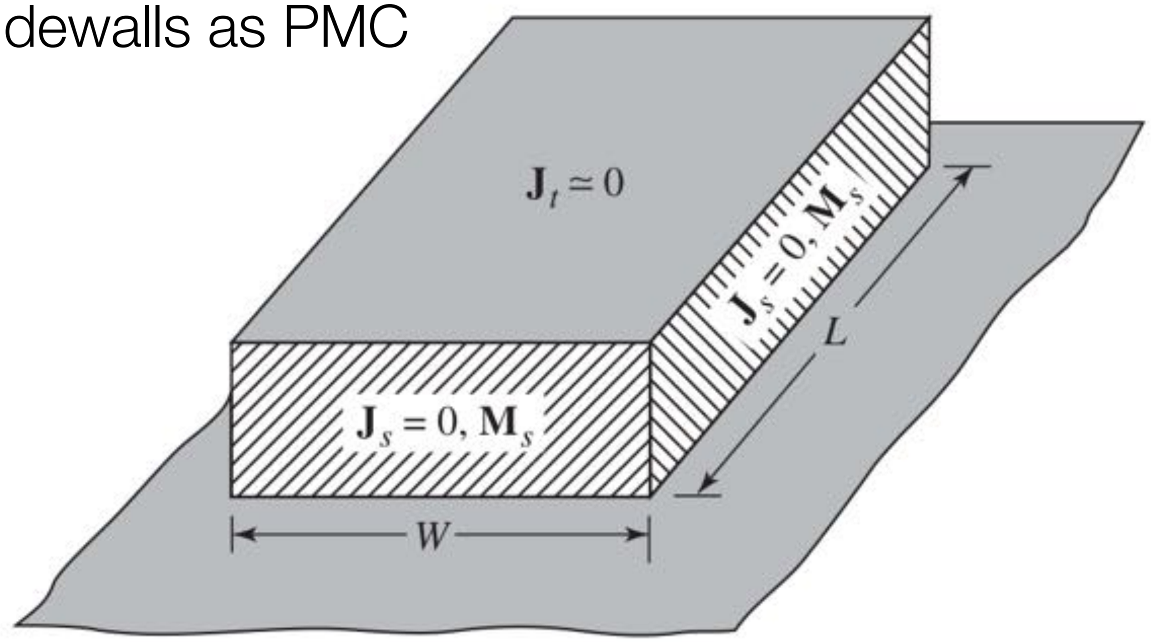
Radiation Pattern

1. Original Problem



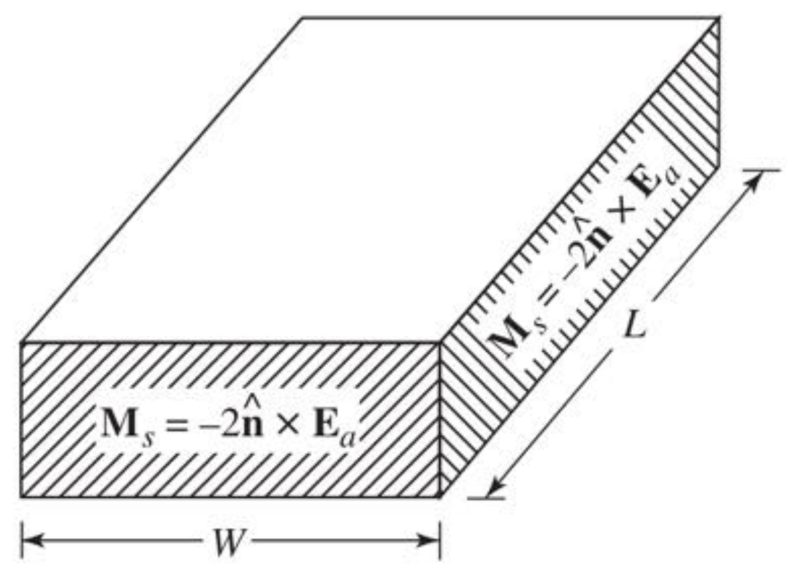
(a) $\mathbf{J}_s$, $\mathbf{M}_s$ with ground plane

2. Let Jt, Js = 0 and
assume 4 sidewalls as PMC



(b) $\mathbf{J}_s = 0$, $\mathbf{M}_s$ with ground plane

3. Remove PMC



(c) $\mathbf{M}_s$ with no ground plane

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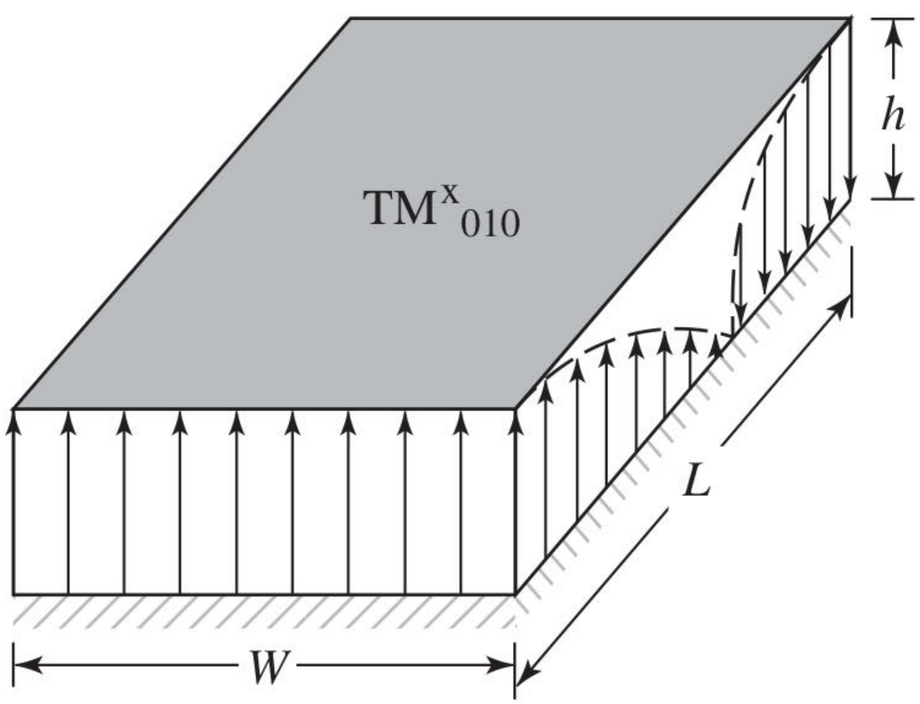
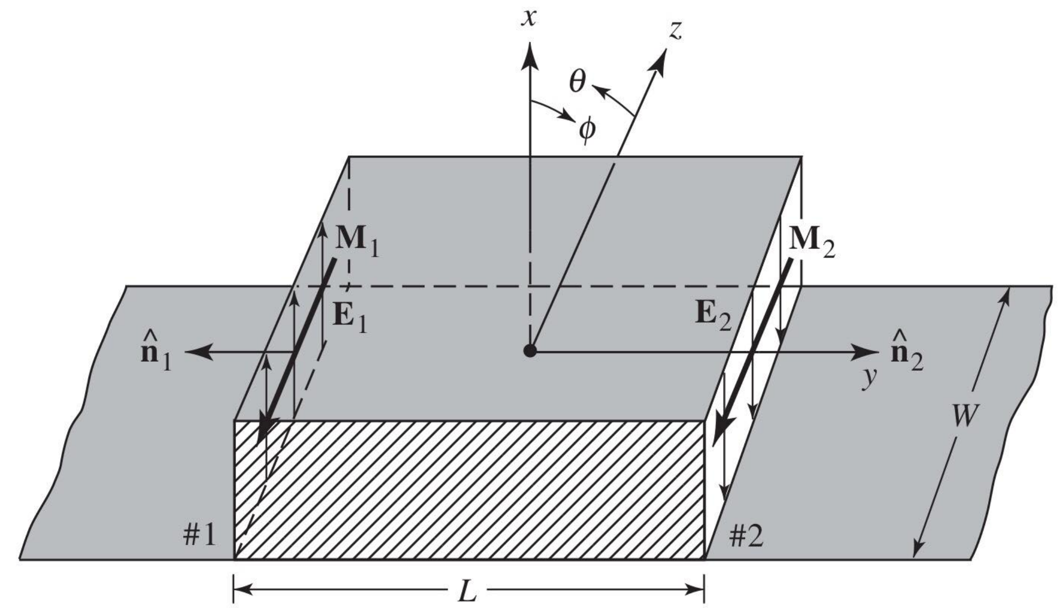
Radiation Pattern

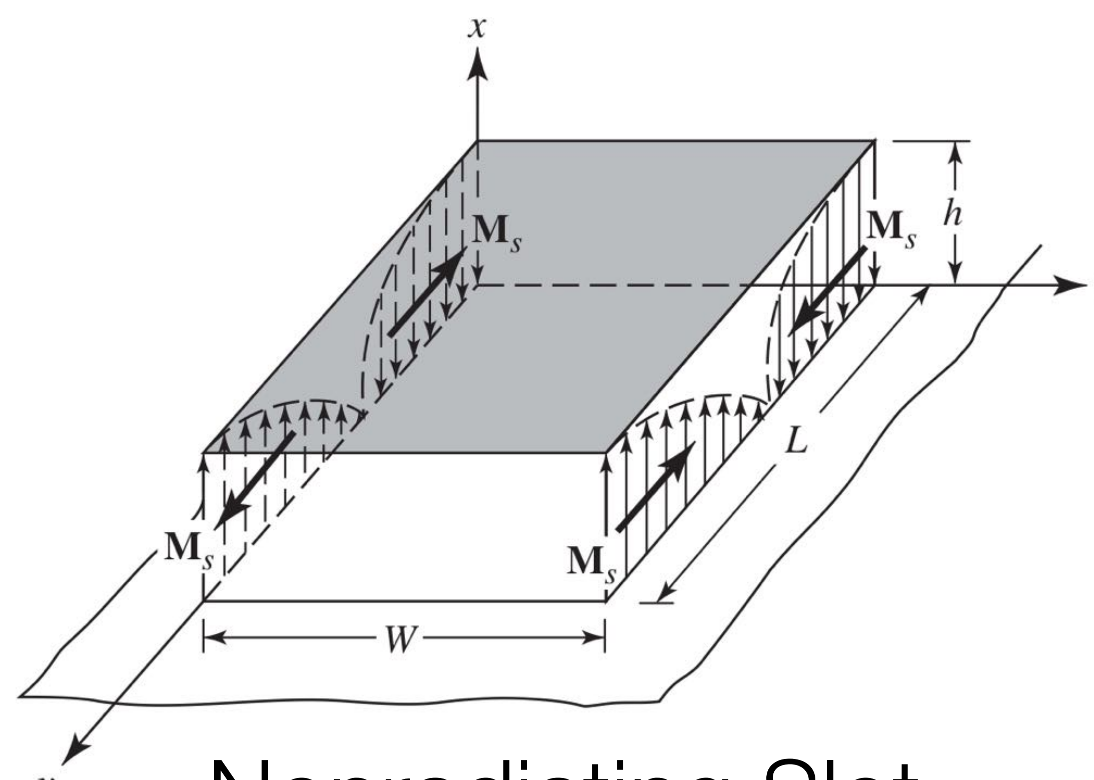
There are 2 types of slot



Cavity Model



Radiating Slot



Nonradiating Slot

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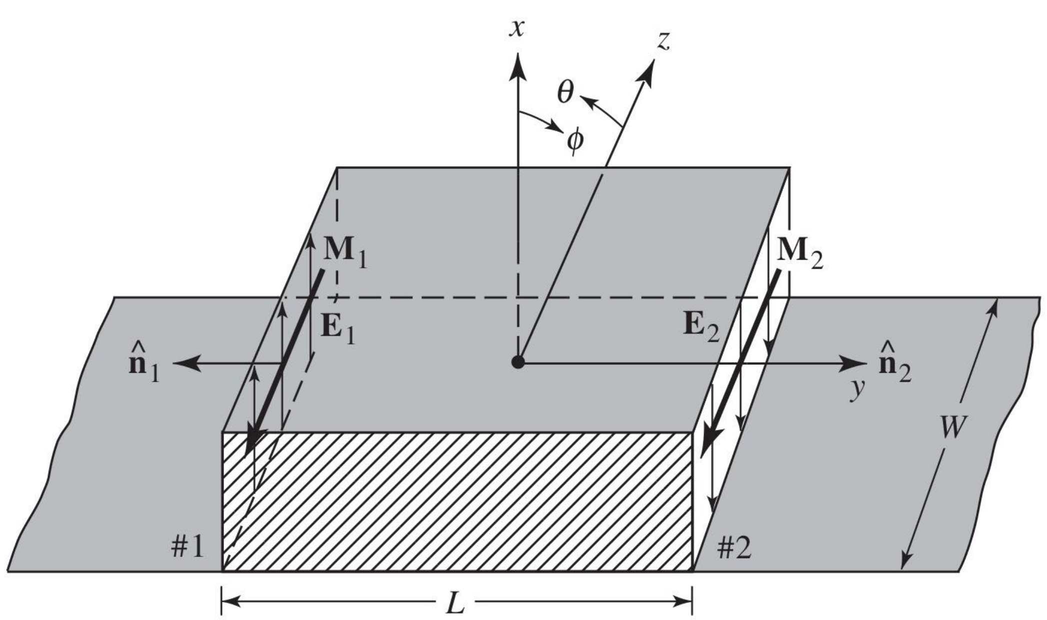
Radiation Pattern



$$\mathbf{E}_F = -\frac{1}{\varepsilon}\nabla \times \mathbf{F} \qquad \nabla \times \mathbf{H}_F = j\omega\varepsilon \mathbf{E}_F$$

$$\mathbf{F} = \frac{\varepsilon}{4\pi} \iint_S \mathbf{M}_s \frac{e^{-jkR}}{R}\, ds'$$

$$\mathbf{M}_s = -2\hat{\mathbf{n}} \times E_a$$

$$E_x = E_0 \cos\left(\frac{\pi}{L} y'\right)$$

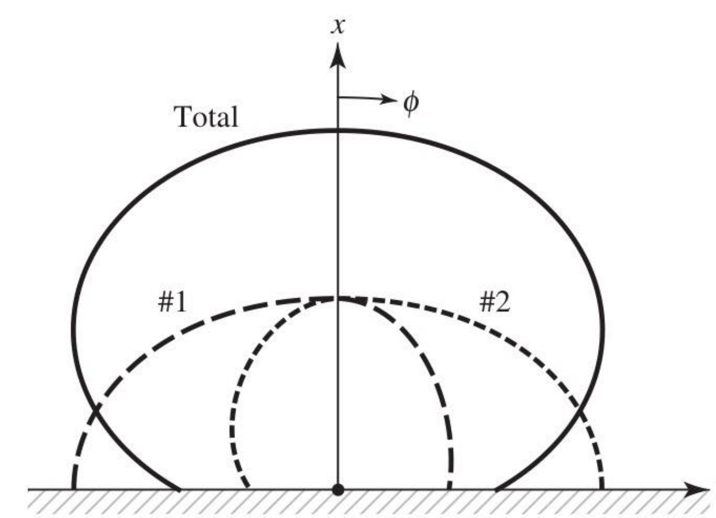
Microstrip Antenna - Radiation Pattern

After solving Maxwell Equation,

$$E_\phi = j\frac{k_0 W V_0}{\pi r}e^{-jk_0 r}\left(\cos\theta\sin\phi\frac{\sin X}{X}\frac{\sin Y}{Y}\right)\times\cos(Z)$$

$$E_\theta = j\frac{k_0 W V_0}{\pi r}e^{-jk_0 r}\left(\cos\phi\frac{\sin X}{X}\frac{\sin Y}{Y}\right)\times\cos(Z)$$

$$f(\theta,\phi) = \sqrt{\vec{E}_\phi^2+\vec{E}_\theta^2} = \sqrt{1-\sin^2\phi\sin^2\theta}\cdot\frac{\sin X}{X}\frac{\sin Y}{Y}\cos Z$$

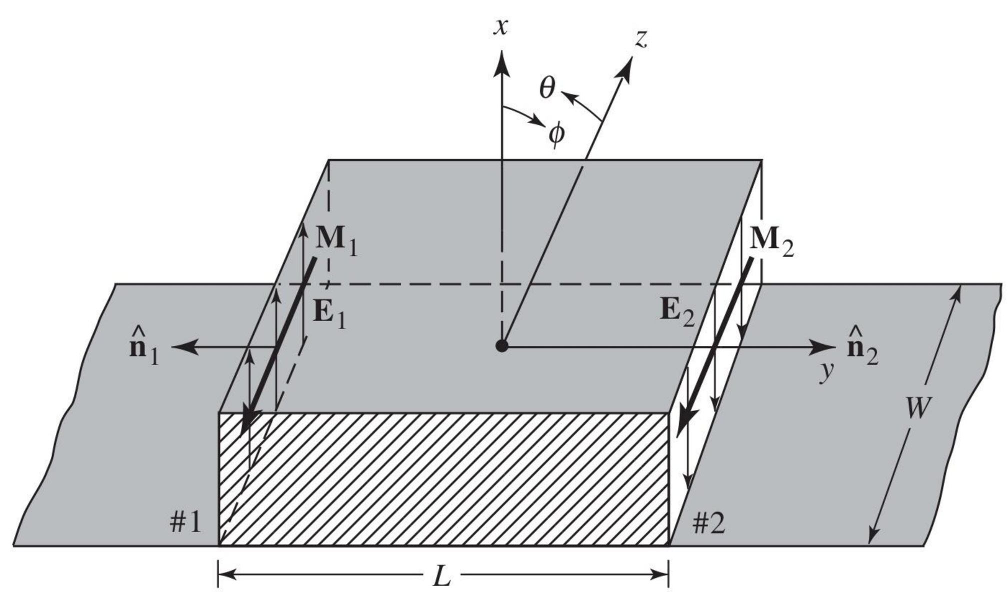


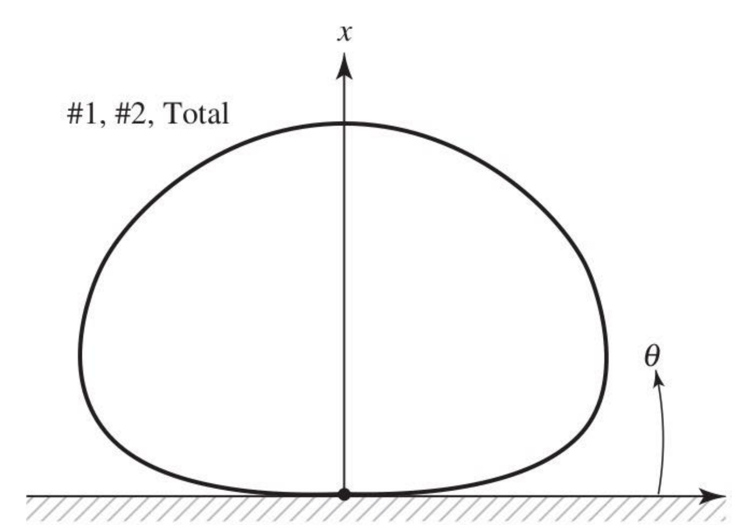
(a) *E*-plane

$$X = \frac{k_0 h}{2}\sin\theta\cos\phi$$

$$Y = \frac{k_0 W}{2}\sin\theta\cos\phi$$

$$Z = \frac{k_0 L_{eff}}{2}\cos\theta$$





(b) *H*-plane

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Microstrip Antenna - Design Procedure(Step 1: Find Width)

For best radiation efficiency

1.

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}}$$
$$= \frac{3 \times 10^8}{2 \times 5.8 \times 10^9}\sqrt{\frac{2}{4.3+1}}$$
$$= 15.8 \text{ mm}$$

Microstrip Antenna -
Design Procedure(Step 2 : Find Length)

2.1

$$\epsilon_{r(eff)} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$
$$= \frac{4.3 + 1}{2} + \frac{4.3 - 1}{2}\left[1 + 12 \times \frac{1.6 \times 10^{-3}}{15.8 \times 10^{-3}}\right]^{-1/2}$$
$$= 3.76$$

2.2

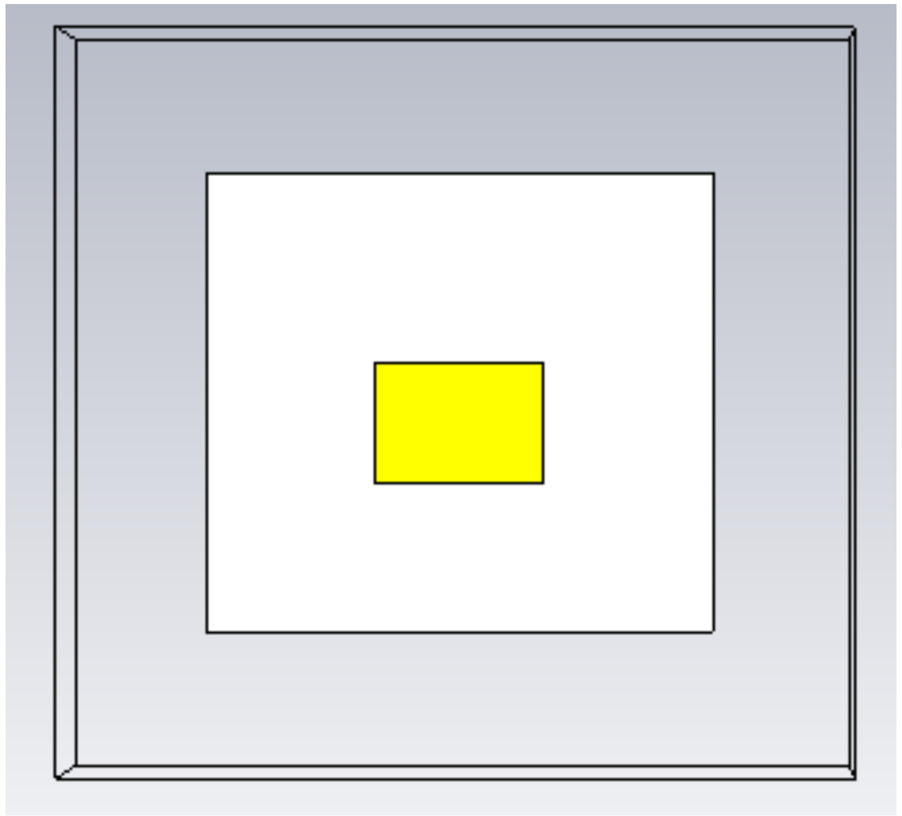
$$\frac{\Delta l}{h} = 0.412\frac{(\epsilon_{r(eff)} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{r(eff)} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$
$$= 0.412\frac{(3.76 + 0.3)\left(\frac{15.8}{1.6} + 0.264\right)}{(3.76 - 0.258)\left(\frac{15.8}{1.6} + 0.8\right)}$$
$$= 0.454$$

2.3

$$\Delta L = 0.454 \times h$$
$$= 0.454 \times 1.6 \text{ mm}$$
$$= 0.726 \text{ mm}$$

2.4

$$L = \frac{c}{2f_r\sqrt{\epsilon_r \mu_r}} - 2\Delta L$$
$$= \frac{3 \times 5 \times 10^8}{2 \times 10^9\sqrt{3.76 \times 1}} - 2 \times 0.454$$
$$= 11.9 \text{ mm}$$



We have the dimension of the patch antenna.
But the standard feedline is 50 Ohm.
Therefore, we have to make create matching circuit

Microstrip Antenna - Design Procedure(Step 3 : Find Input Impedance)

3.1

$$X = k_0 W = \frac{2\pi f_0}{c} \times W$$
$$= \frac{2\pi \times 5.8 \times 10^9}{3 \times 10^8} \times 15.8 \times 10^{-3}$$
$$= 1.92$$

3.2

$$I_1 = -2 + \cos(X) + XSi(X) + \frac{\sin(X)}{X}$$
$$= -2 + \cos(1.92) + 1.92 \times 15.8 \times 10^{-3} \times Si(1.92) + \frac{\sin(1.92)}{1.92}$$
$$= 1.17$$

3.3

$$G_1 = \frac{I_1}{120\pi^2}$$
$$= \frac{1.17}{120\pi^2}$$
$$= 0.988\ mS$$

3.4

$$Y = k_0 L = \frac{2\pi f_0}{c} \times L$$
$$= \frac{2\pi \times 5.8 \times 10^9}{3 \times 10^8} \times 11.9 \times 10^{-3}$$
$$= 1.45$$

3.5

$$G_{12} = \frac{1}{120\pi^2} \int_0^\pi \left[\frac{\sin\left(\frac{X}{2}\cos\theta\right)}{\cos\theta} \right]^2 J_0(Y\sin\theta)\sin^3\theta d\theta$$
$$= \frac{1}{120\pi^2} \int_0^\pi \left[\frac{\sin\left(\frac{1.92}{2}\cos\theta\right)}{\cos\theta} \right]^2 J_0(1.45\sin\theta)\sin^3\theta d\theta$$
$$= 0.613\ mS$$

3.6

$$Z_{in} = \frac{1}{2(G_1 \pm G_{12})}$$
$$= \frac{1}{2(0.988 \times 10^{-3} + 0.613 \times 10^{-3})}$$
$$= 312.6\ \Omega$$

G1 is defined as slot admittance

G12 is defined as mutual slot admittance

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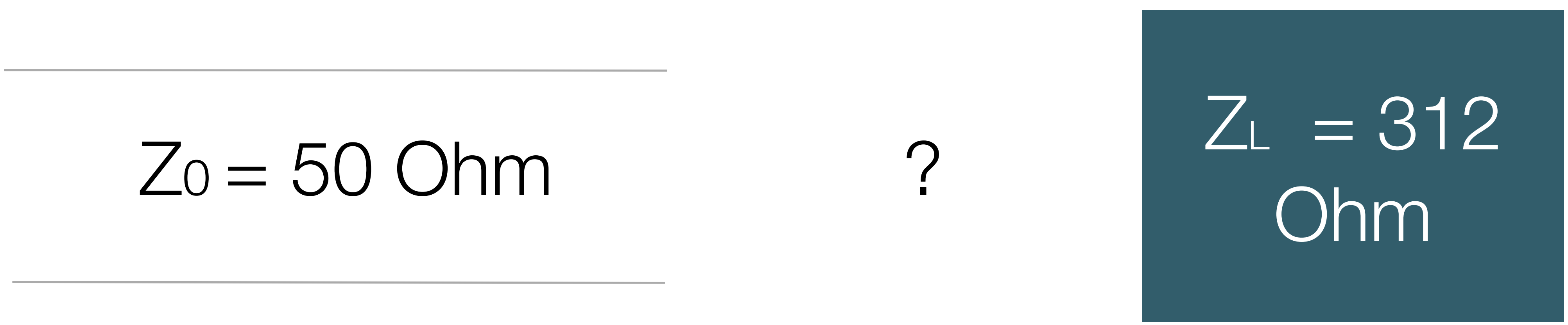
What do we have now?



A matching circuit is required due to impedance mismatch

Solution: Use Quarter Wave Transformer

Microstrip Antenna - Design Procedure(Step 4: Design QWT)

$$Z_{QWT} = \sqrt{Z_{in} Z_L} = \sqrt{50 \times 312.6} = 125\ \Omega$$

Hammerstad's

$$W_{QWT} = 0.37 \text{ mm}$$

Effective Dielectric Constant

$$L_{QWT} = \frac{c}{4 f_r \sqrt{\epsilon_{r(eff)}}}$$

$$L_{QWT} = 7.6 \text{ mm}$$

Microstrip Antenna - Design Procedure(Hammerstad's Equation)

$$\frac{W}{h} = \begin{cases} \dfrac{8}{e^{A} - 2e^{-A}}, & \text{for } \dfrac{W}{h} \leqslant 2 \\ \dfrac{2}{\pi}\left\{B - 1 - ln(2B - 1) + \dfrac{\epsilon_r - 1}{2\epsilon_r}\left[ln(B - 1) + 0.39 - \dfrac{0.61}{\epsilon_r}\right]\right\}, & \text{for } \dfrac{W}{h} > 2 \end{cases}$$

$$A = \frac{\pi}{\eta_0}\sqrt{2(\epsilon_r + 1)}Z + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(0.23 + \frac{0.11}{\epsilon_r}\right)$$

$$B = \frac{\pi\eta_0}{2\sqrt{\epsilon_r}Z}$$

Microstrip Antenna -
Design Procedure(Effective Dielectric Constant)

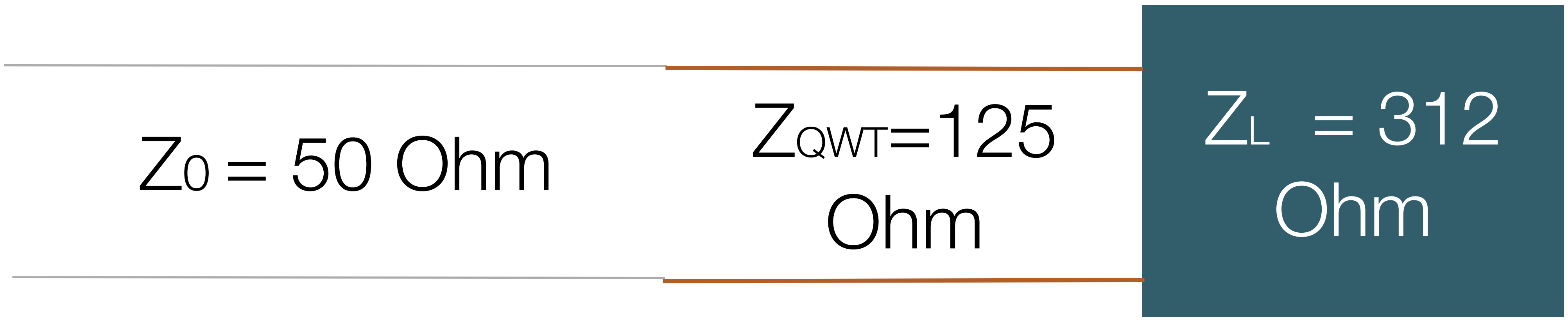
For $\frac{W}{h} > 1$

$$\epsilon_{r(eff)} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

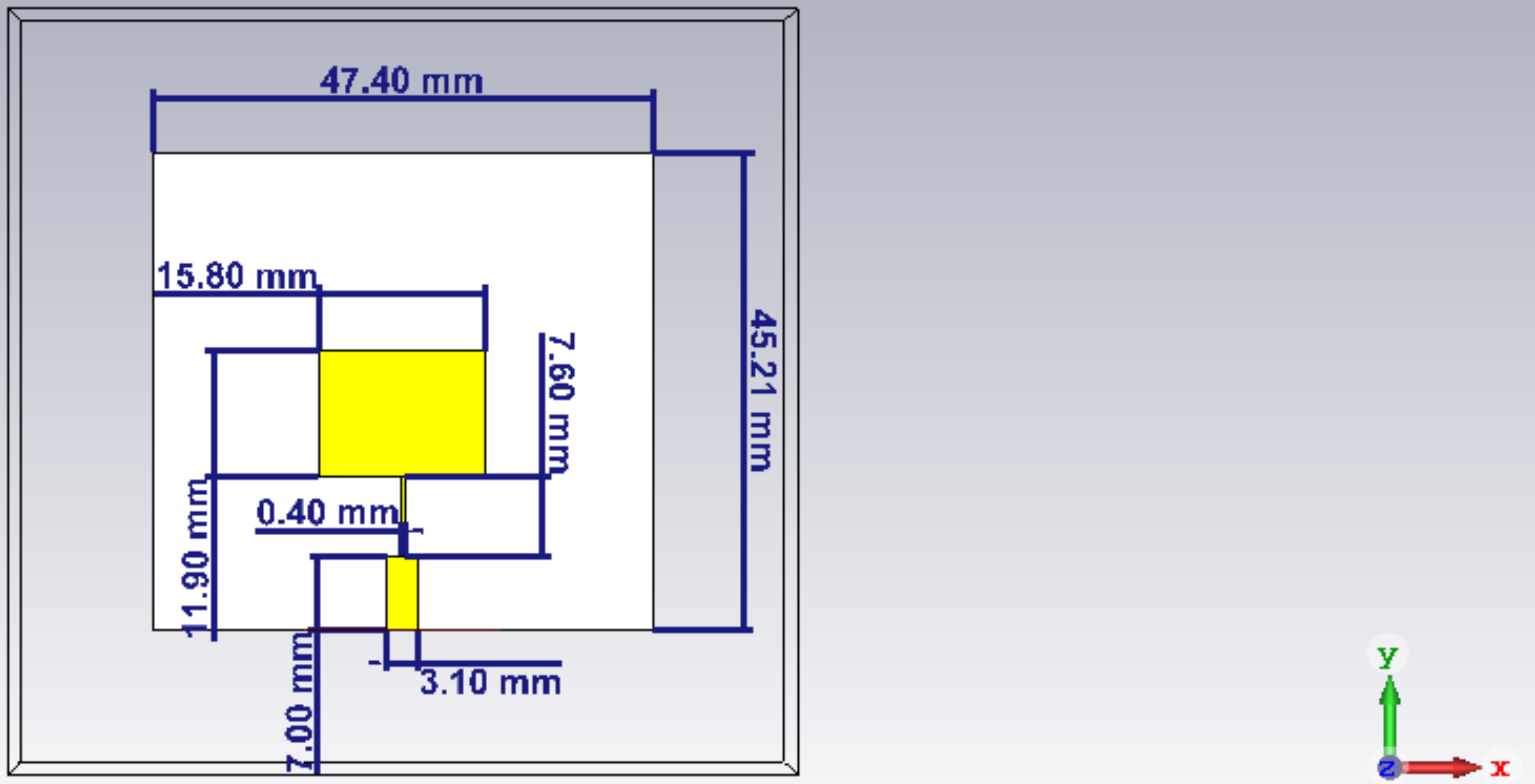
For $\frac{W}{h} \leqslant 1$

$$\epsilon_{r(eff)} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left\{\left[1 + 12\frac{h}{W}\right]^{-1/2} + 0.04\left[1 - \frac{W}{h}\right]^2\right\}$$

What do we have now?



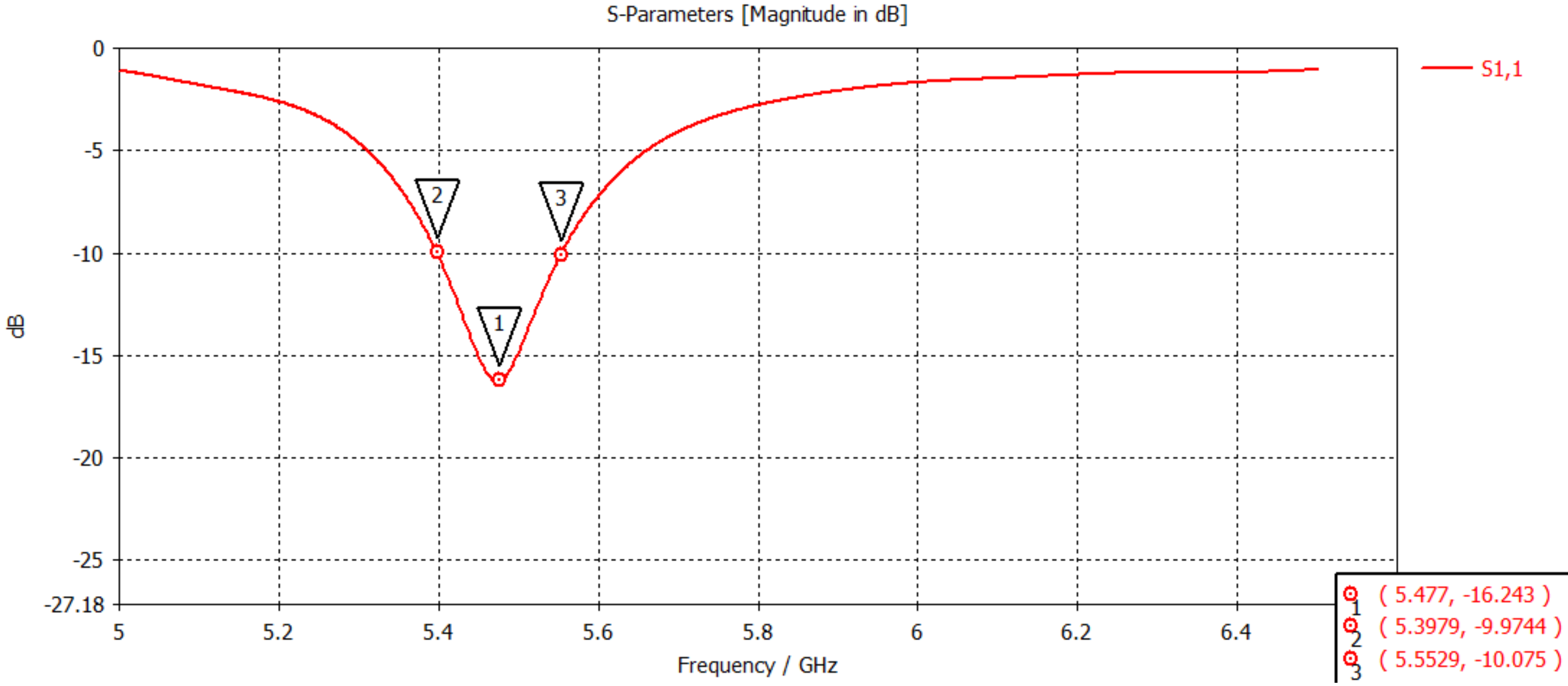
The circuit is completed



Microstrip Antenna

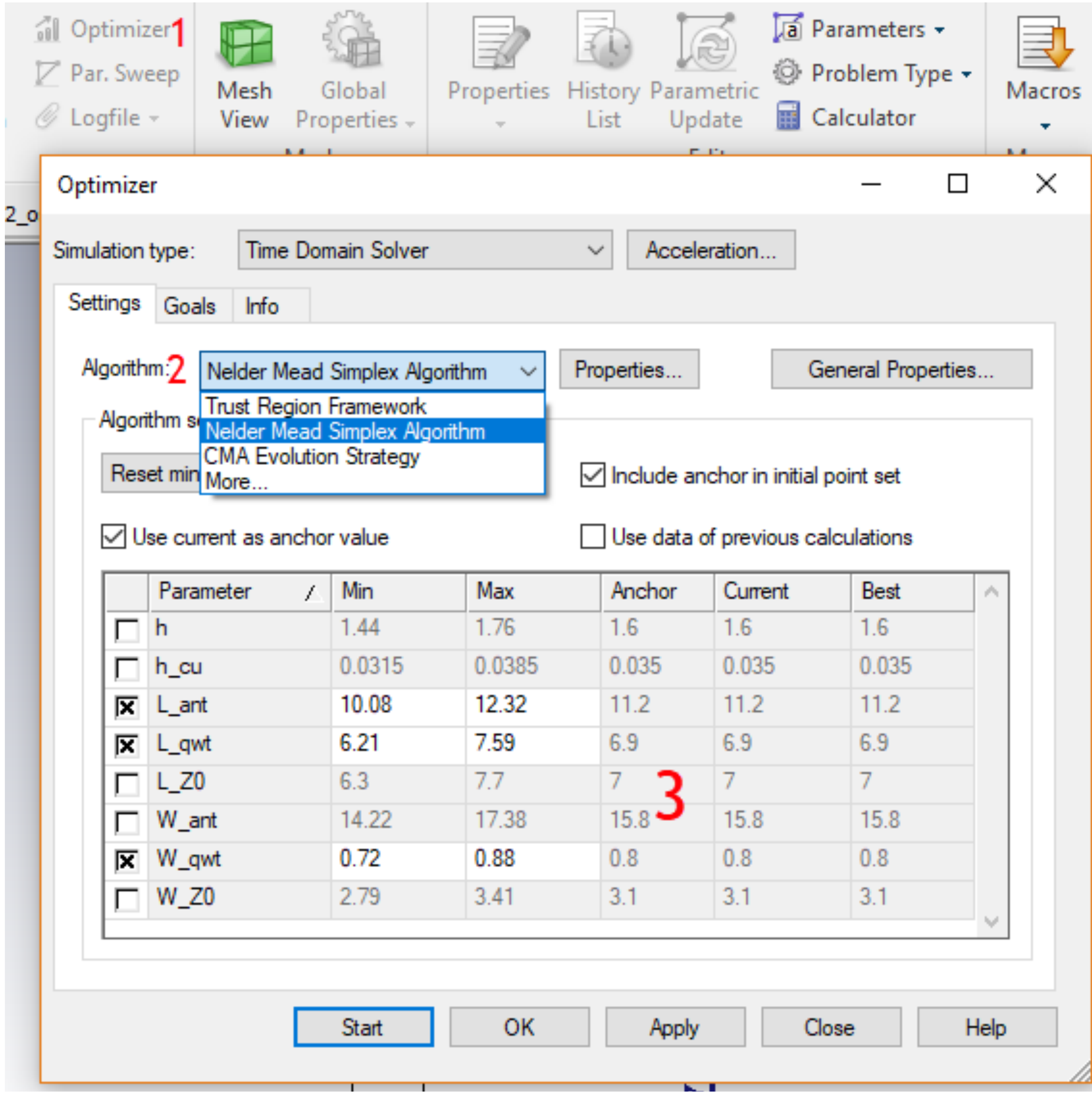
Prototype

Simulate and wait about 10 minutes

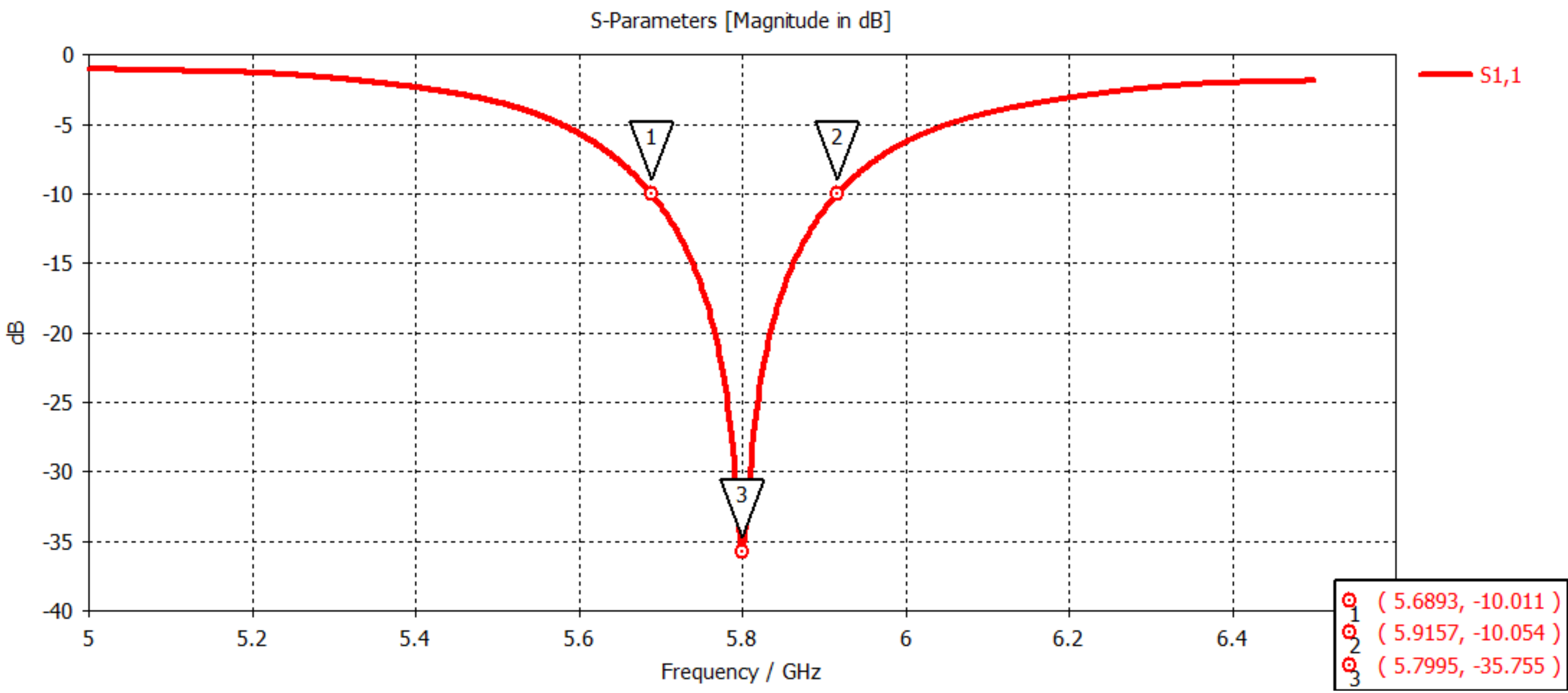


S11 | First Prototype

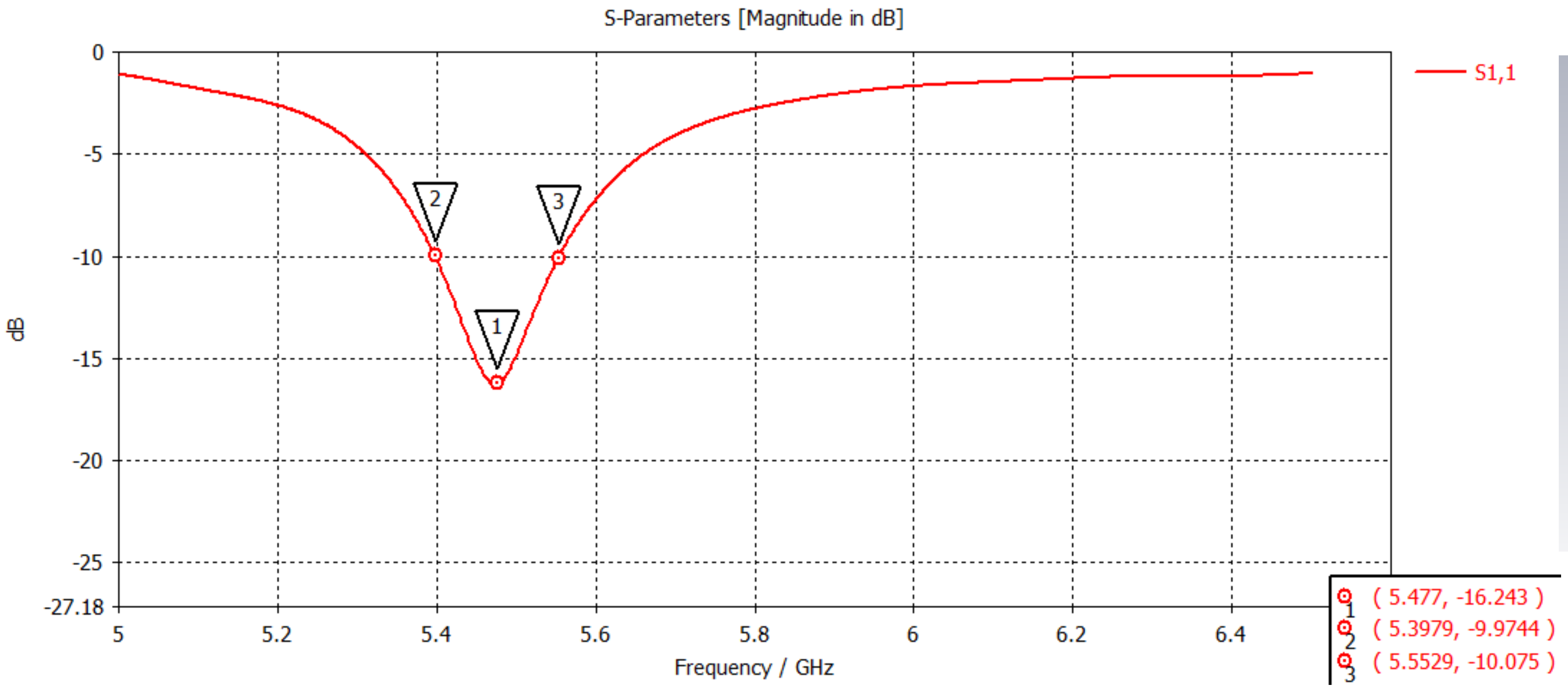
Optimization for the best S11

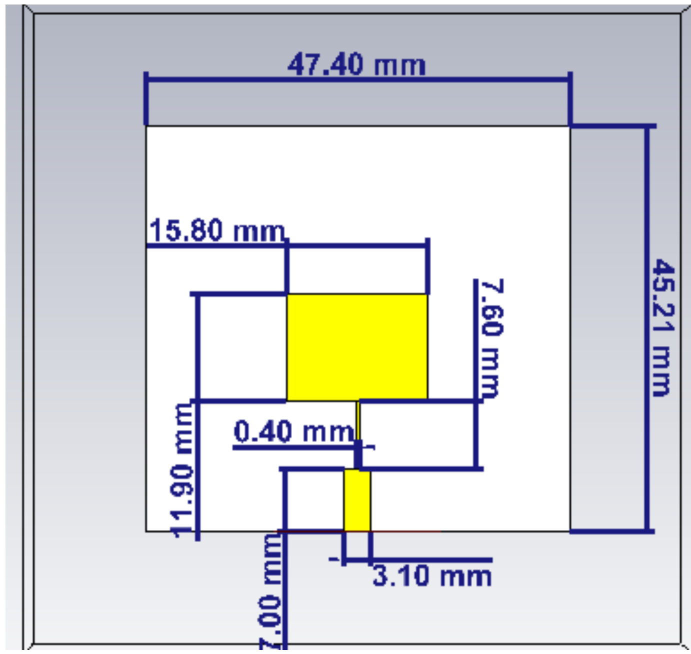


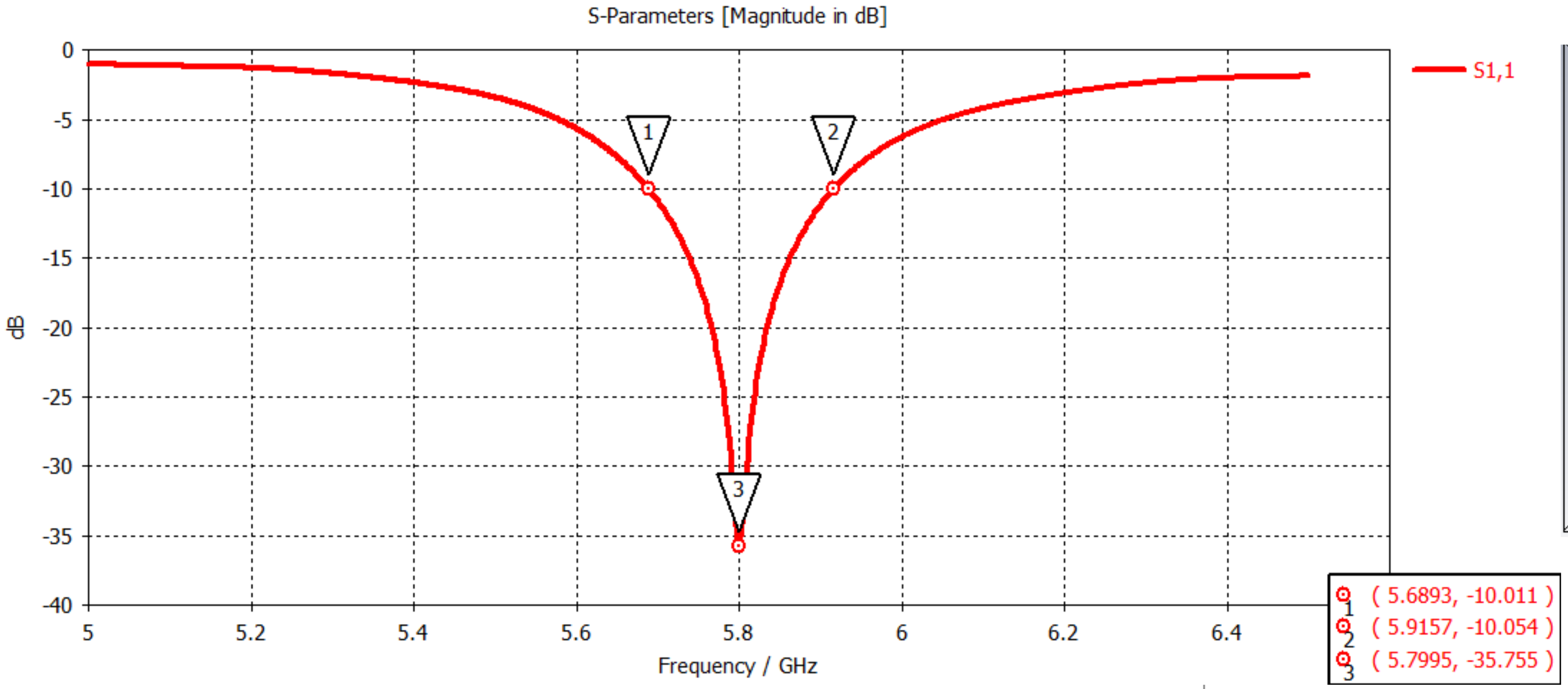
Wait about 10 hours

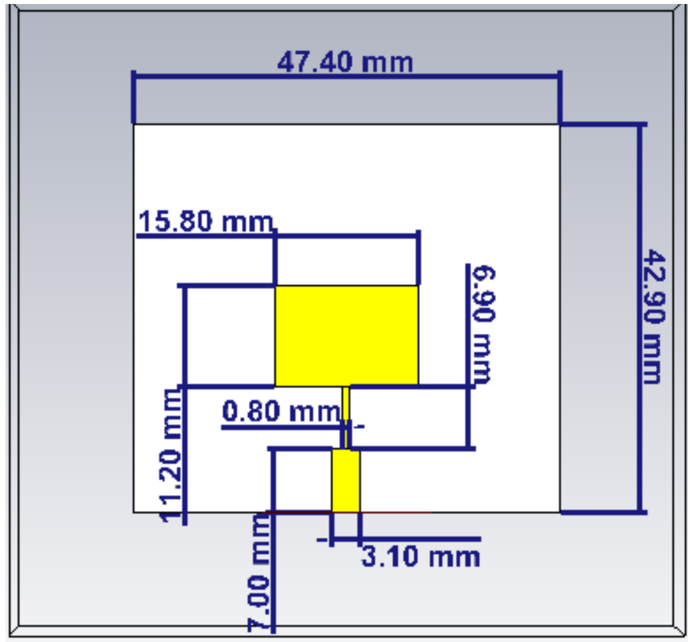


S11 | Optimized



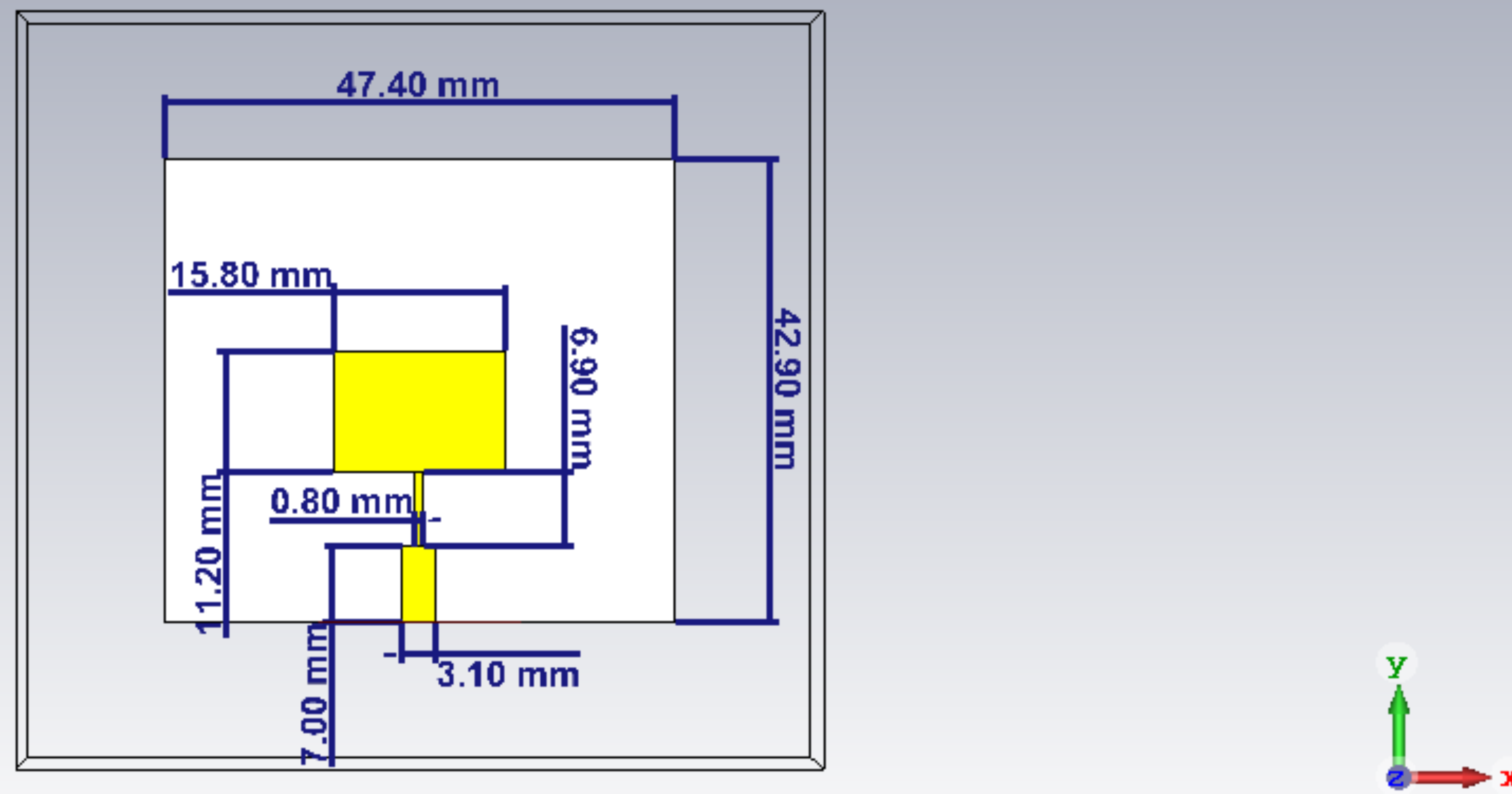






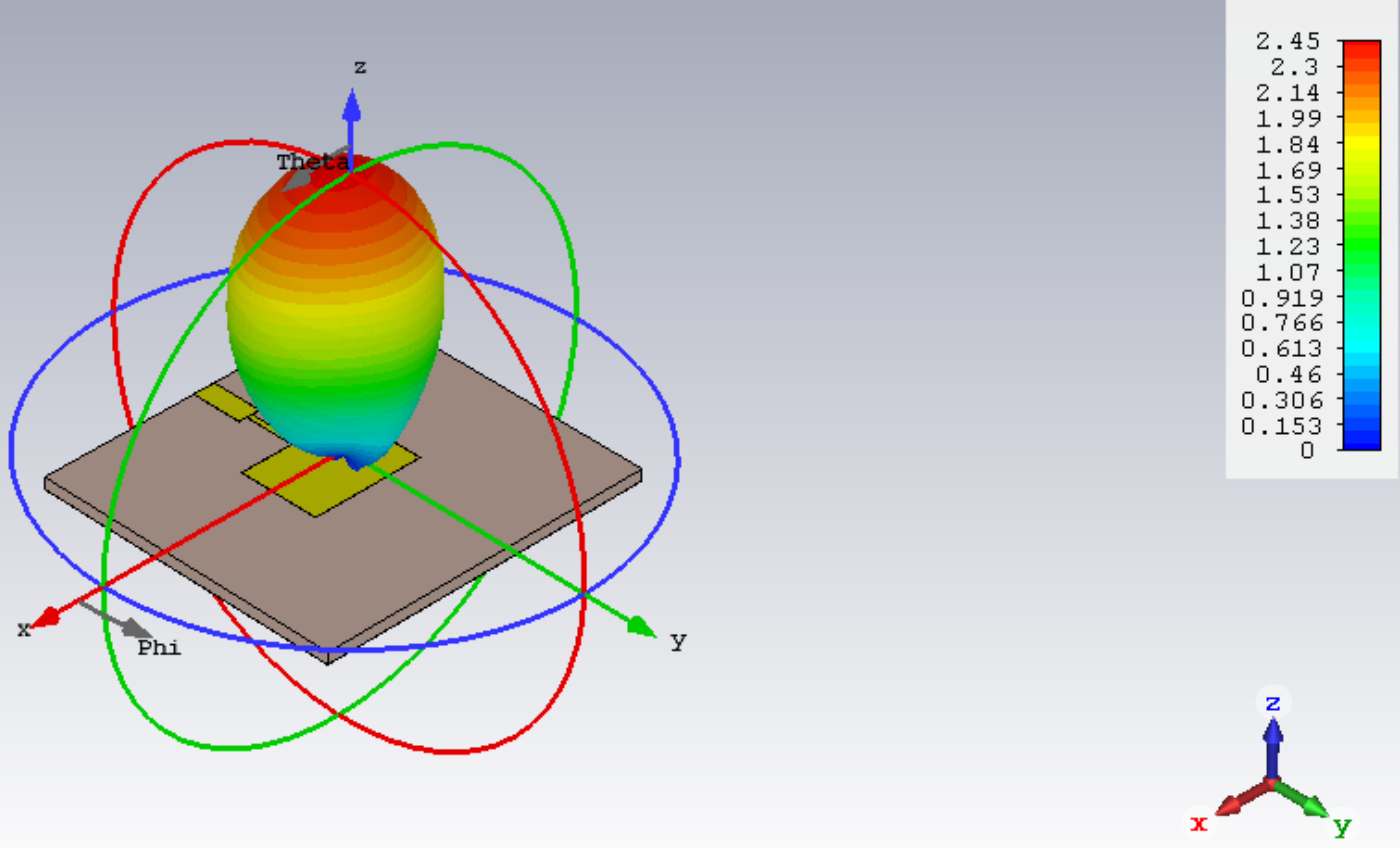
Comparison

Prototype vs Optimized



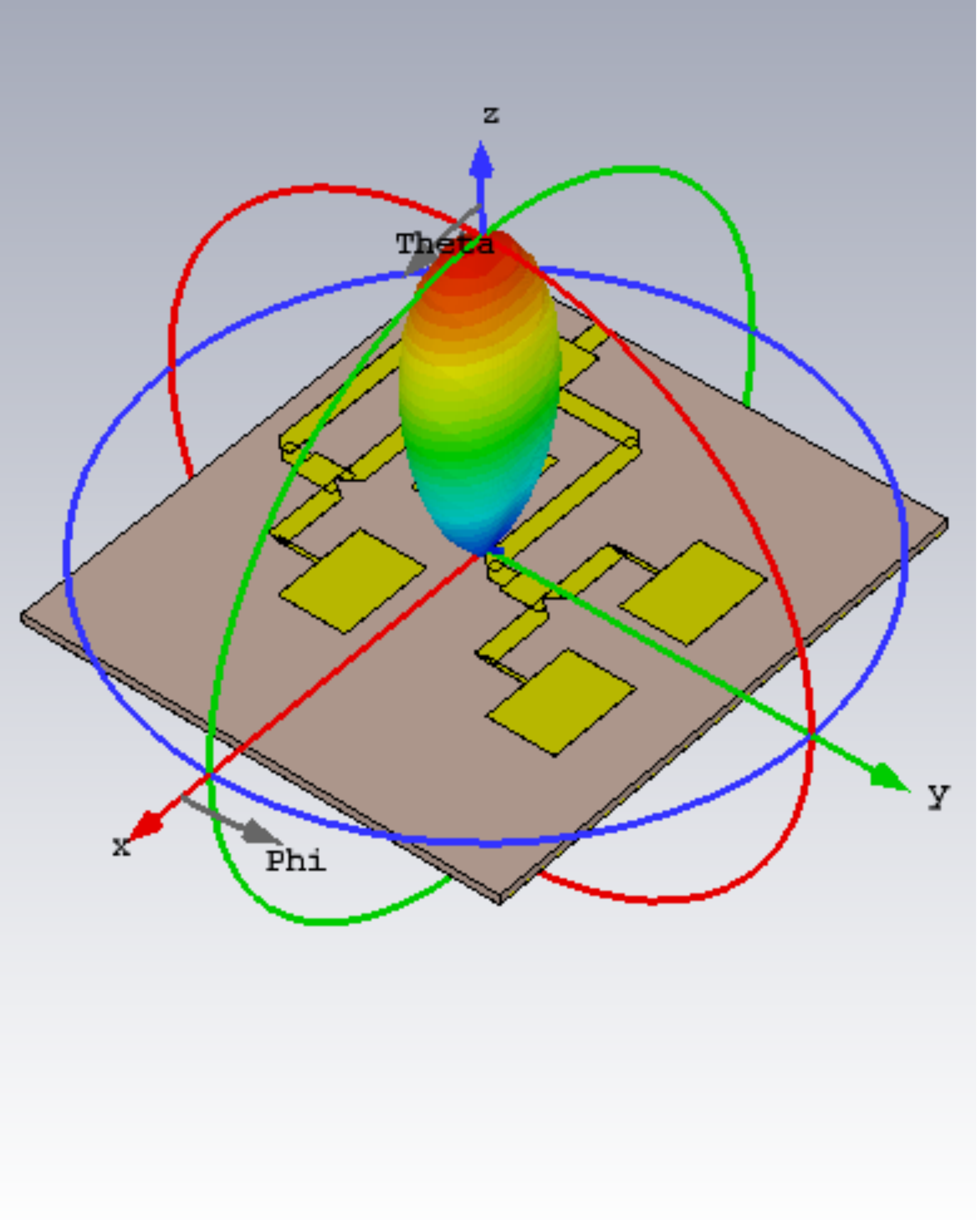
Microstrip Antenna

Optimized



Farfield

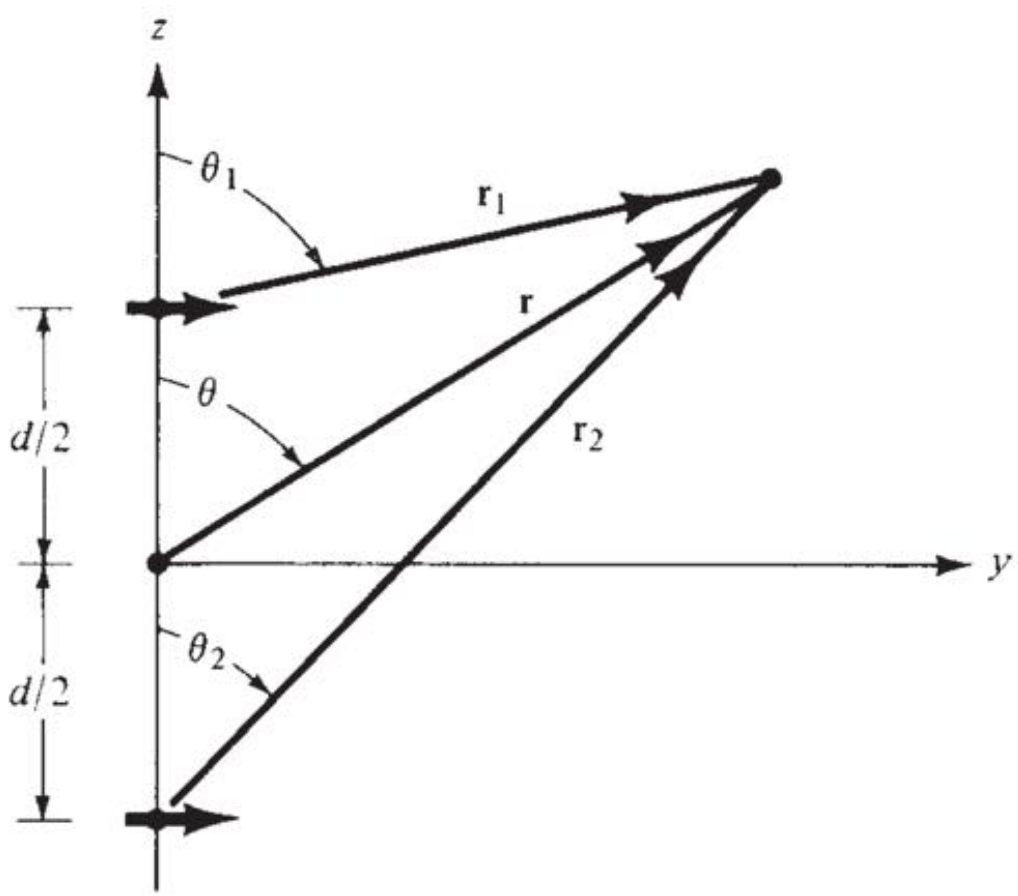
Optimized S11



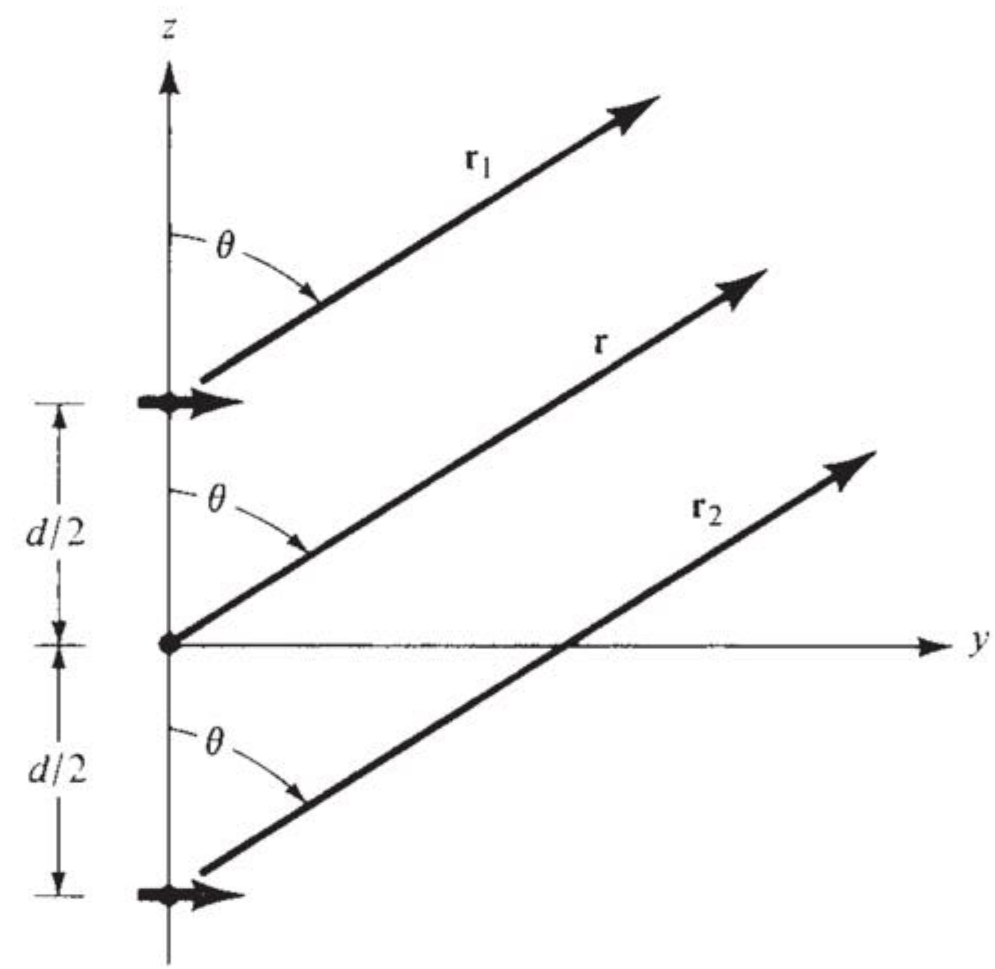
Array Antenna

Array of Dipoles
Array Factor
Power Divider
1x2
2x2

Array Antenna - Array of Dipoles



(a) Two infinitesimal dipoles



(b) Far-field observations

Array Antenna - Array of Dipoles

$$\vec{E}_t = \vec{E}_1 + \vec{E}_2 = \hat{a}_\theta j\eta \frac{kI_0 l}{4\pi} \left\{ \frac{e^{-j[kr_1 - (\beta/2)]}}{r_1} \cos\theta_1 + \frac{e^{-j[kr_2 - (\beta/2)]}}{r_2} \cos\theta_2 \right\}$$

$$\theta_1 \simeq \theta_2 \simeq \theta$$

$$\left.\begin{aligned} r_1 &\simeq r - \frac{d}{2}\cos\theta \\ r_2 &\simeq r + \frac{d}{2}\cos\theta \end{aligned}\right\} \text{for phase variation}$$

$$r_1 \simeq r_2 \simeq r \quad \text{for amplitude variation}$$

$$\vec{E}_t = \hat{a}_\theta j\eta \frac{kI_0 l}{4\pi r} \cos\theta \left[e^{+j(kd\cos\theta + \beta)/2} + e^{-j(kd\cos\theta + \beta)/2} \right]$$

$$\vec{E}_t = \hat{a}_\theta j\eta \frac{kI_0 l}{4\pi r} \cos\theta \left[2\cos\left(\frac{kd\cos\theta + \beta}{2} \right) \right]$$

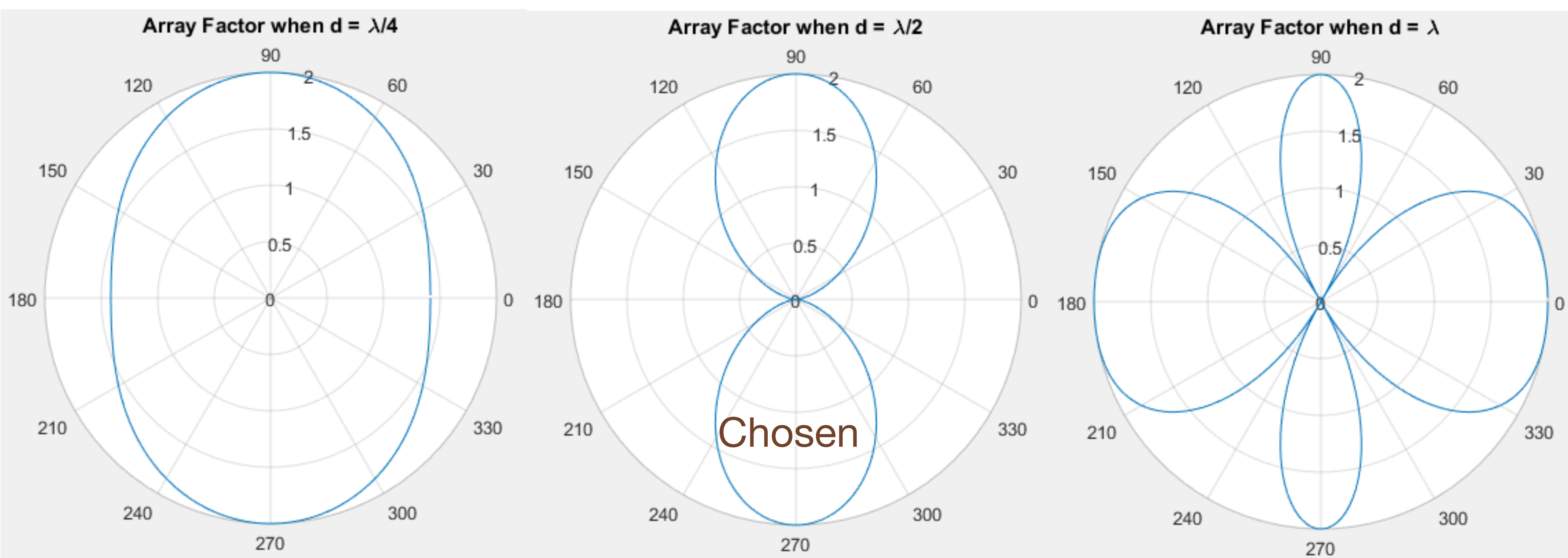
$$AF = 2\cos\left(\frac{kd\cos\theta + \beta}{2} \right)$$

$$f(\theta, \phi) = E(\theta, \phi) \times AF(\theta, \phi)$$

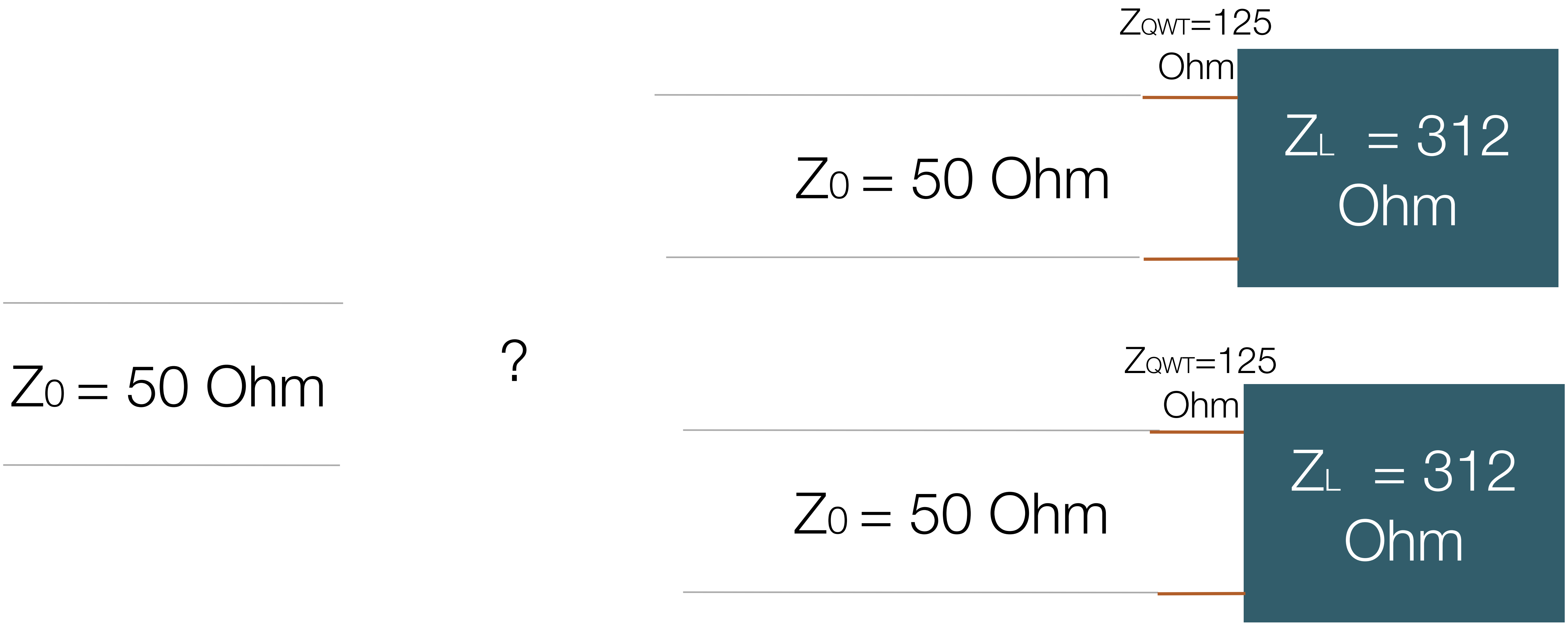
Array Antenna - Array Factor

$$AF = 2\cos\left(\frac{kd\cos\theta + \beta}{2}\right)$$

```
lambda = 1;
d = lambda;
k = 2*pi/lambda;
beta = 0;

x = 1:1:360;

af = 2*cos(k*d * cos(2*pi*x / 360)/2 + beta);

polarplot(2*pi*x/360,abs(af))
title('Array Factor when d = \lambda')
```

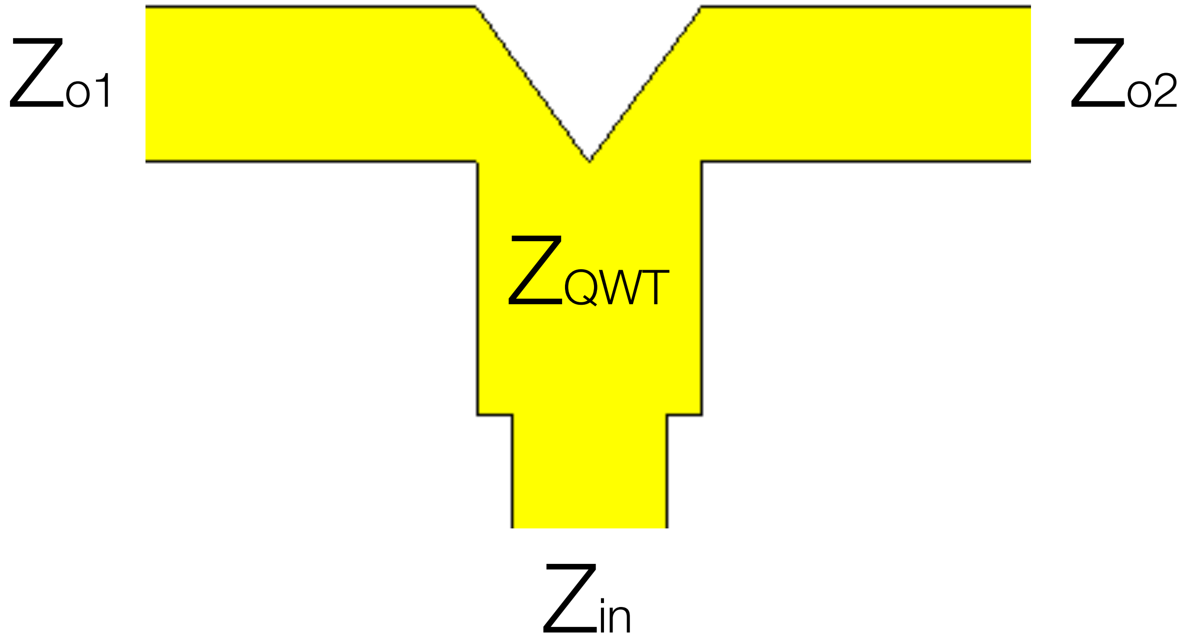


What do we have now?



We need a power divider with 50 Ohm matching

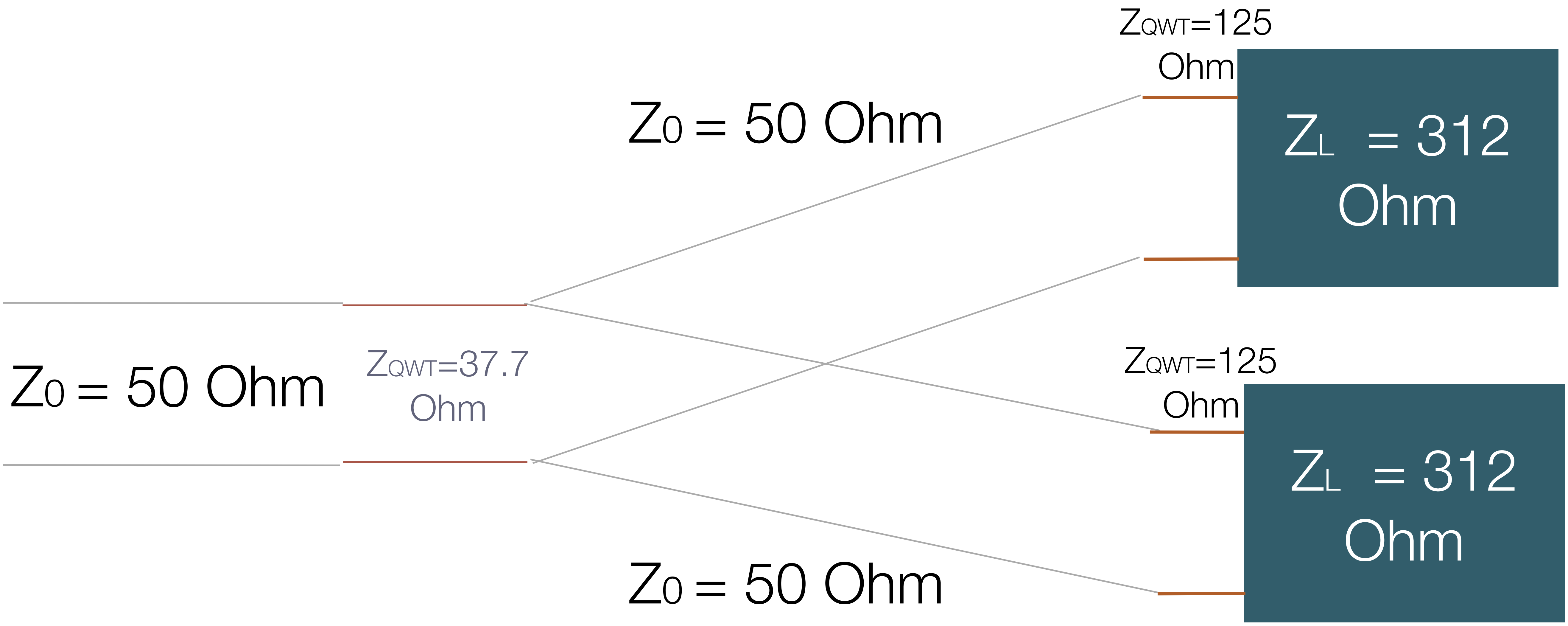
Power Divider with Matching



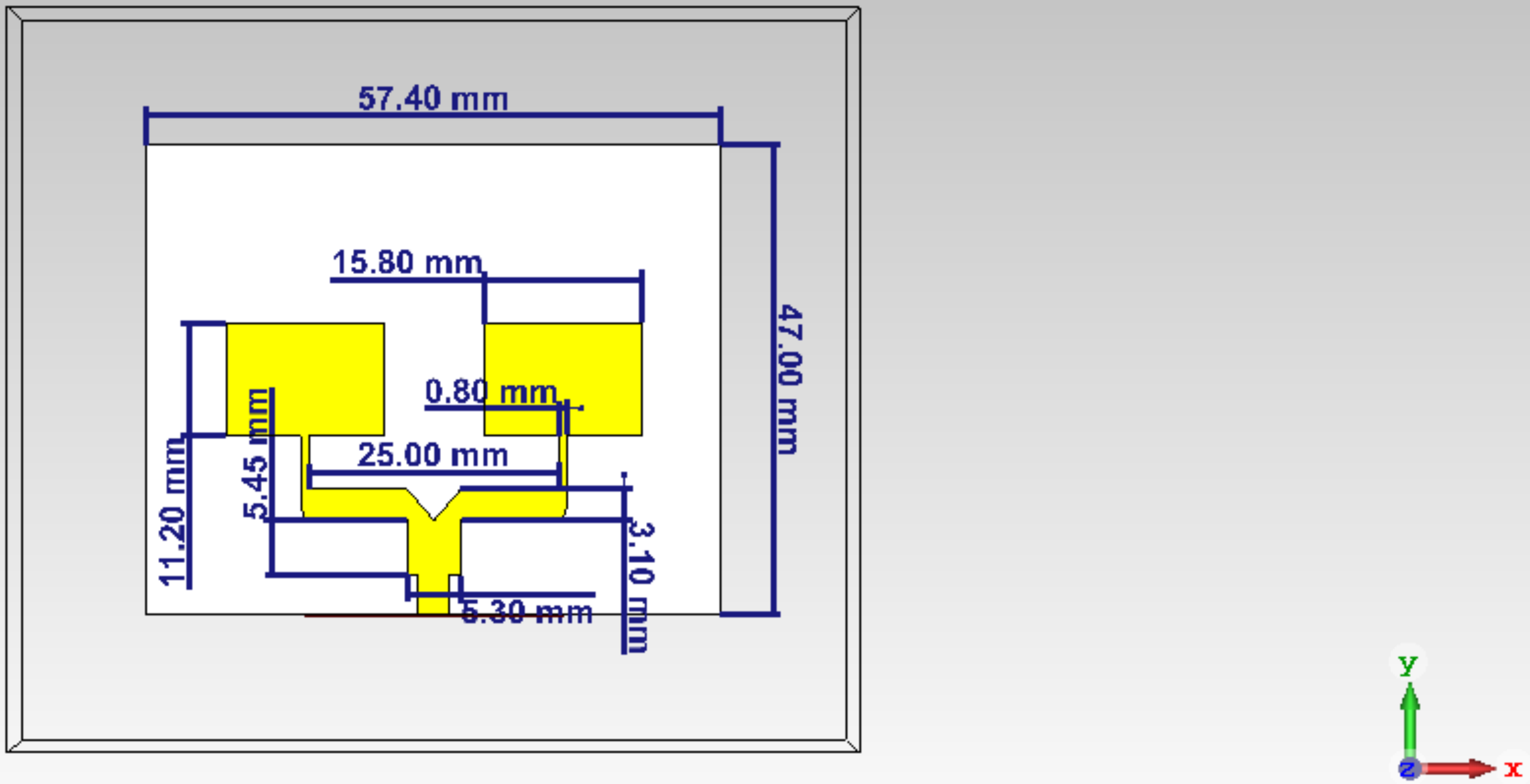
$$Z_{QWT} = \sqrt{Z_{in} \times \frac{Z_{o1} \times Z_{o2}}{Z_{o1} + Z_{o2}}}$$

To match all 3 ports as 50 Ohm, Z_{QWT} will be 37.7 Ohm

What do we have now?



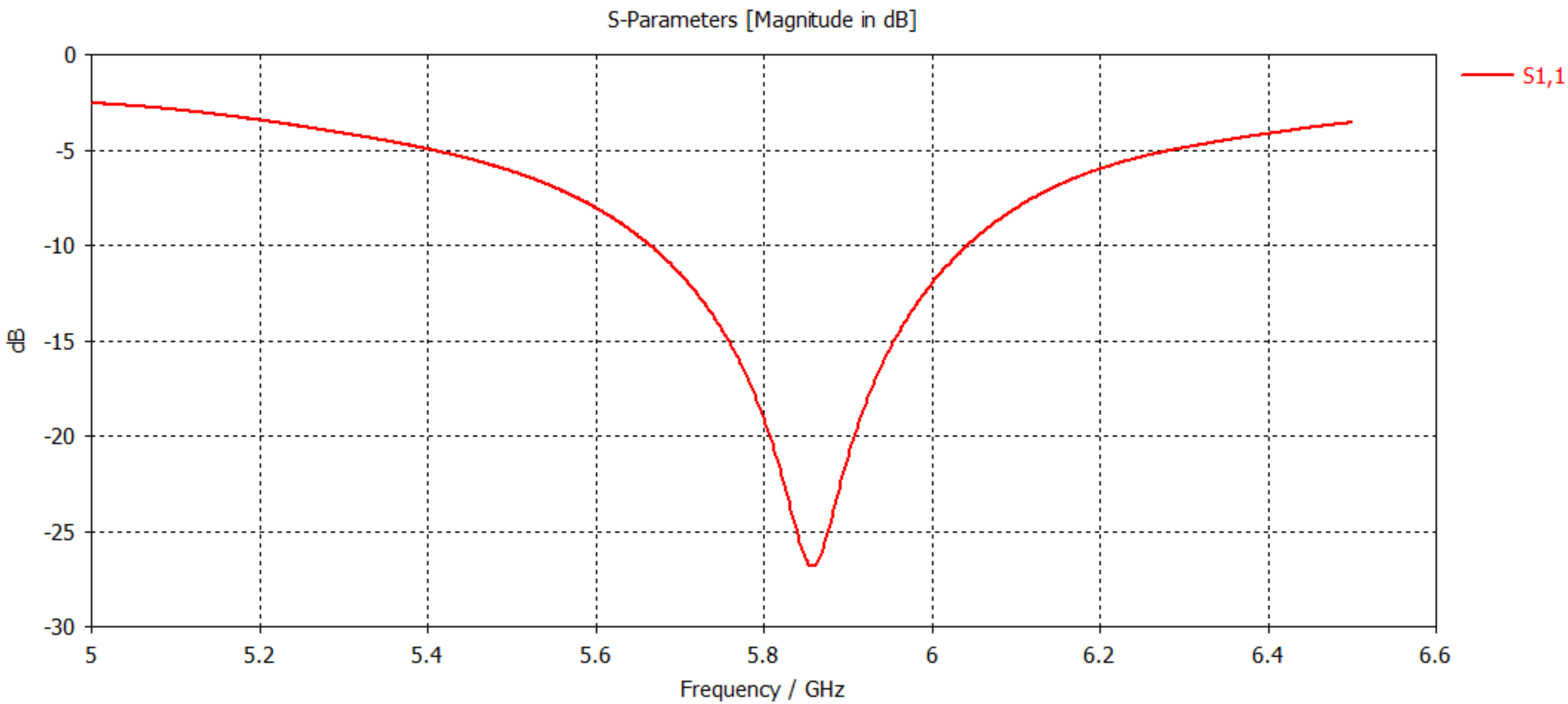
The circuit is completed



1x2 Microstrip Antenna

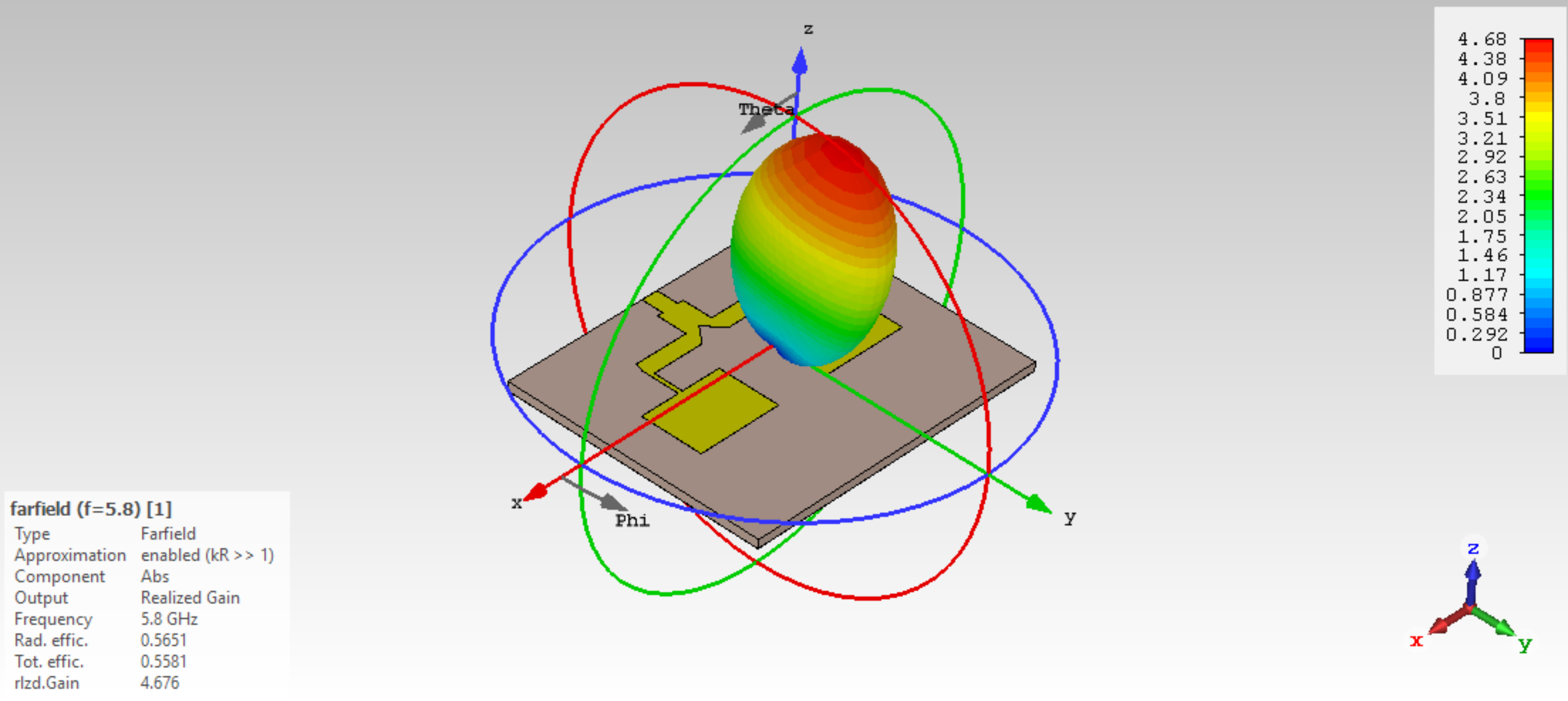
Prototype

Simulate and wait about 20 minutes



S11
(Not yet perfect)

1x2 Prototype

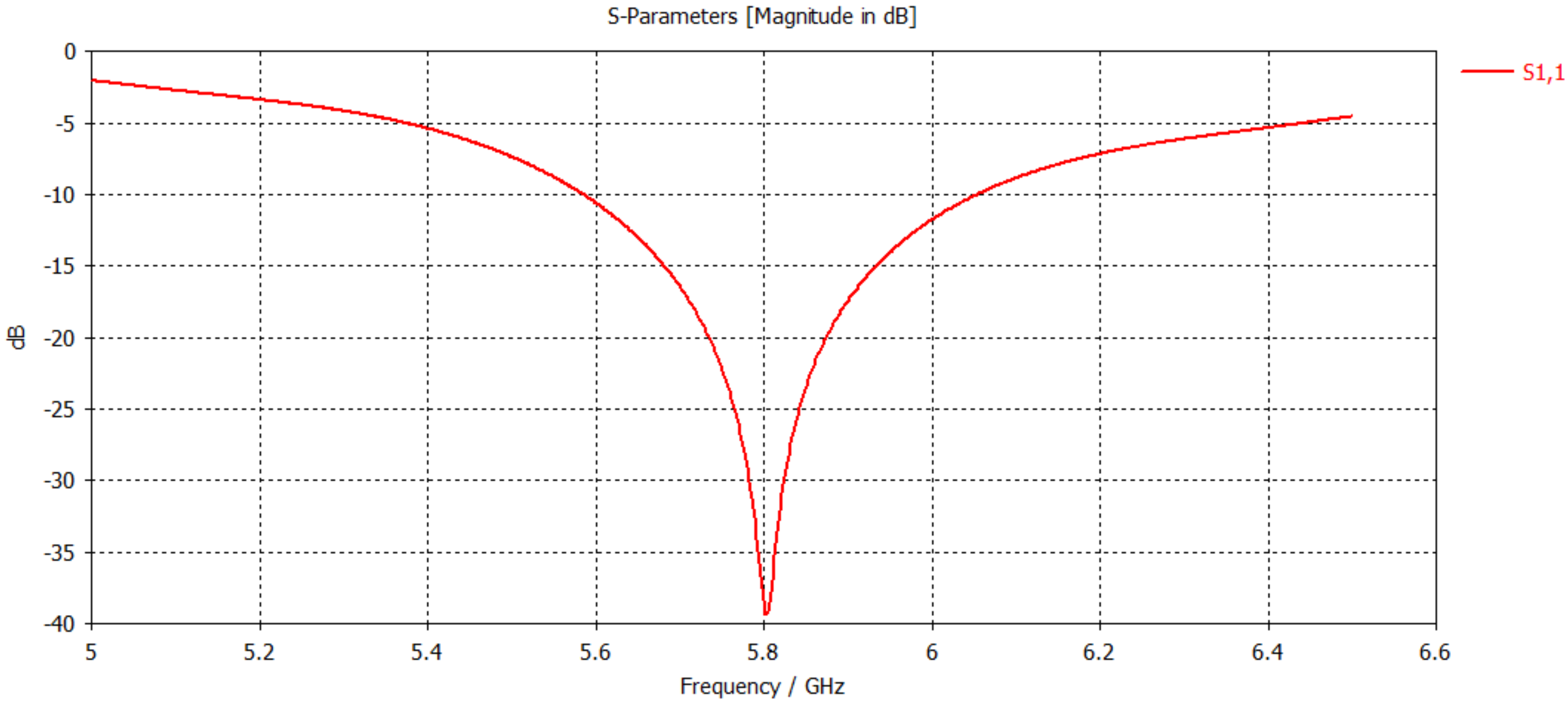


Farfield(Linear Scale)

(Beam is tilted)

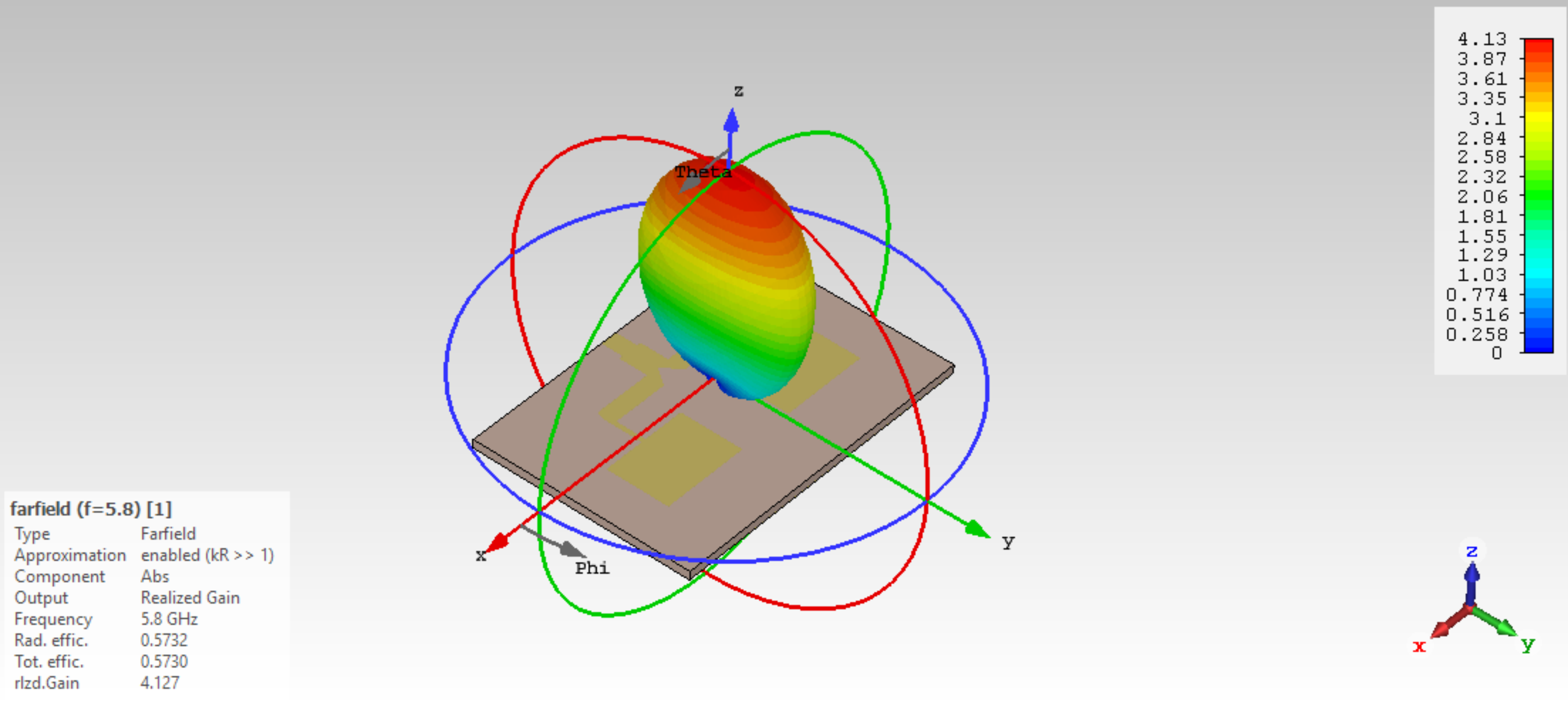
1x2 Prototype

To fix that, we have to reduce the ground plane.
Also, the optimization is required.



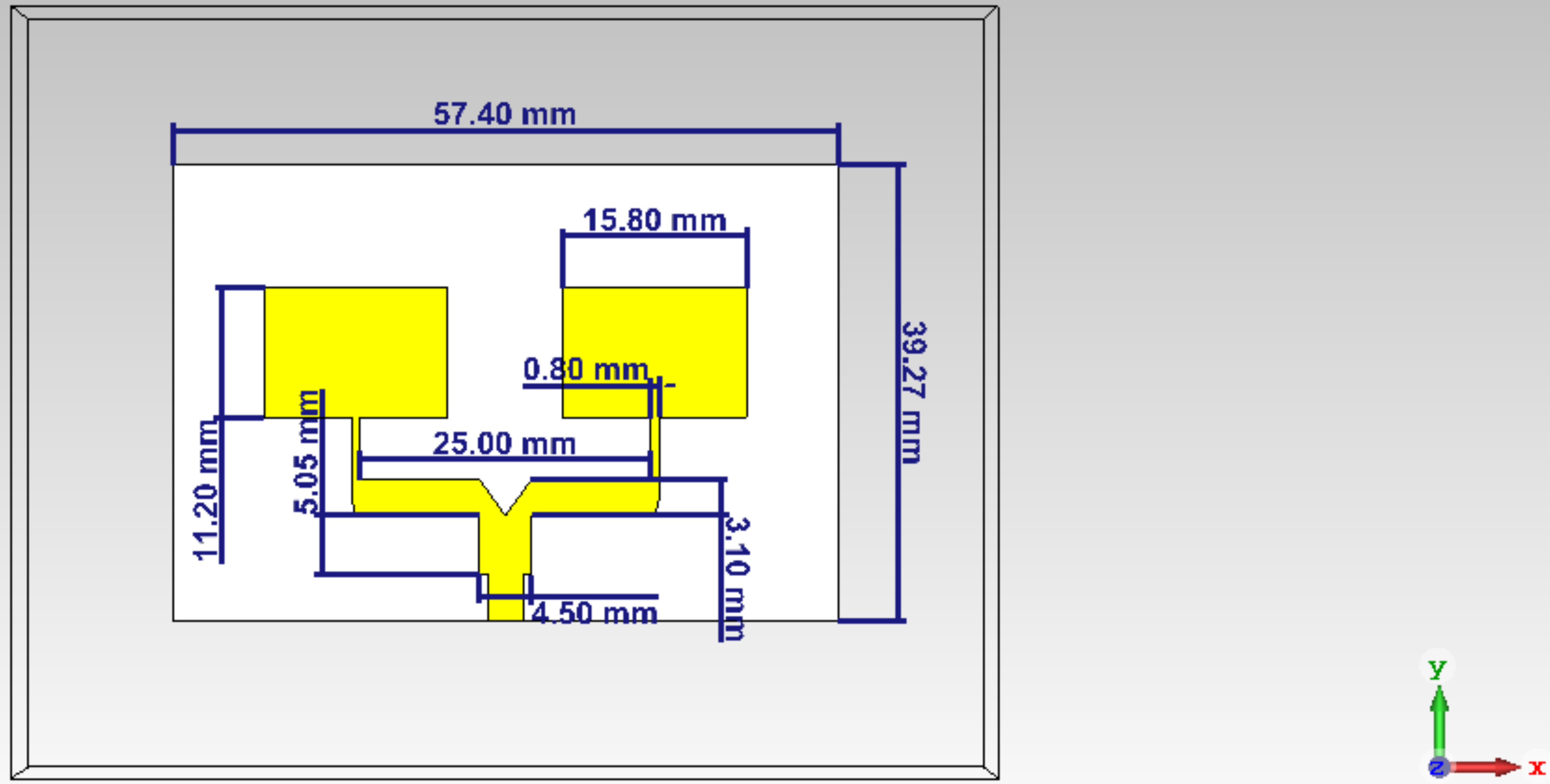
S11

1x2 Optimized, ground reduced



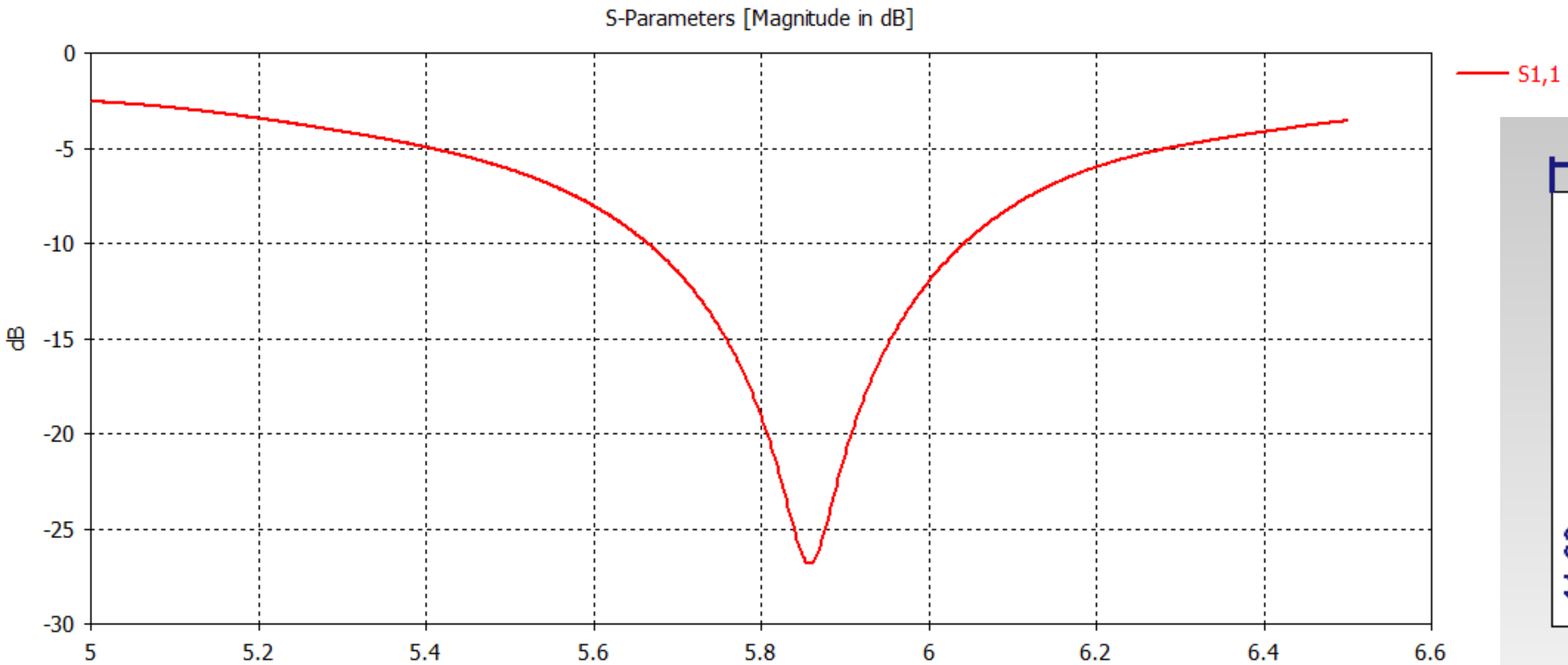
Farfield(Linear Scale)

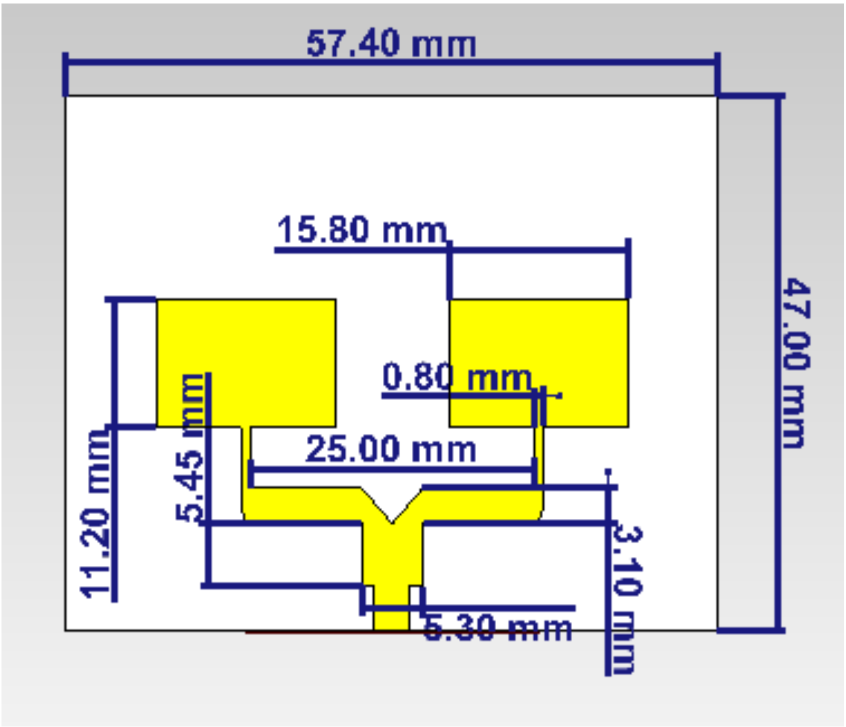
1x2 Optimized, ground reduced

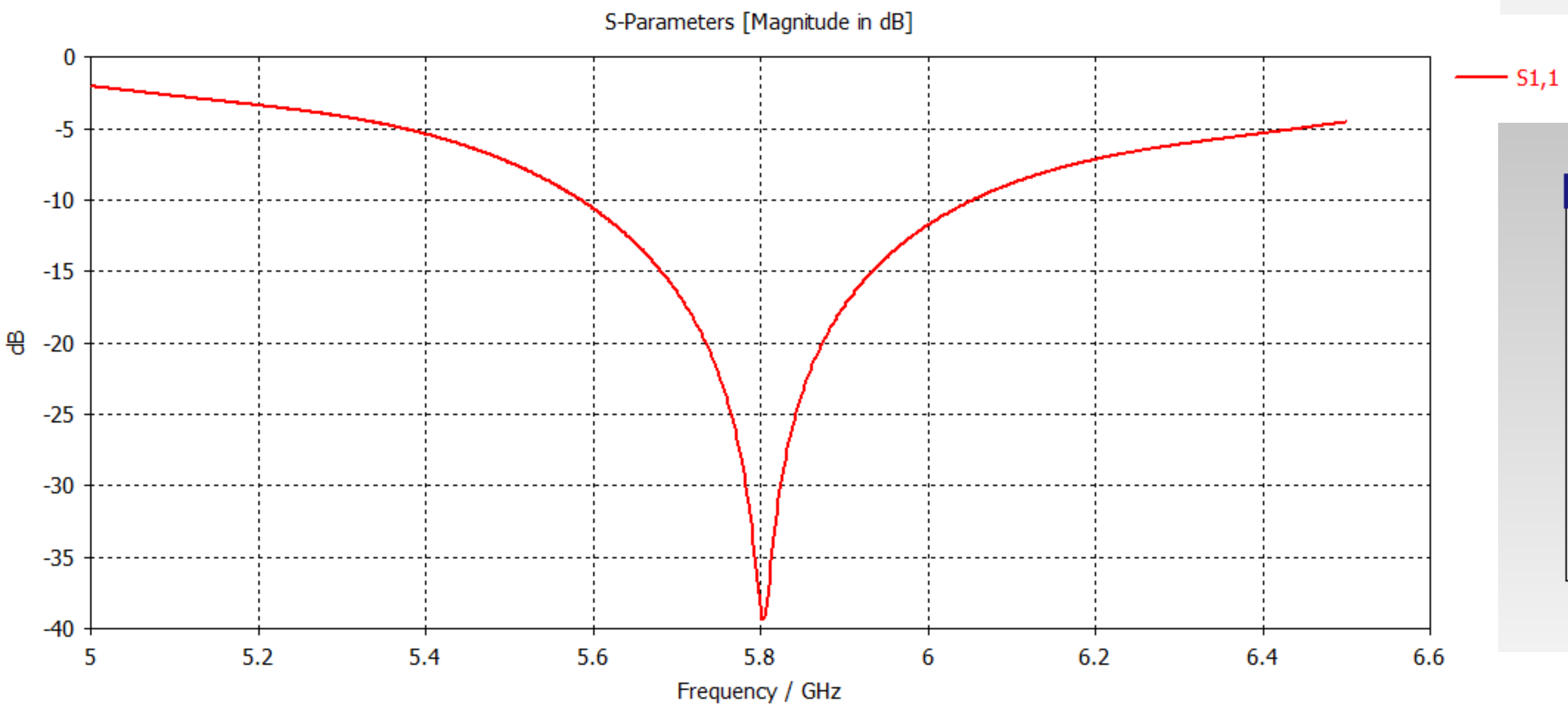


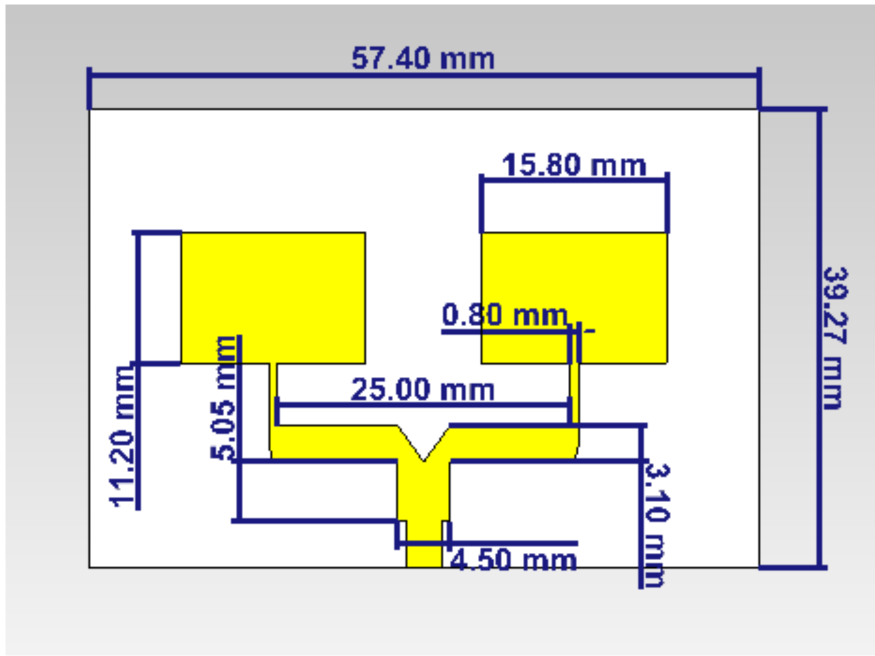
1x2 Microstrip Antenna

Optimized, ground reduced







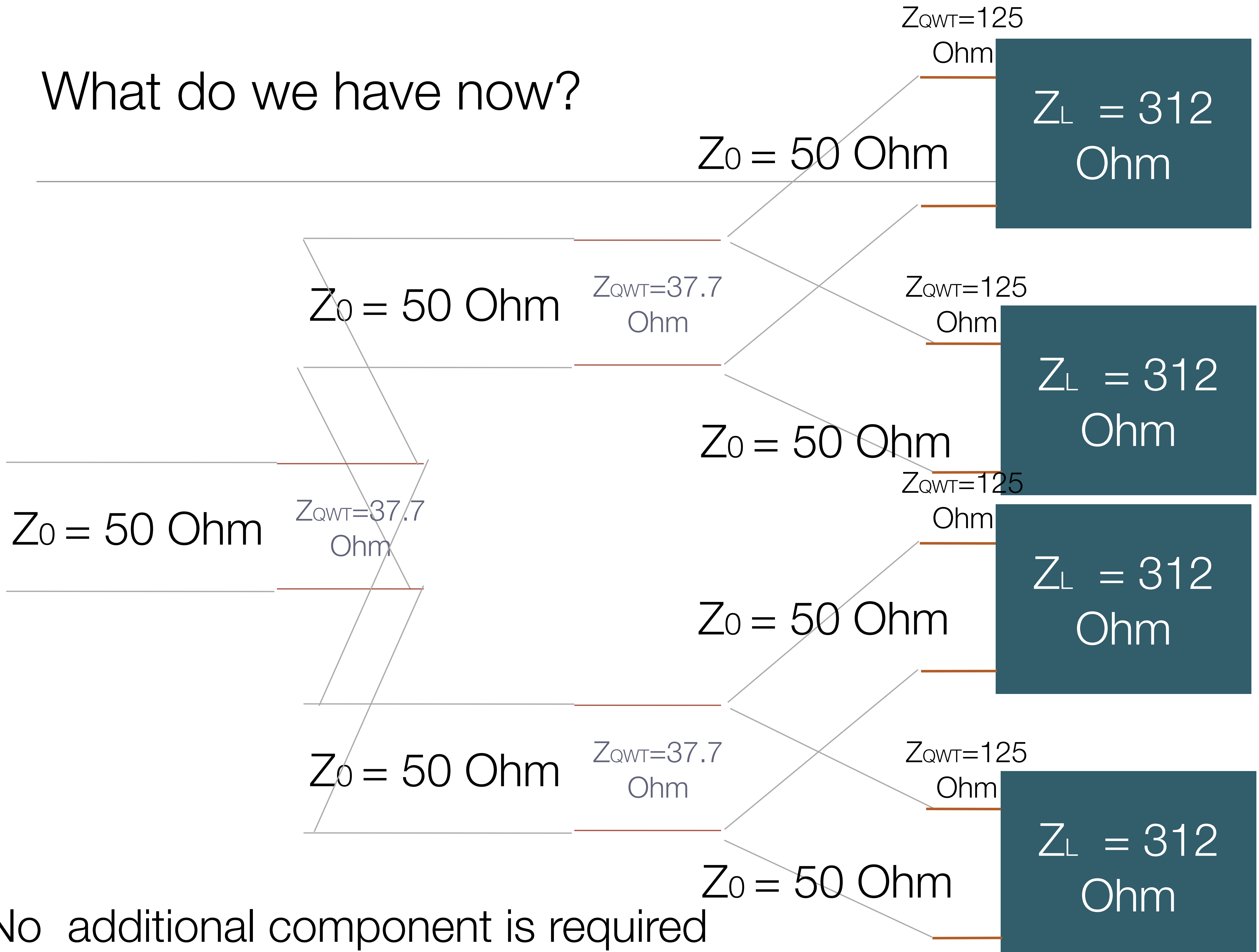


Comparison

Optimized vs Prototype

For 2x2, just copy to another pair and connect them altogether and then optimize the power divider

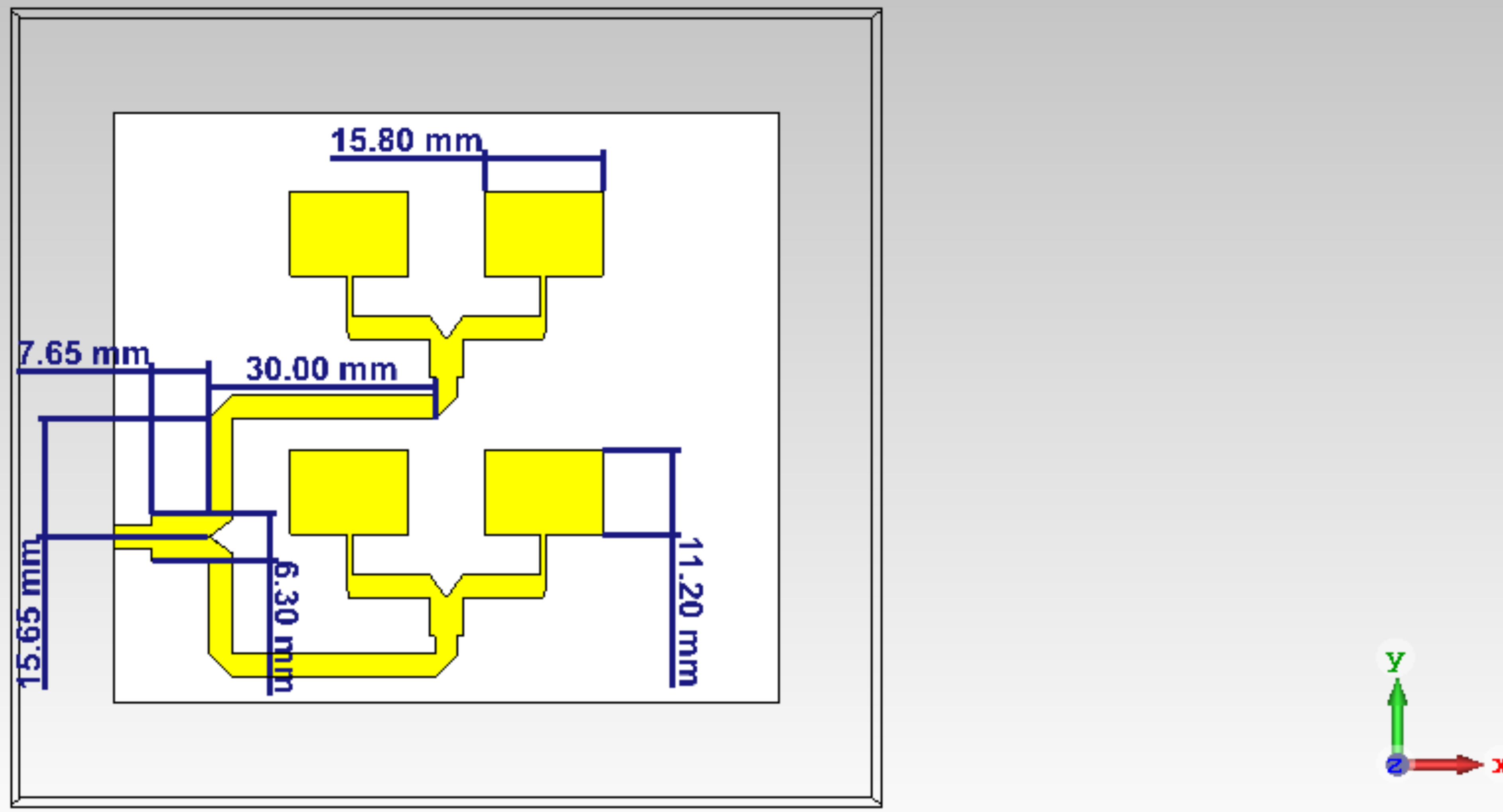
What do we have now?



No additional component is required

“Type a quote here.”

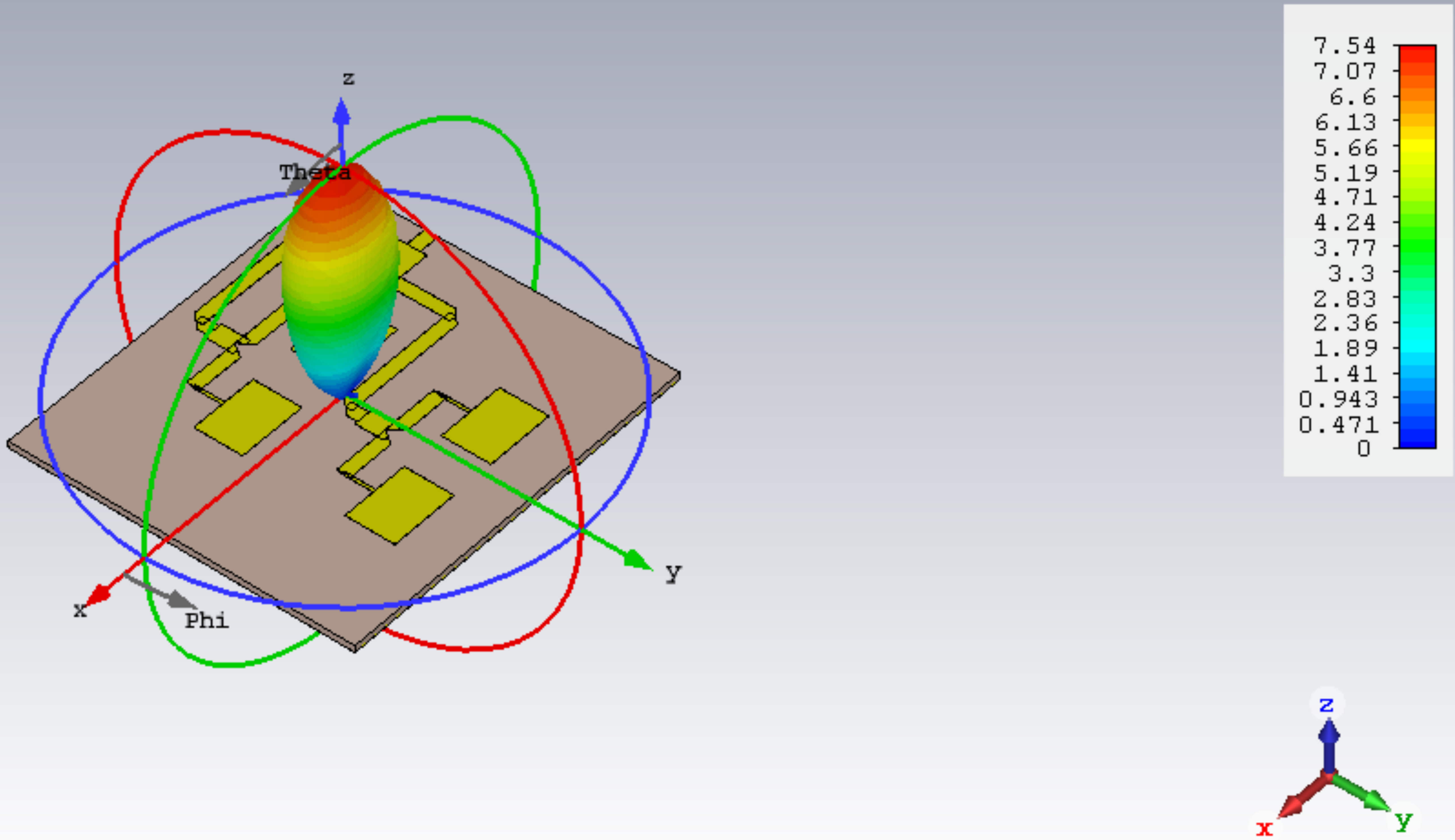
–Johnny Appleseed



2x2 Microstrip Antenna

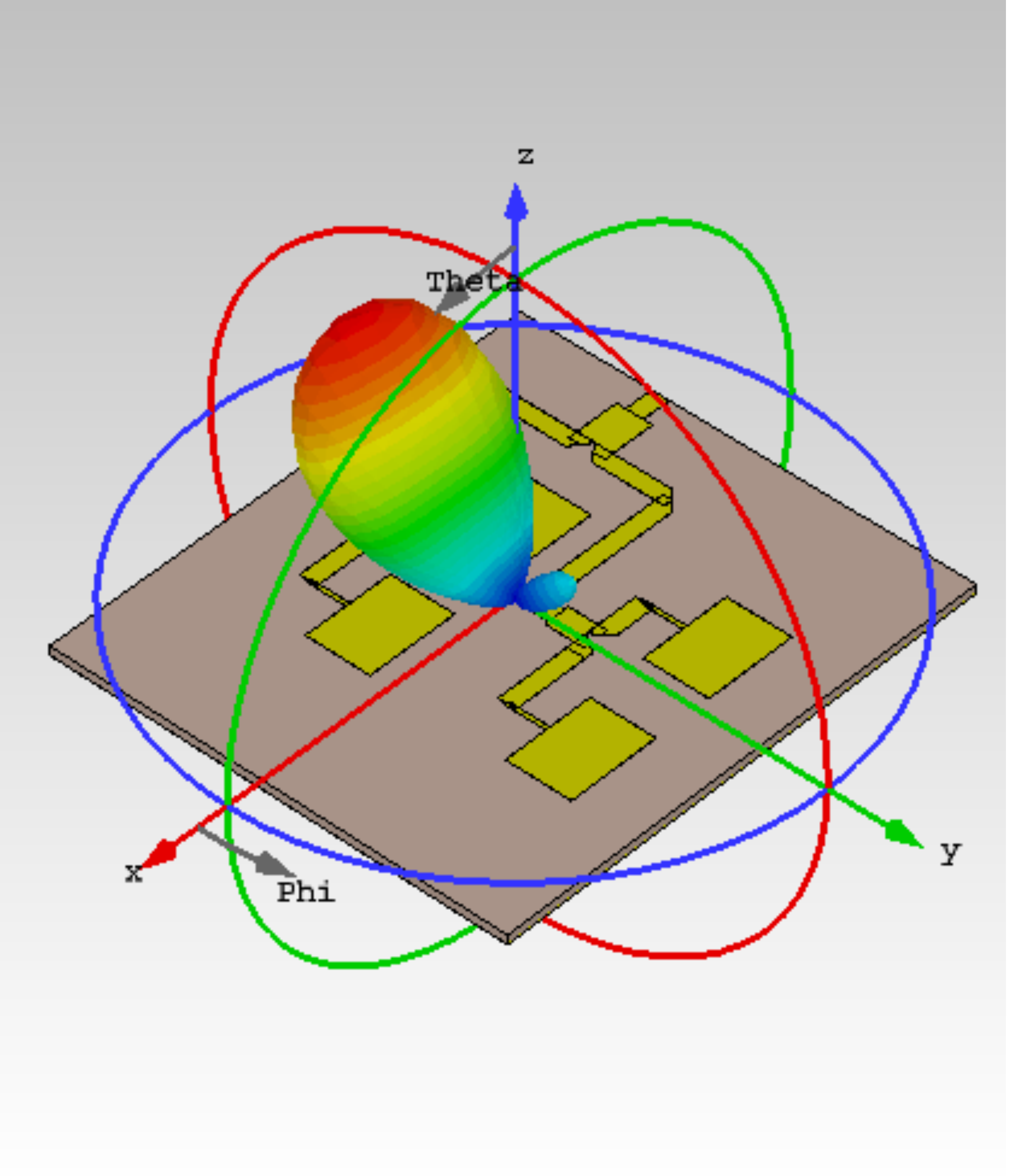
Optimized

Y-axis distance is 2*pi/3



Farfield(Linear Scale)

2x2 Array Antenna

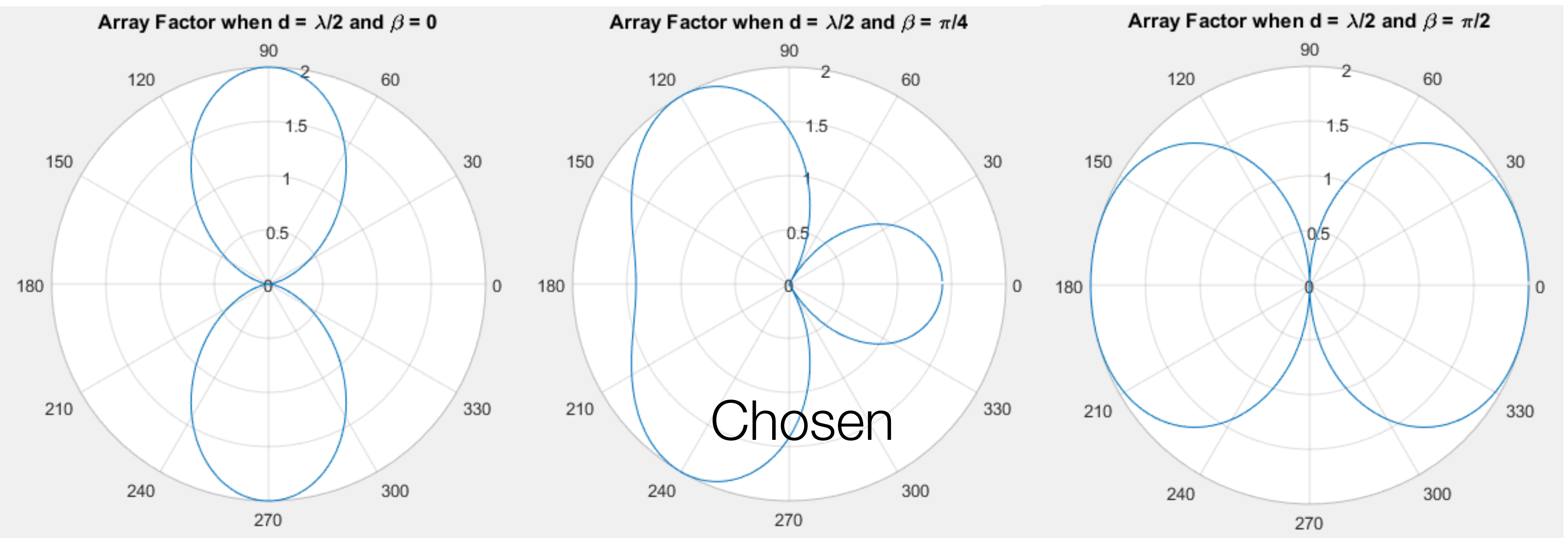


Phased Array Antenna

Phase variation from Array Factor
Feed-Translation Technique
1x2 Phased Array Design
2x2 Phased Array Design

Phased Array Antenna -
Phased Variation from Array Factor

$$AF = 2\cos\left(\frac{kd\cos\theta + \beta}{2}\right)$$



Phased Array Antenna - Feed-Translation Technique

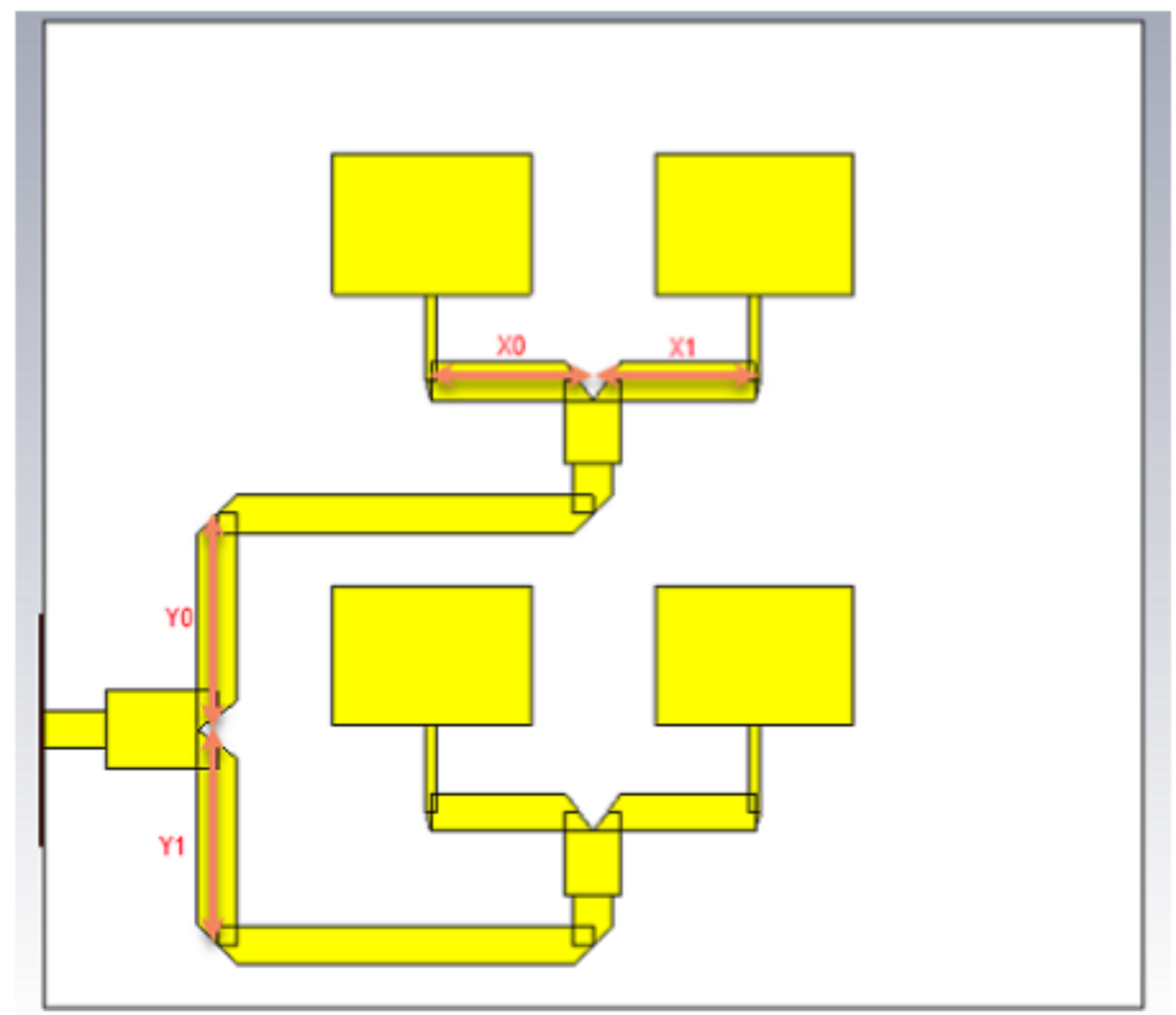
To lock the distance of the patch, the Feed-Translation technique was used.
It's very convenient to use for phased array

$$x_0 + x_1 = d_x$$

$$x_0 - x_1 = \Delta\phi_x$$

$$y_0 + y_1 = d_y$$

$$y_0 - y_1 = \Delta\phi_y$$



Create a 1x2 Phased Array Antenna with Quadrature Phase

Phased Array Antenna - 1x2 Phased Array Design

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8}{5.8 \times 10^9} = 51.7 \text{ mm}$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{r(eff)}}} = \frac{51.7 \times 10^{-3}}{\sqrt{3.26}} = 28.6 \text{ mm}$$

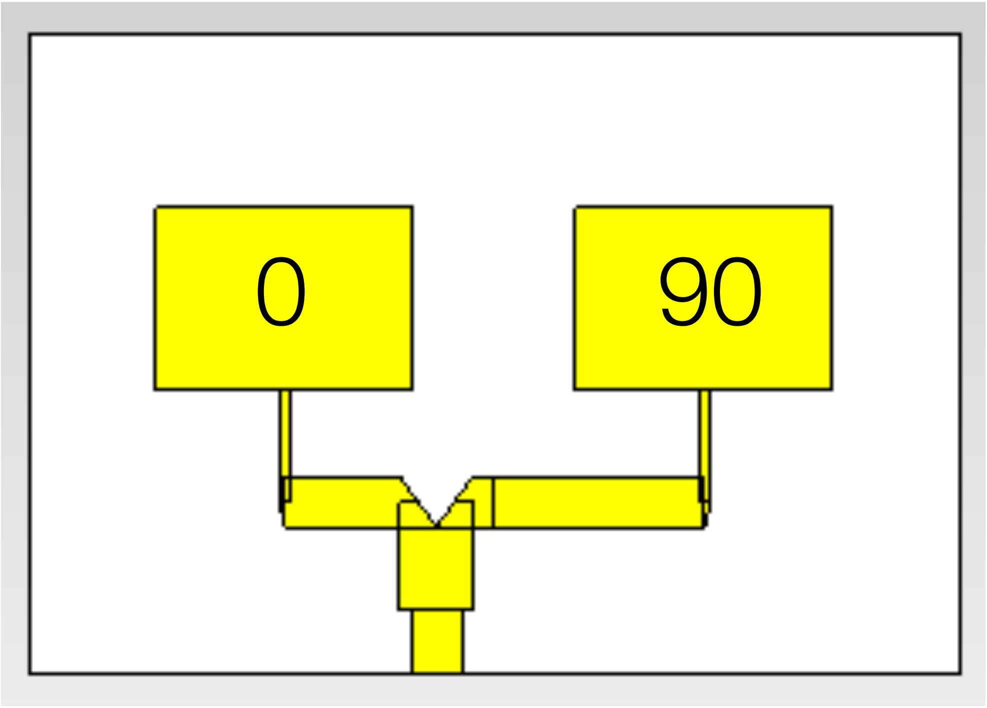
$$x_0 + x_1 = d_x = \frac{\lambda_0}{2} = 25.8$$

$$x_0 + x_1 = \Delta\phi_x = \frac{\lambda_g}{4} = \frac{28.6}{4} = 7.1$$

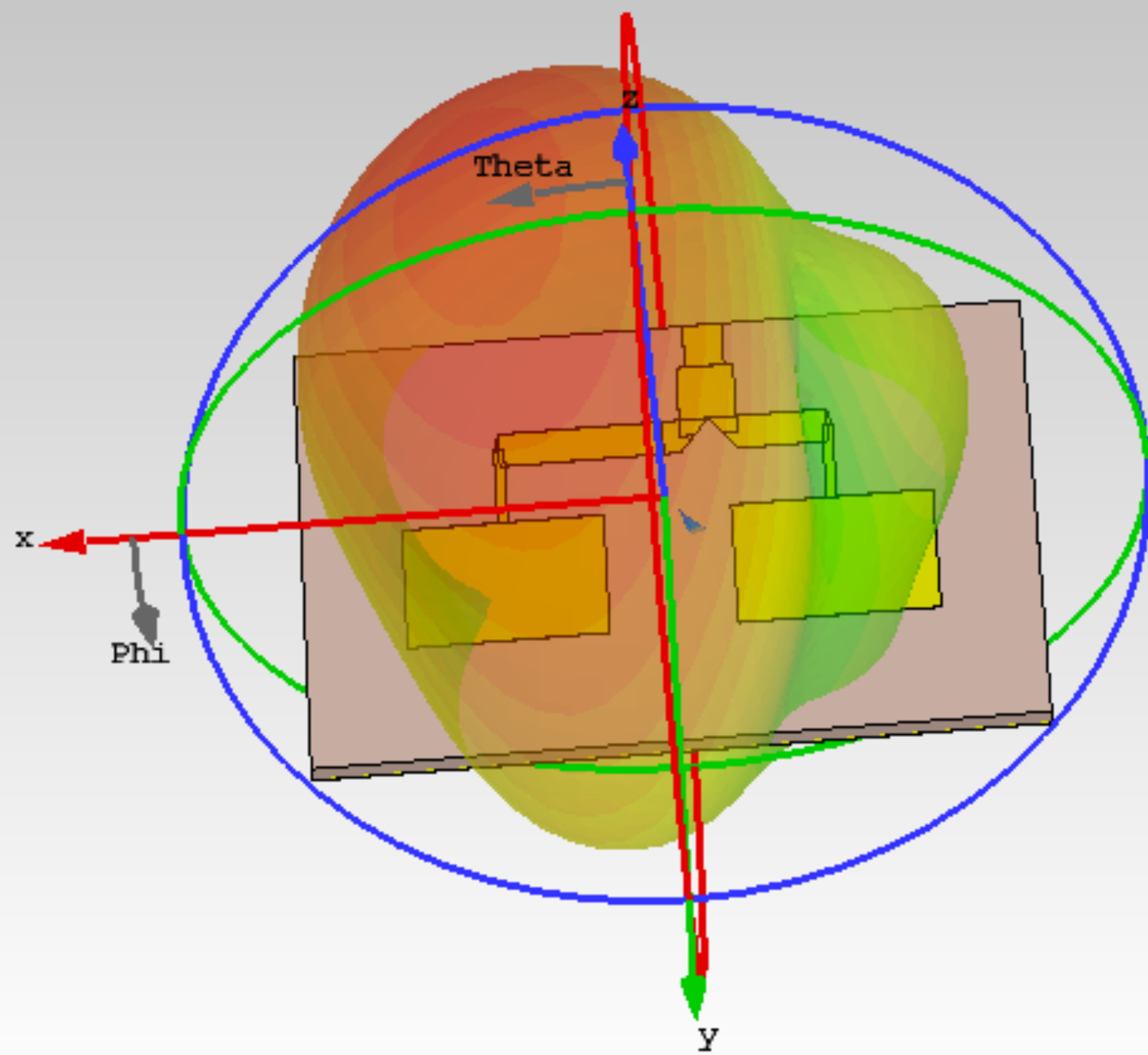
$$2x_0 = 32.9$$

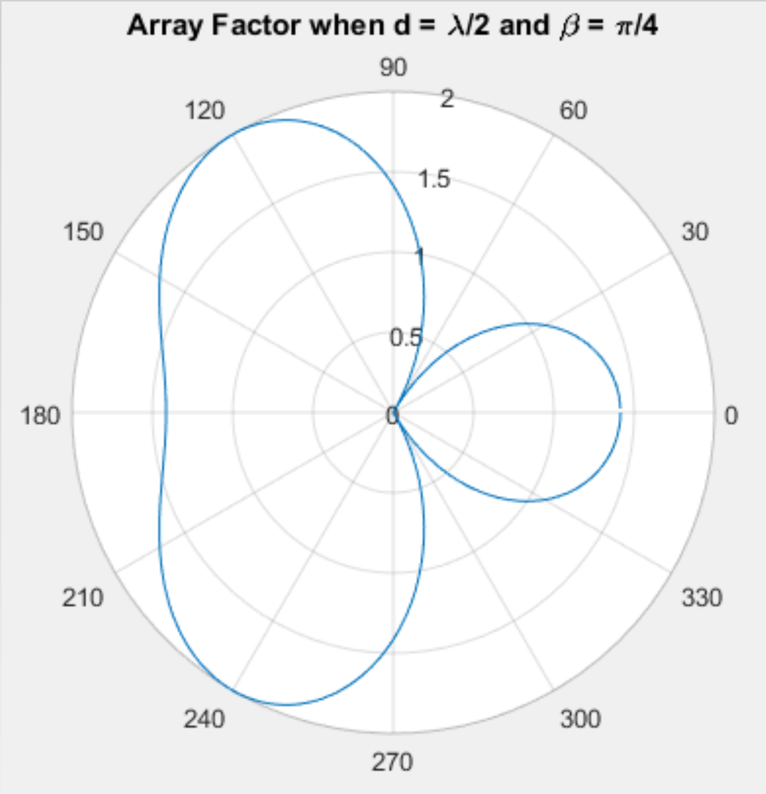
$$x_0 = 16.5$$

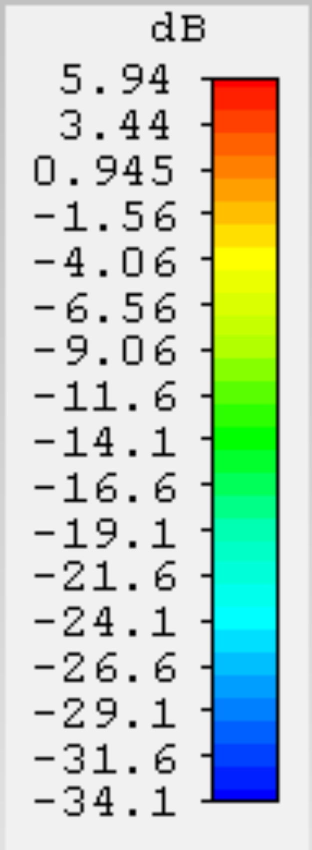
$$\text{middle point} = \frac{d_x}{2} = 12.9 \text{ mm}$$



- Therefore, the feed point must be translated by 16.5 -12.9 = 3.6 mm







1x2 Phased Array Antenna (Beta = 90)

Farfield

Create a 2x2 Phased Array Antenna with Quadrature, Hexature Phase

Phased Array Antenna - 2x2 Phased Array Design

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8}{5.8 \times 10^9} = 51.7 \text{ mm}$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{r(eff)}}} = \frac{51.7 \times 10^{-3}}{\sqrt{3.26}} = 28.6 \text{ mm}$$

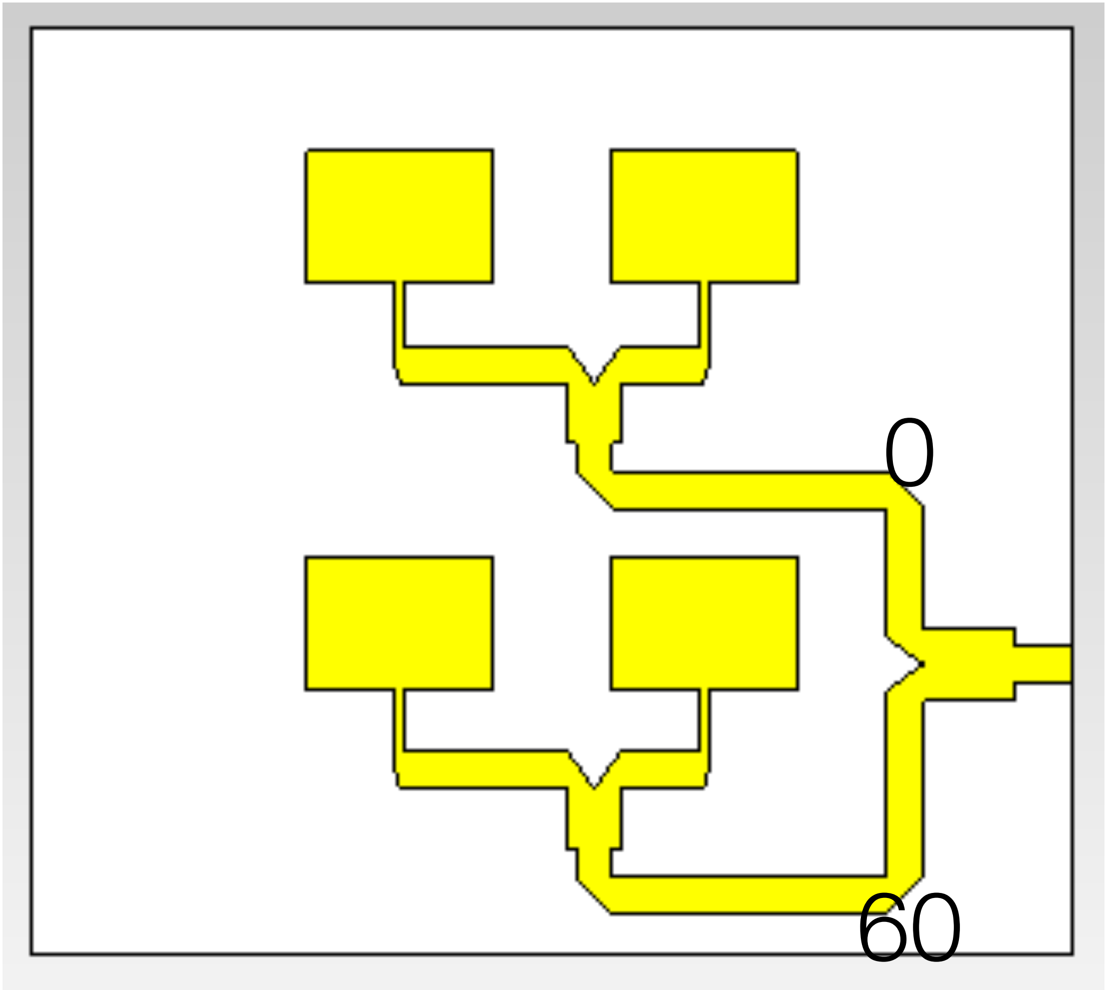
$$y_0 + y_1 = d_y = \frac{2\lambda_0}{3} = 34.4$$

$$y_0 - y_1 = \Delta\phi_y = \frac{\lambda_g}{6} = 4.8$$

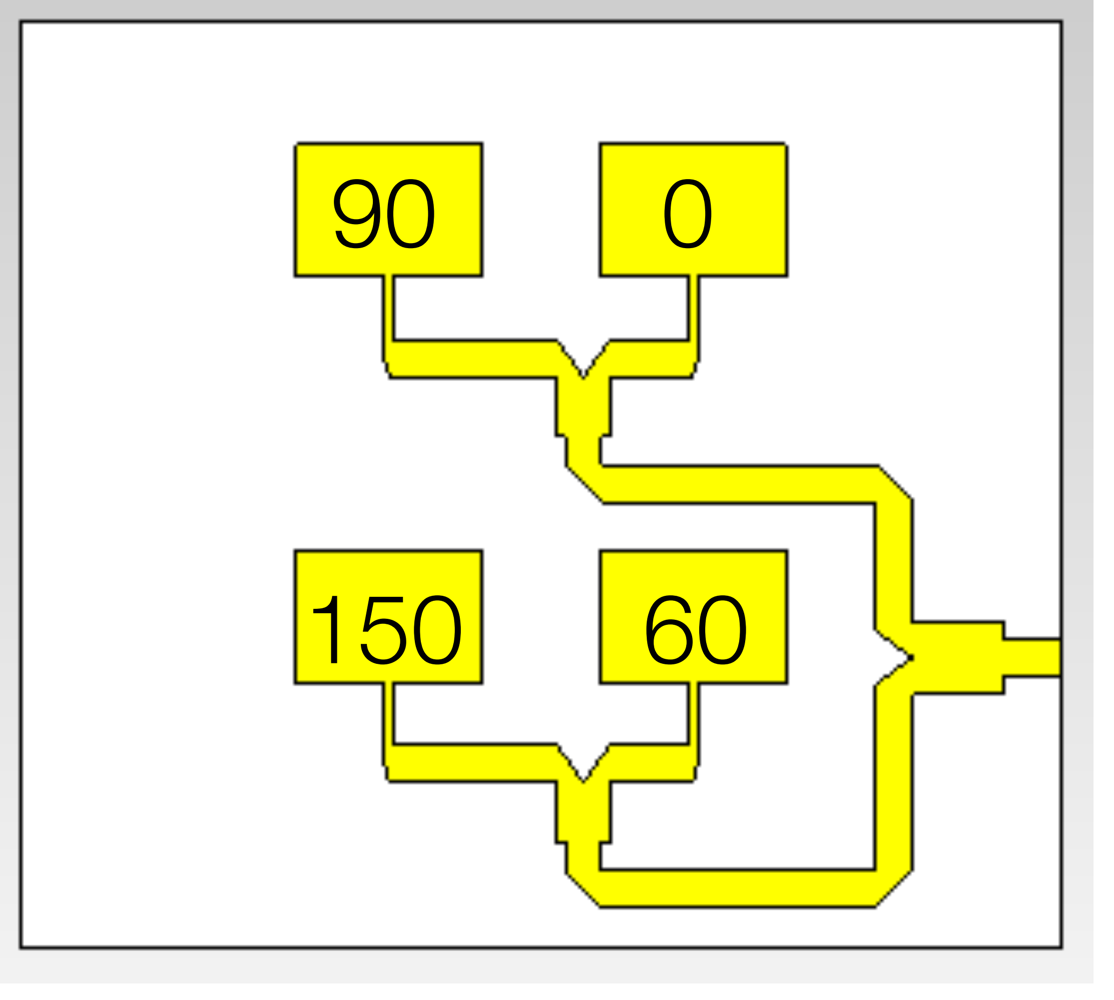
$$2y_0 = 39.2$$

$$y_0 = 19.6$$

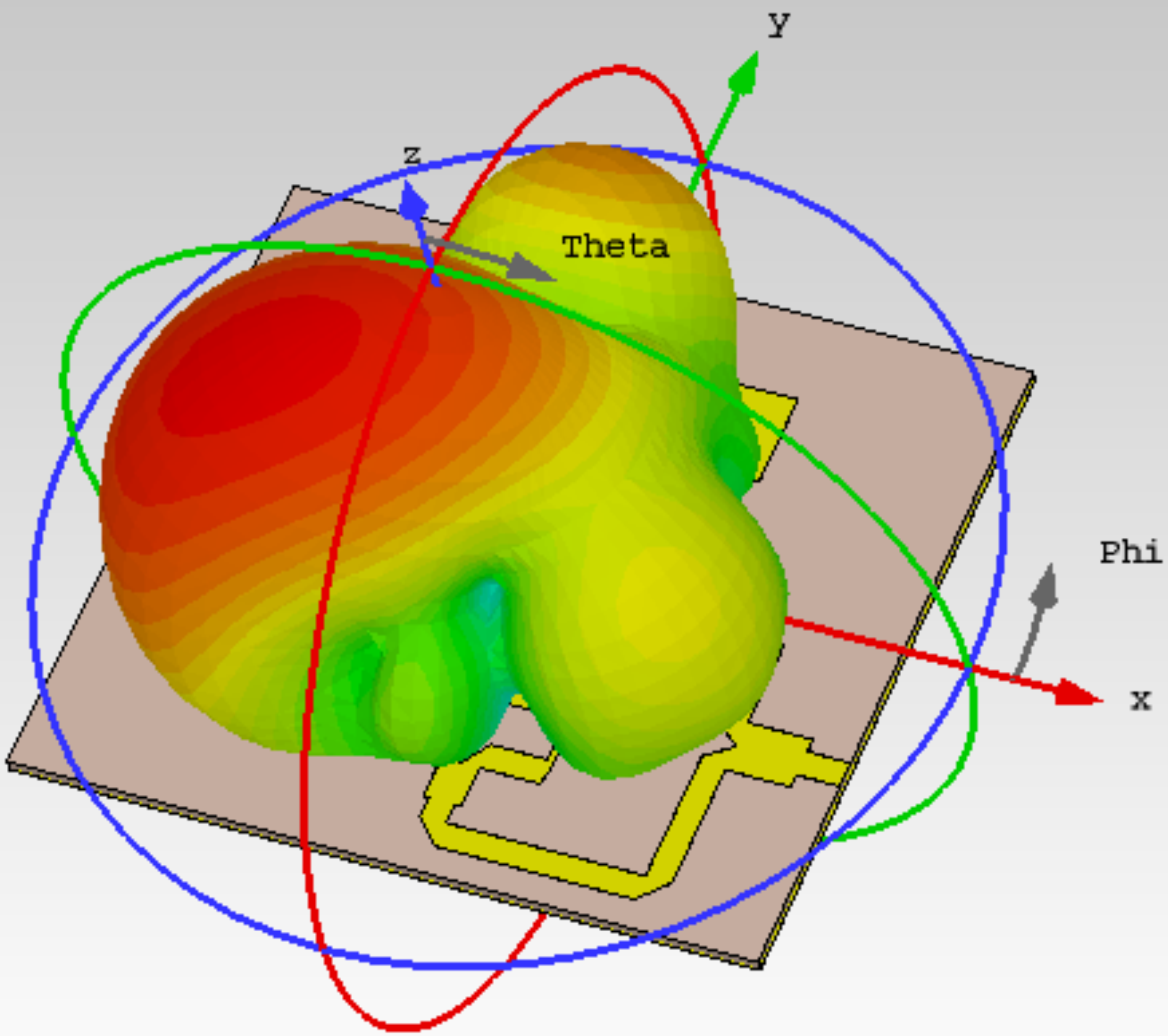
$$\text{middle point} = \frac{d_y}{2} = 17.2 \text{ mm}$$

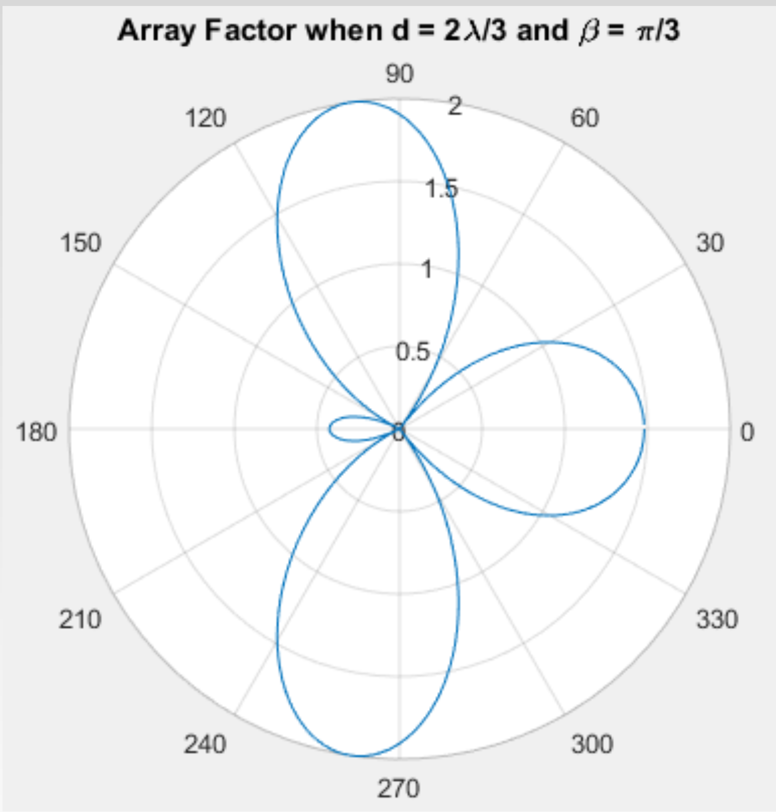


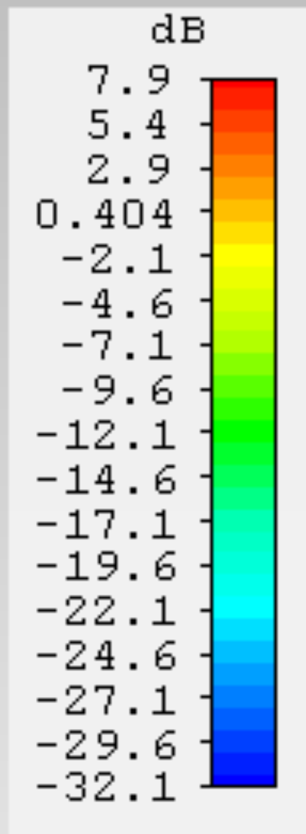
- Therefore, the feed point must be translated by 19.6 -17.2 = 2.4 mm



90
0
150
60







2x2 Phased Array Antenna(Beta = 90,60)

Farfield

Fabrication

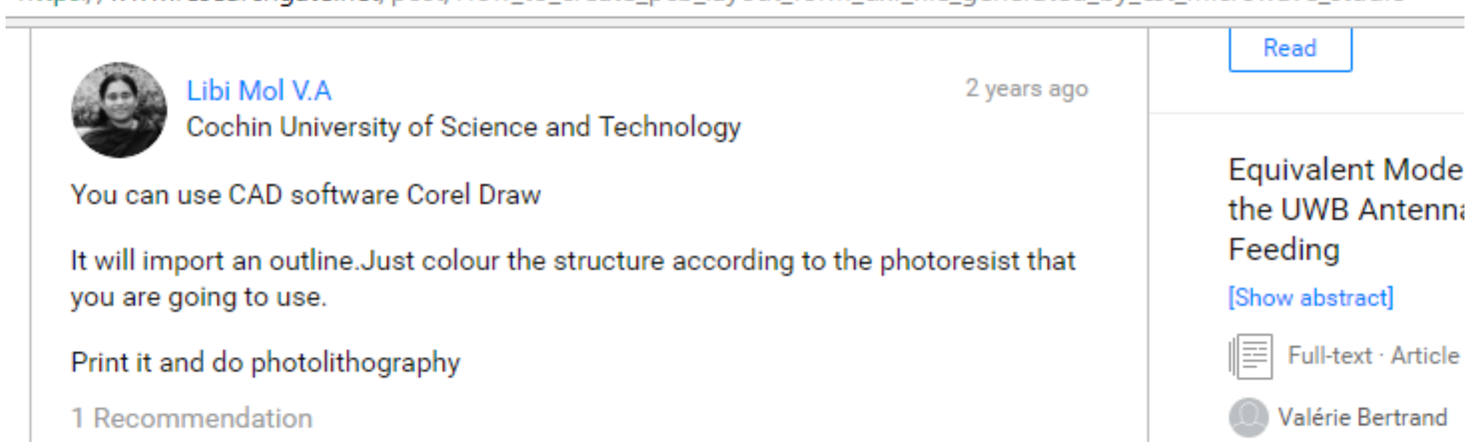
Step by step

Photo by Dane Deaner on Unsplash

Make the PCB file into Glossy Paper

- 1. Export antenna CST files as DXF Extension
- 2. Import DXF Files using CorelDraw X7
- 3. Fill black color into the necessary boundary
- 4. Remove the boundary lines
- 5. Print

https://www.researchgate.net/post/How_to_create_pcb_layout_form_dxf_file_generated_by_cst_microwave_studio

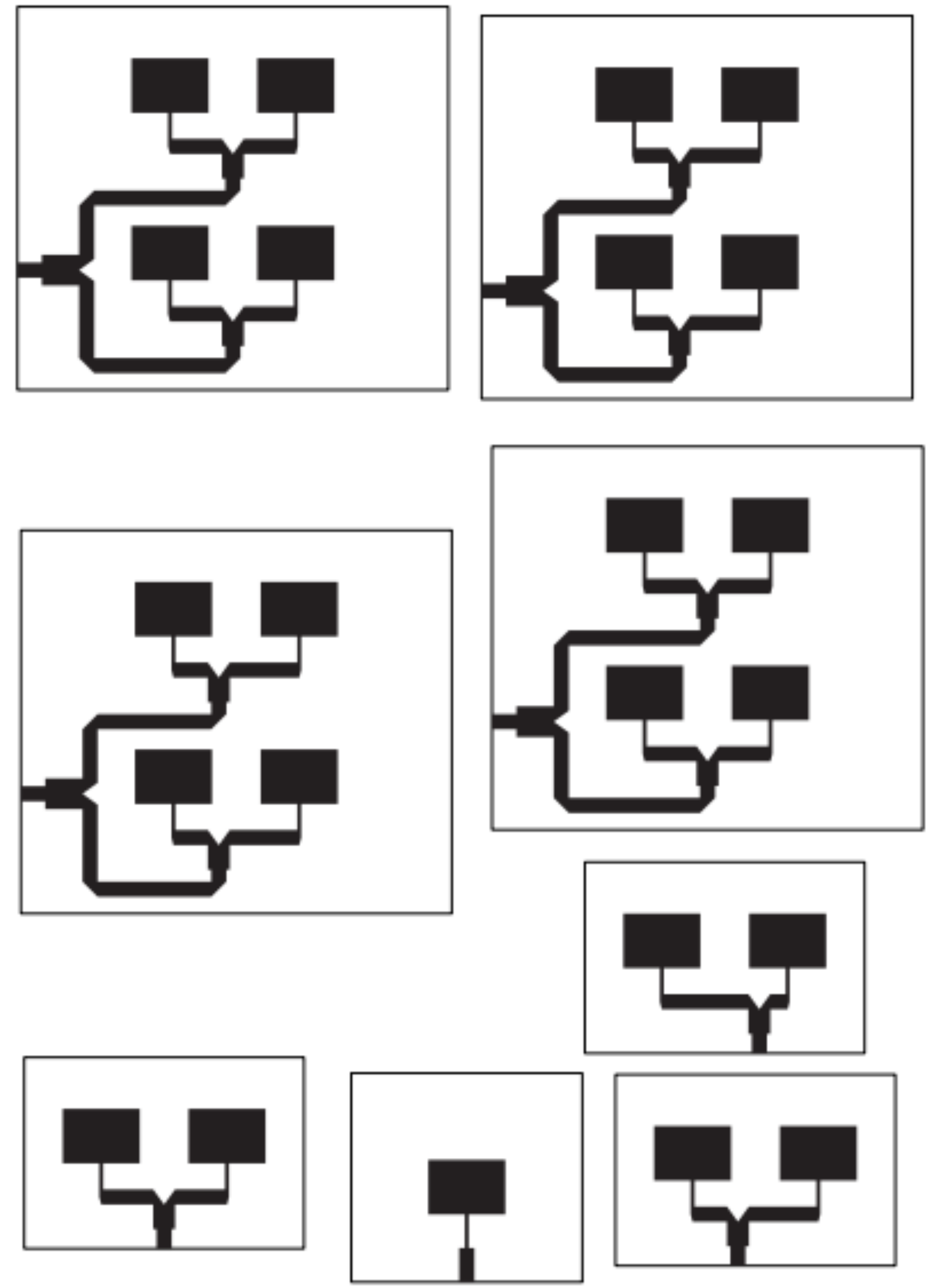

Libi Mol V.A
Cochin University of Science and Technology
2 years ago

You can use CAD software Corel Draw

It will import an outline.Just colour the structure according to the photoresist that you are going to use.

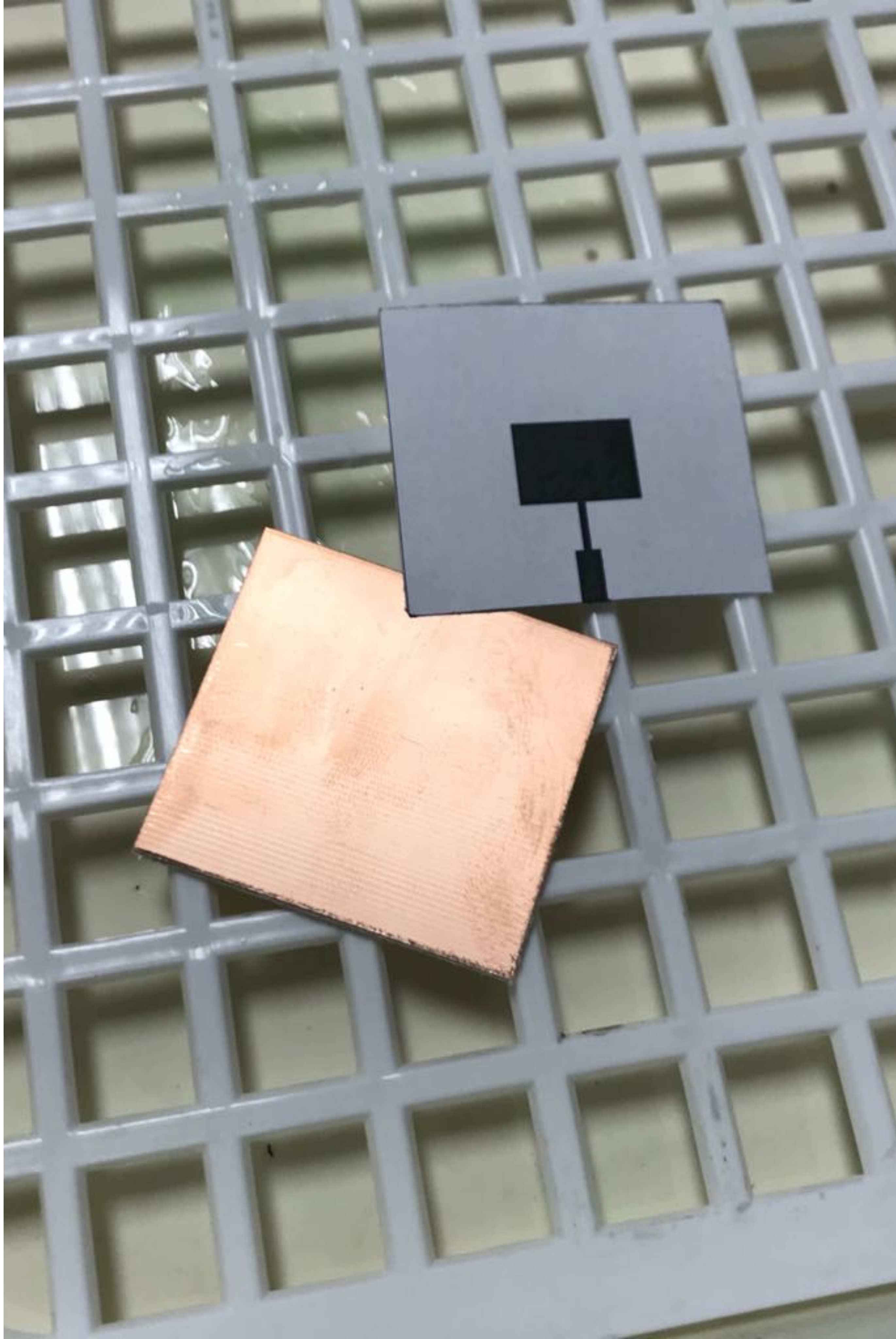
Print it and do photolithography

1 Recommendation



Move the ink from Glossy Paper to FR-4

- 1. Pour the DE-2X into the FR-4
- 2. Cover the FR-4 with the printed glossy paper
- 3. Wait until dry
- 4. Gently remove the paper with pure water
- 5. Draw additional necessary line using permanent marker



Facilities were used in King Mongkut's University of Technology North Bangkok

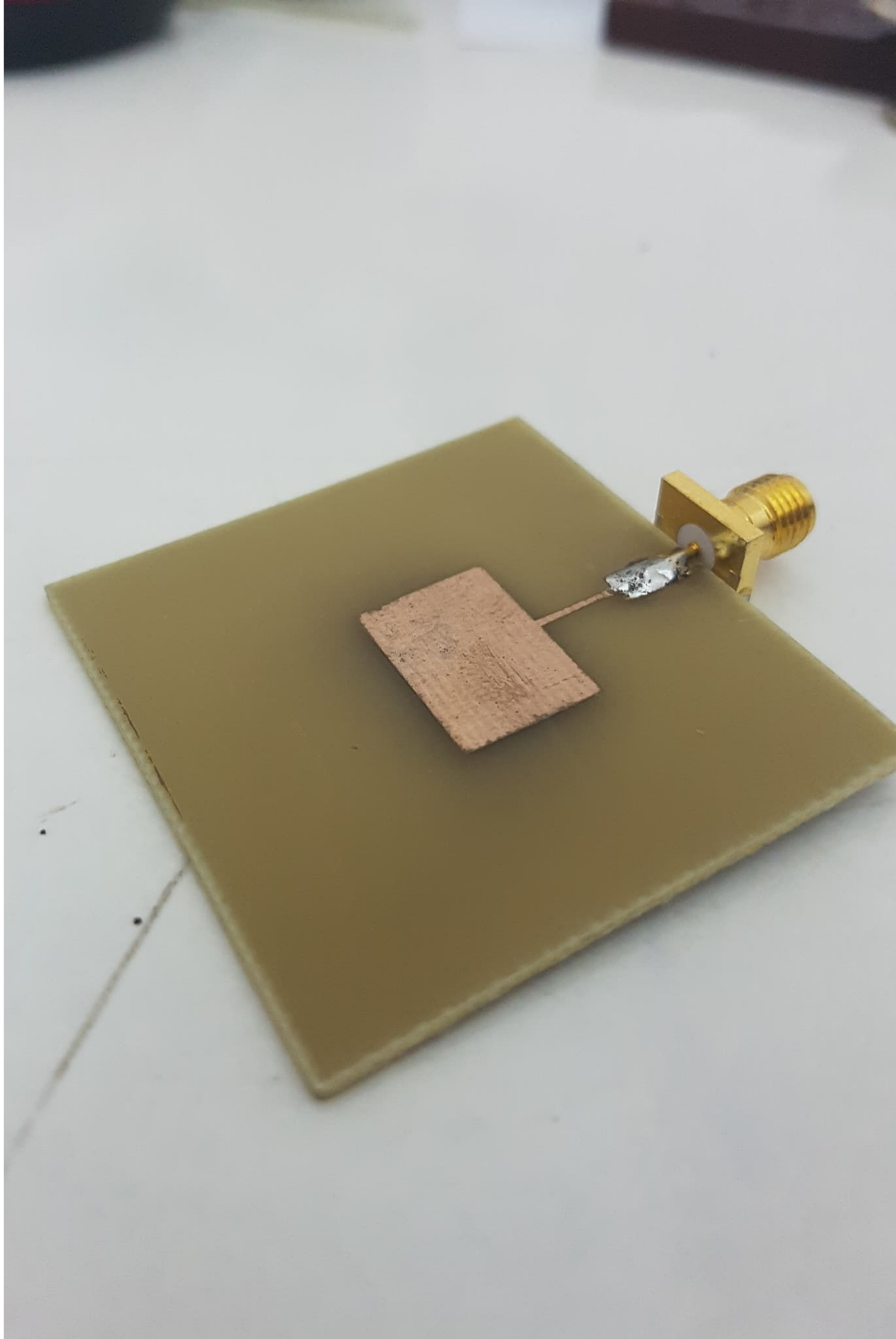
Shake with FeCl3

- 1. Fill warm water and FeCl3 into the basin
- 2. Put sticker into the other side of the PCB
- 3. Throw PCB into the basin

Facilities were used in King Mongkut's University of Technology North Bangkok

Finish it

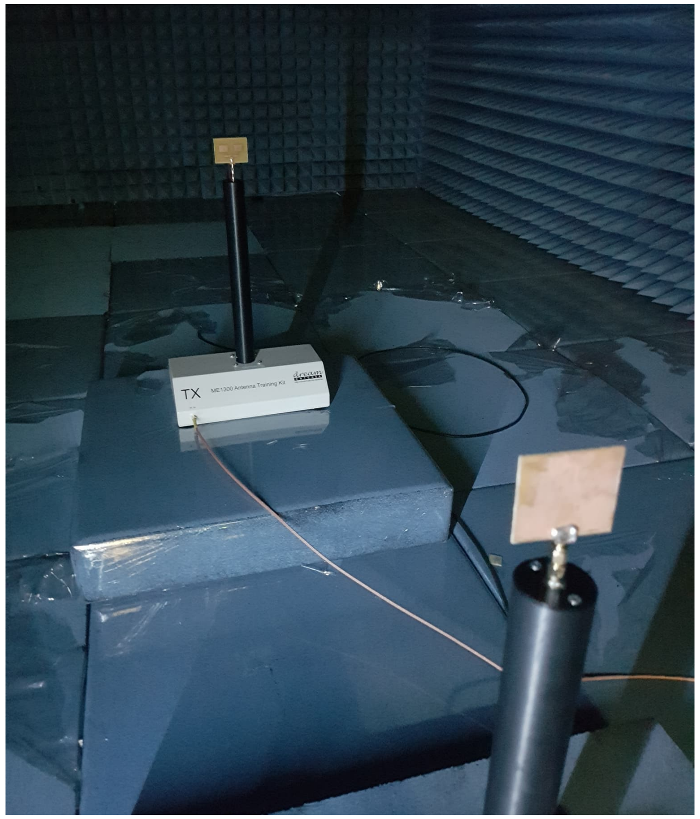
- 1. Clean with pure water
- 2. Connect to the SMA Port



Results & Discussion

Simulation and actual value

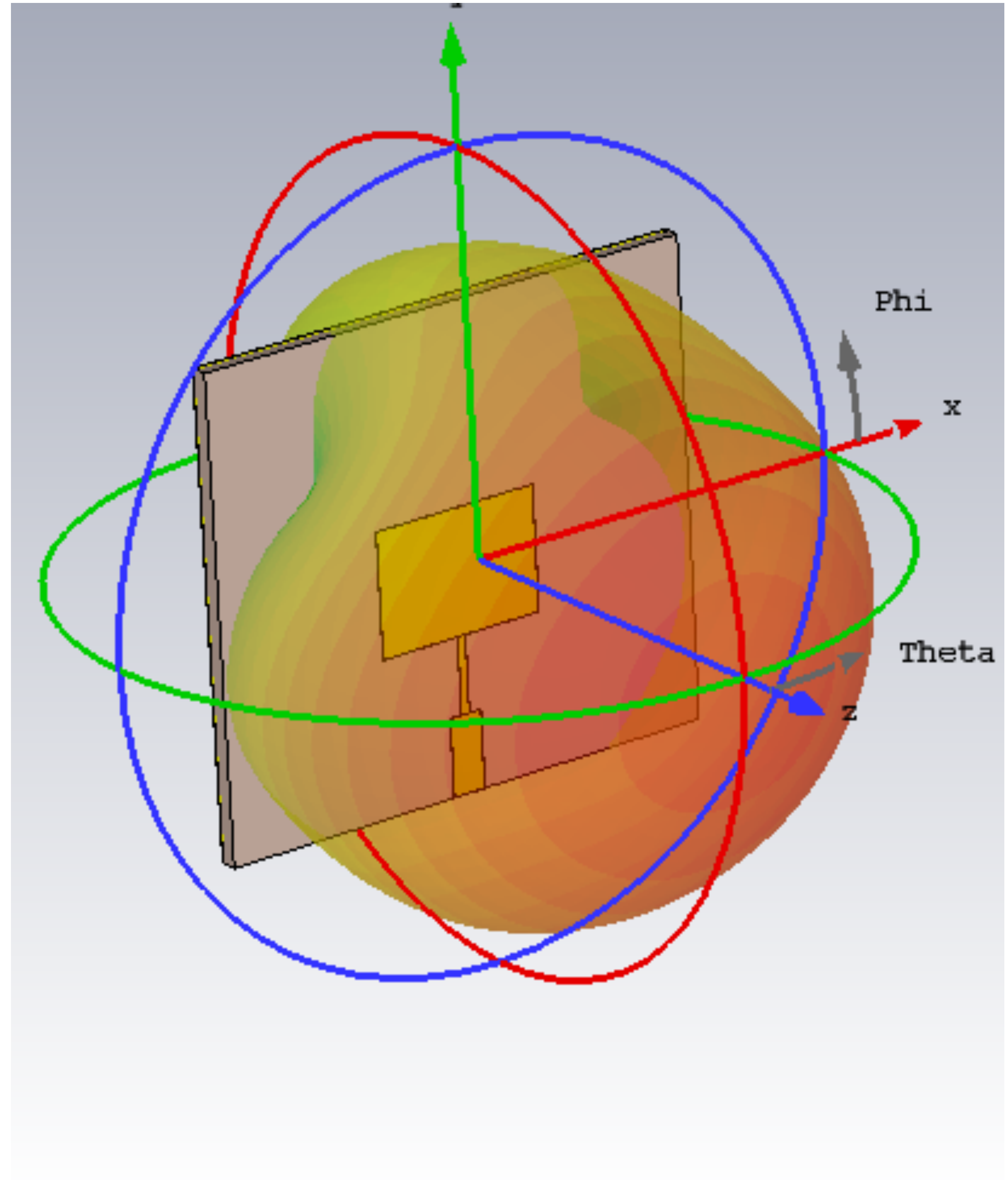
Photo by rampixel on Unsplash

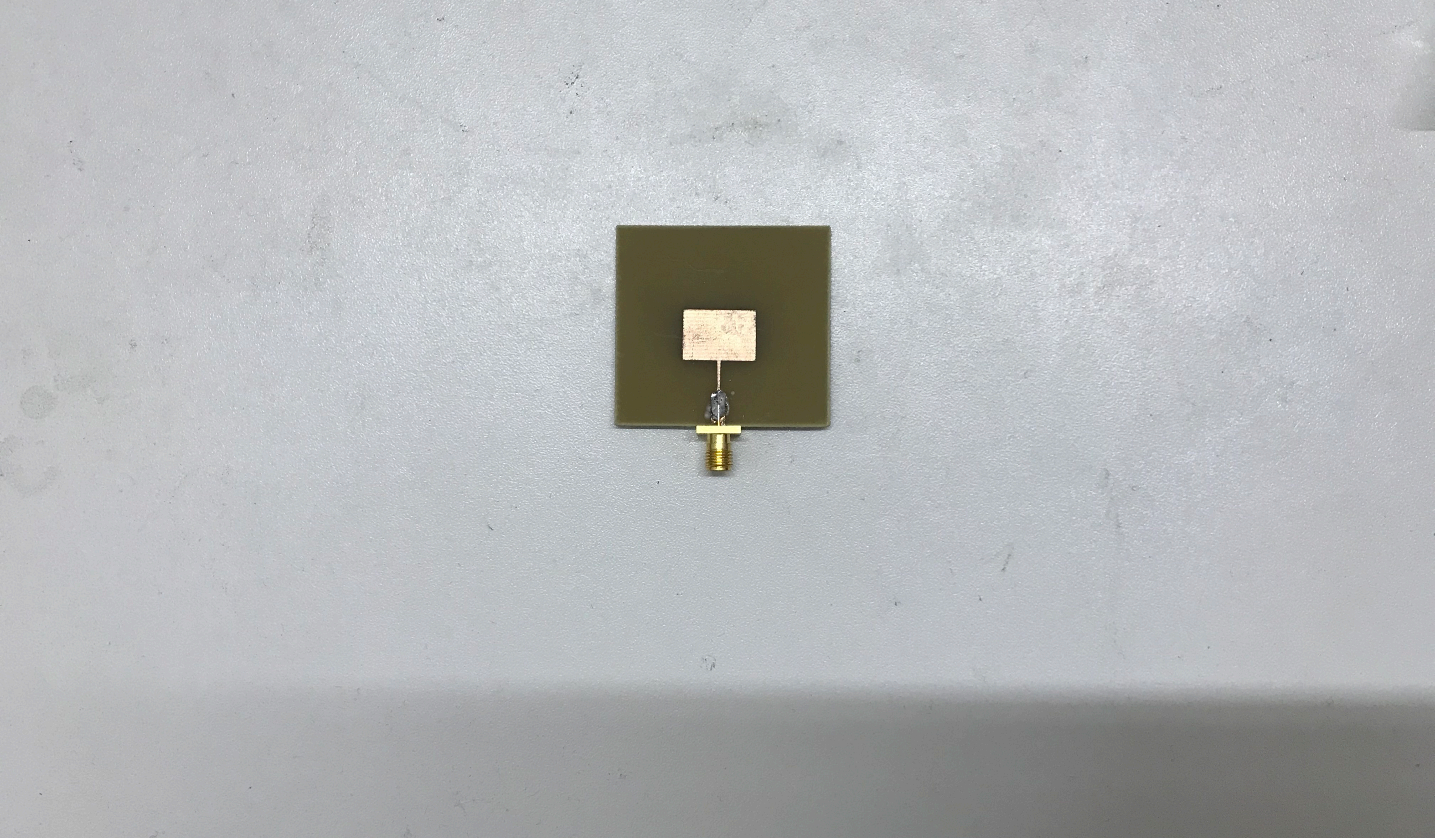


The results were taken from
King Mongkut's Institute of Technology Ladkrabang

Testing Condition

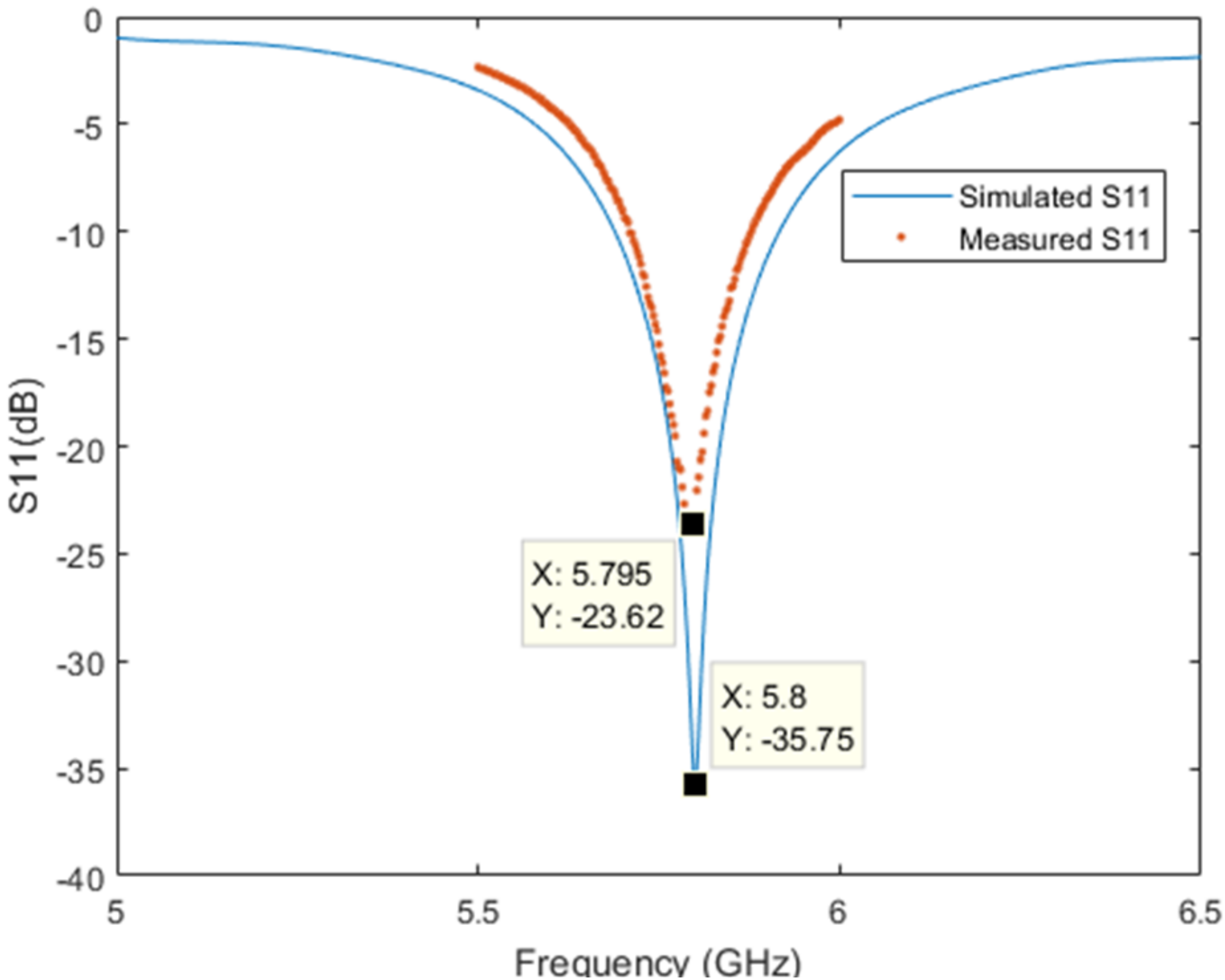
- The results were normalized
- The results were co-polarized only.
- E-Plane were defined as Phi = 90 (Red Circle Line)
- H-Plane were defined as Phi = 0 (Green Circle Line)

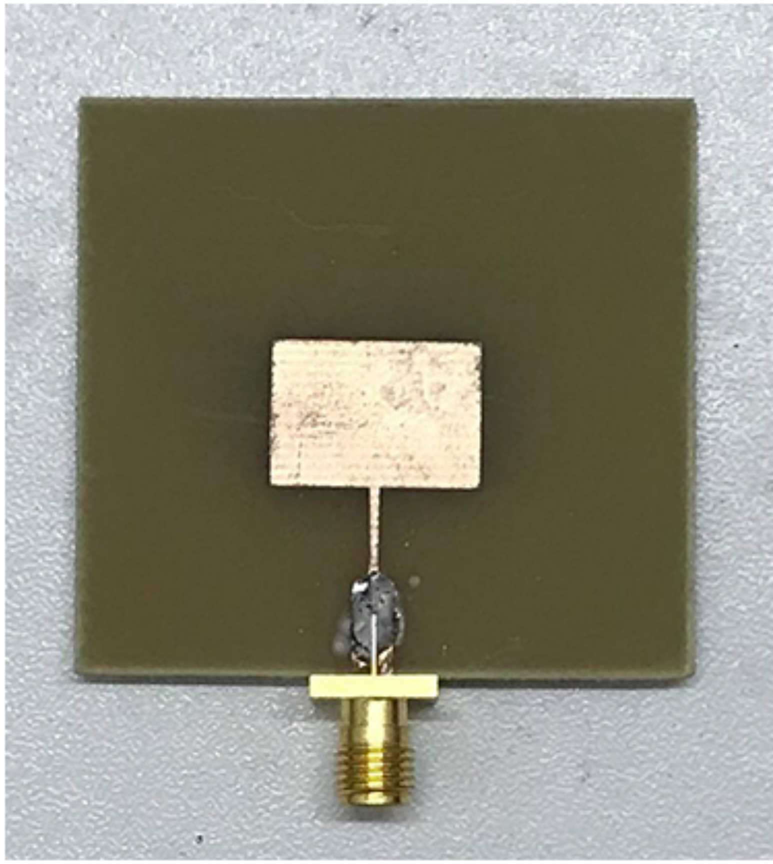




Single Patch Microstrip Antenna

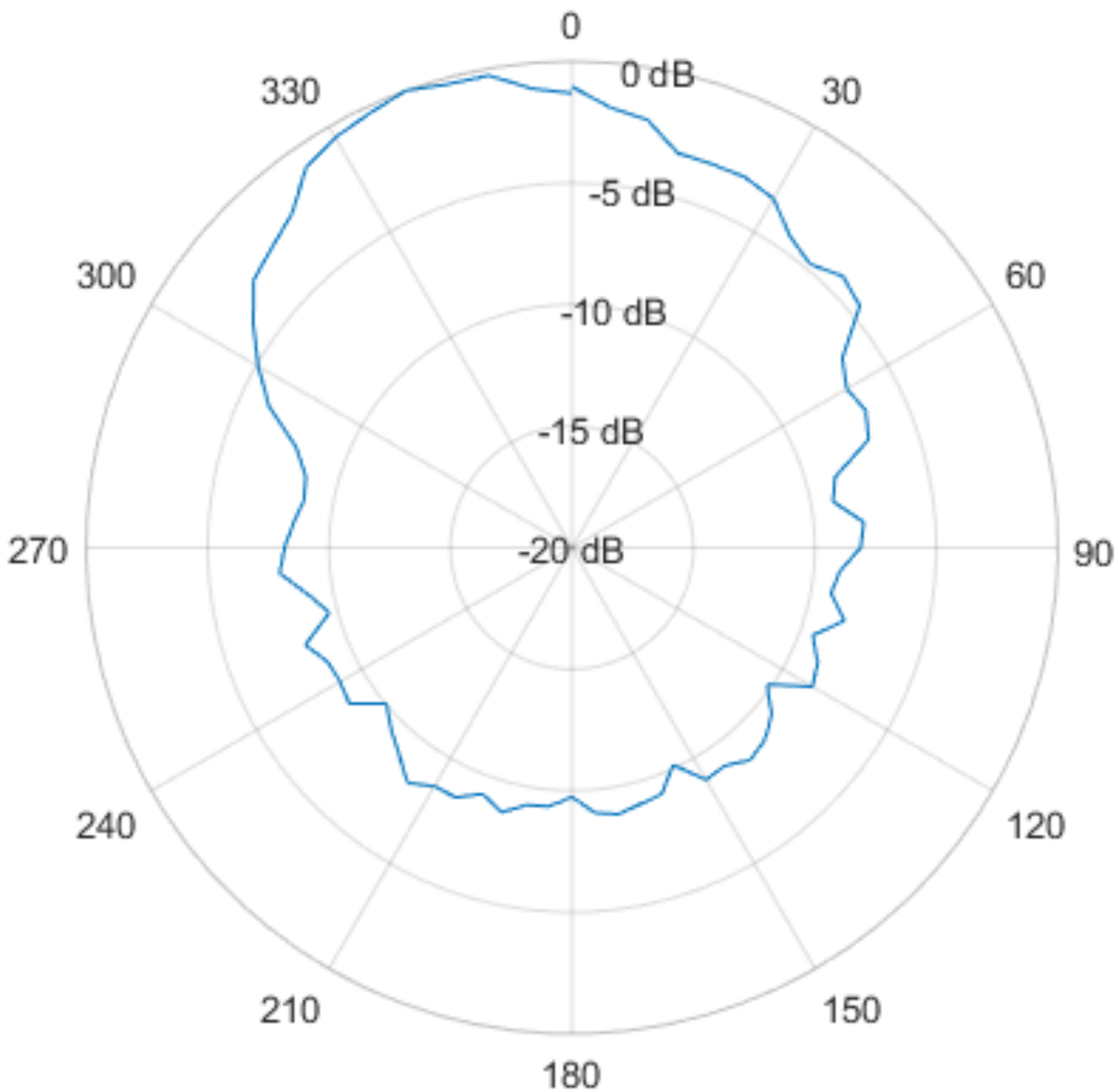
Actual



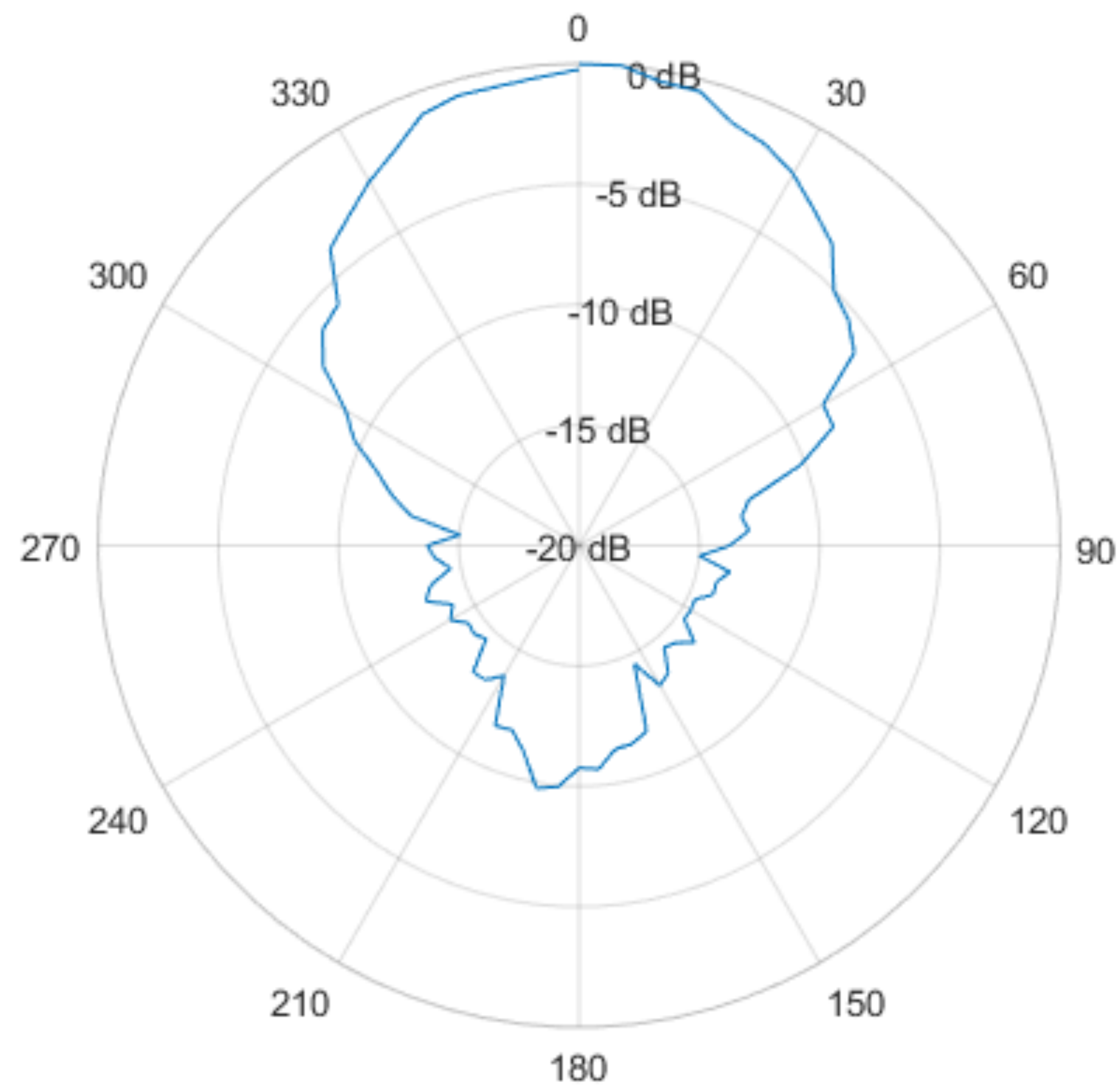


Single Patch Microstrip Antenna

S11



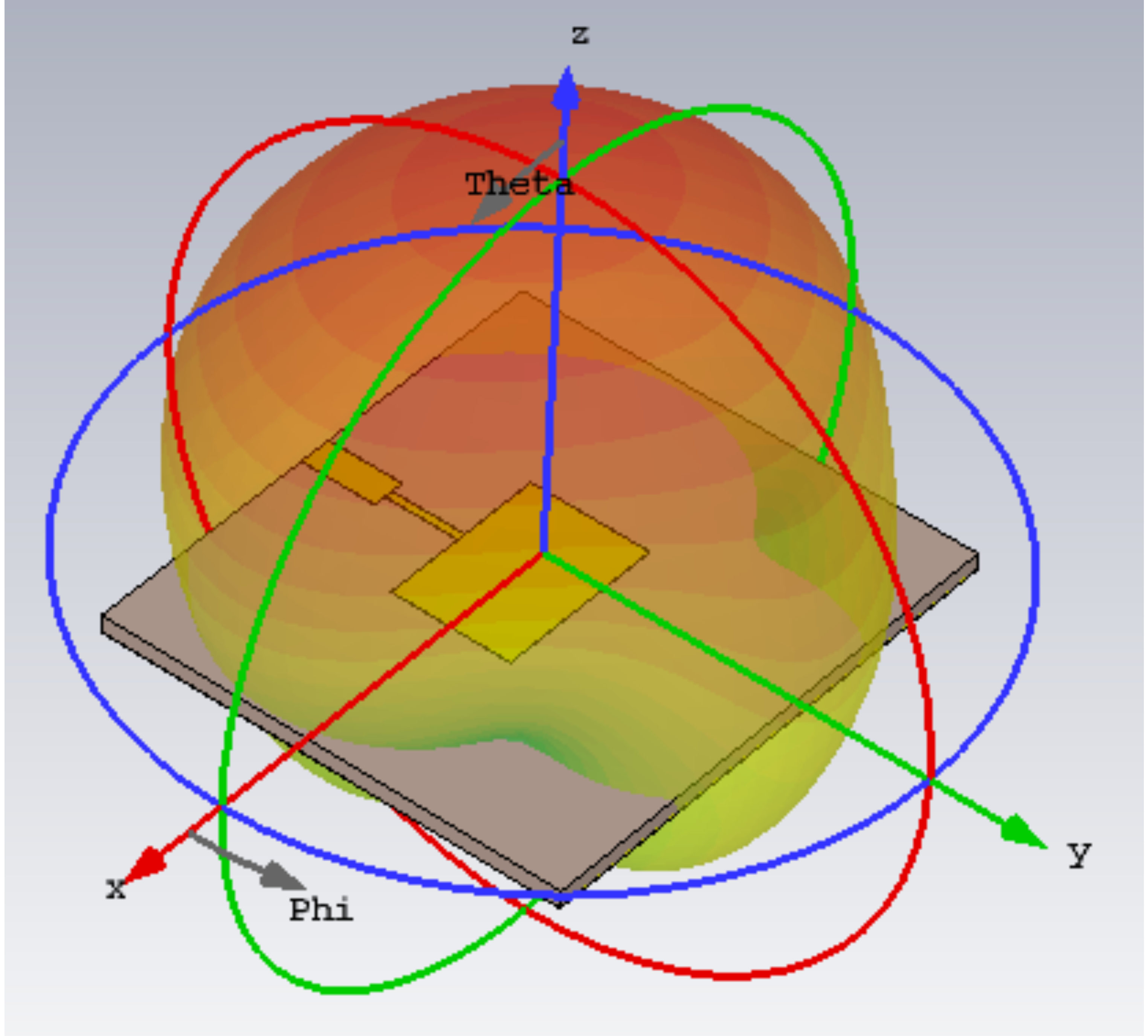
E-Plane



H-Plane

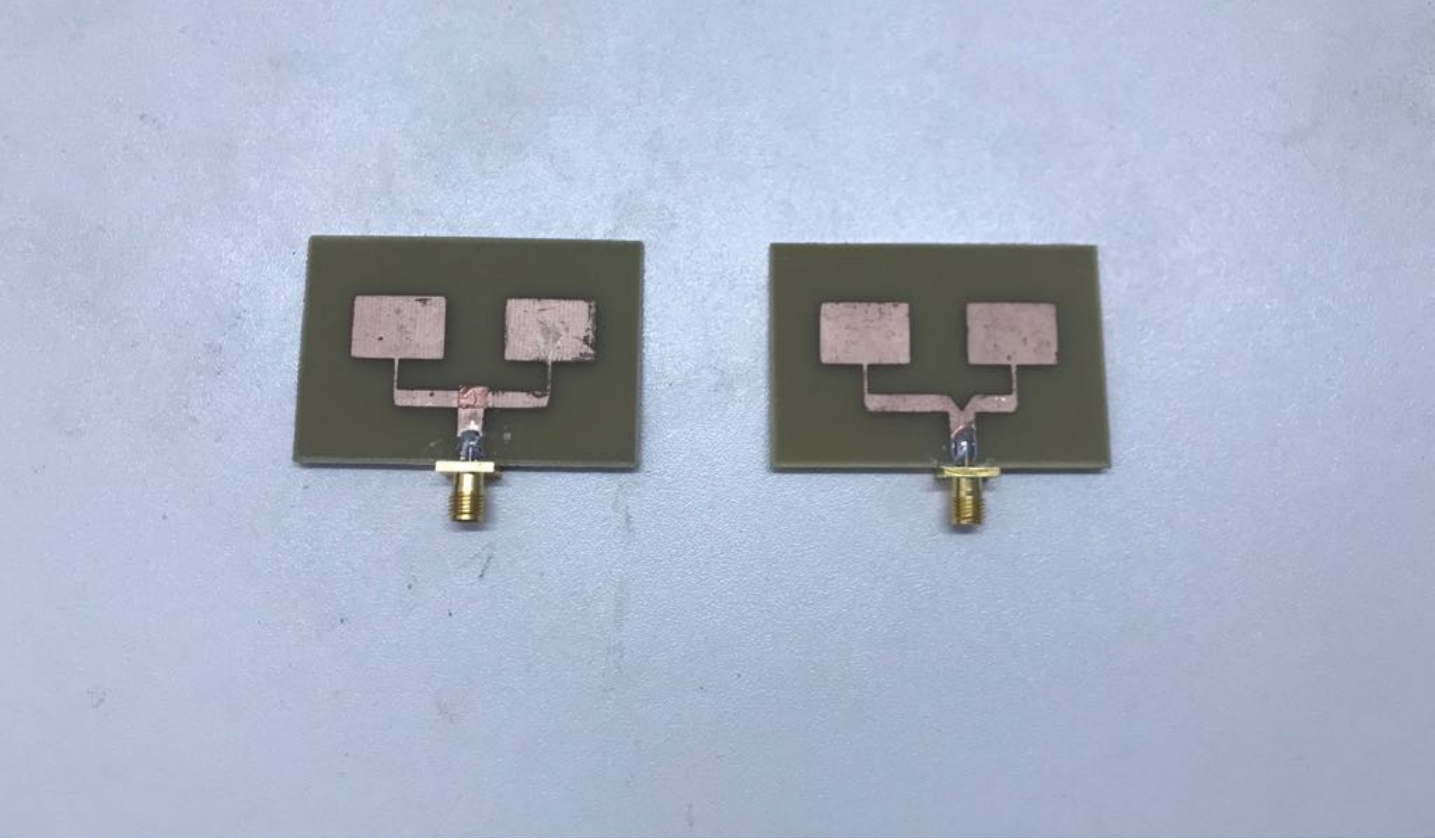
Single Patch Microstrip Antenna

Farfield

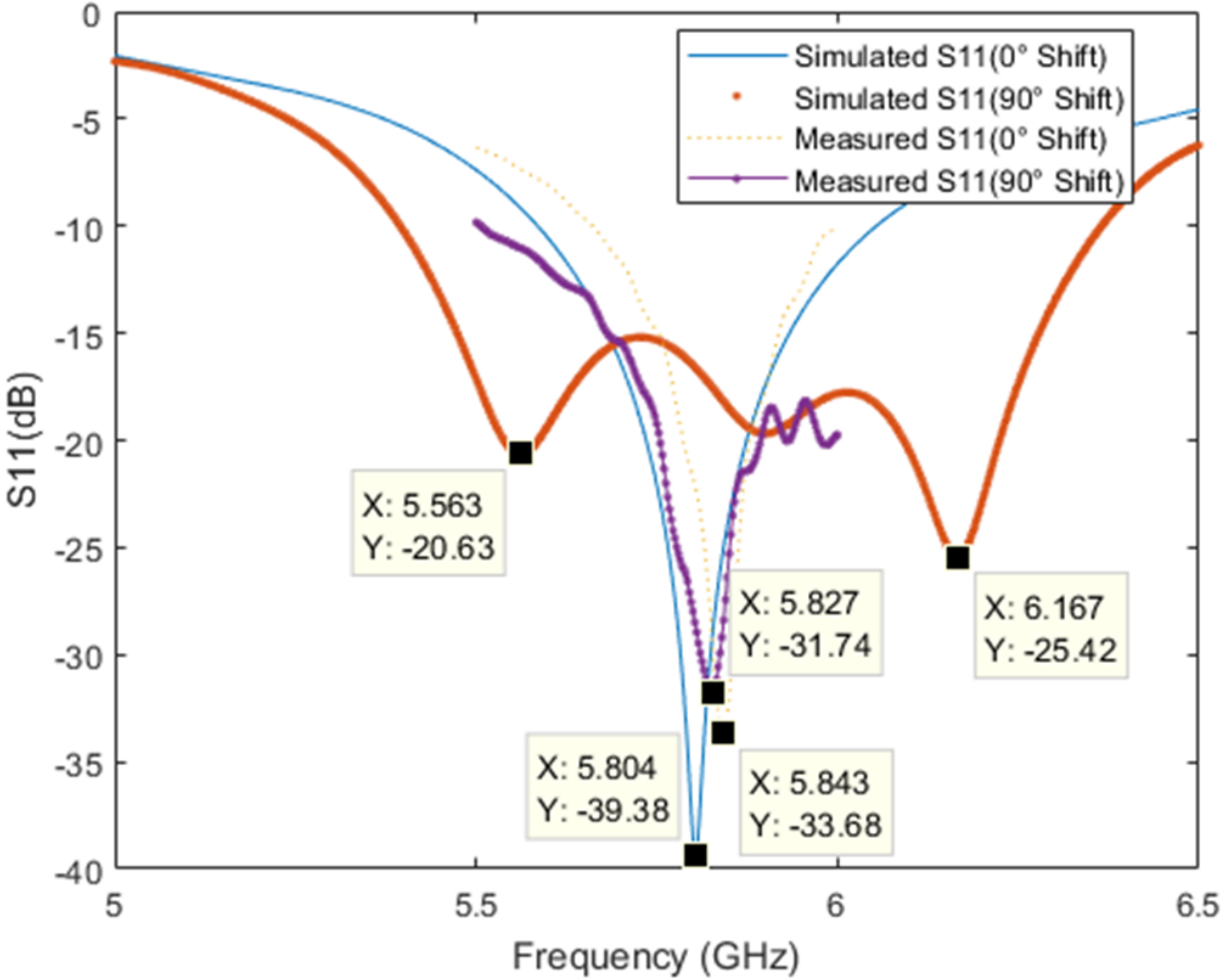


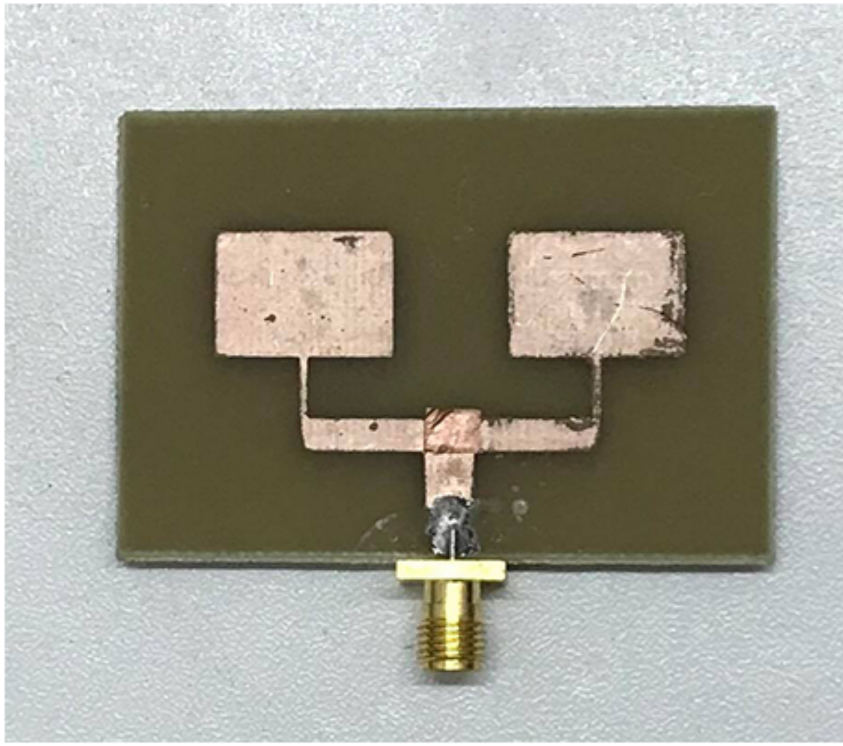
Single Patch Microstrip Antenna

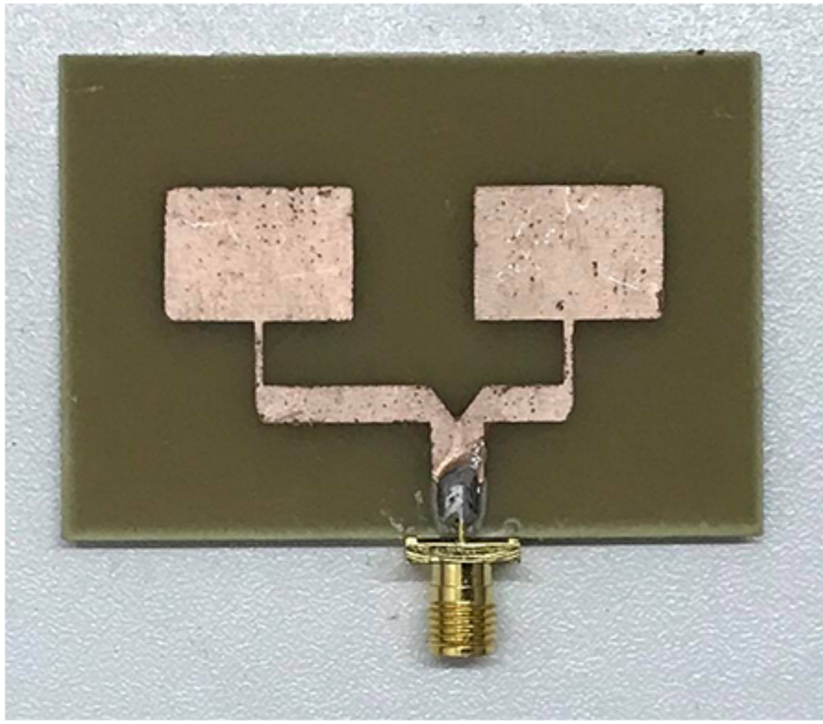
Simulated(for comparison)



1x2 Array Antennas | Actual

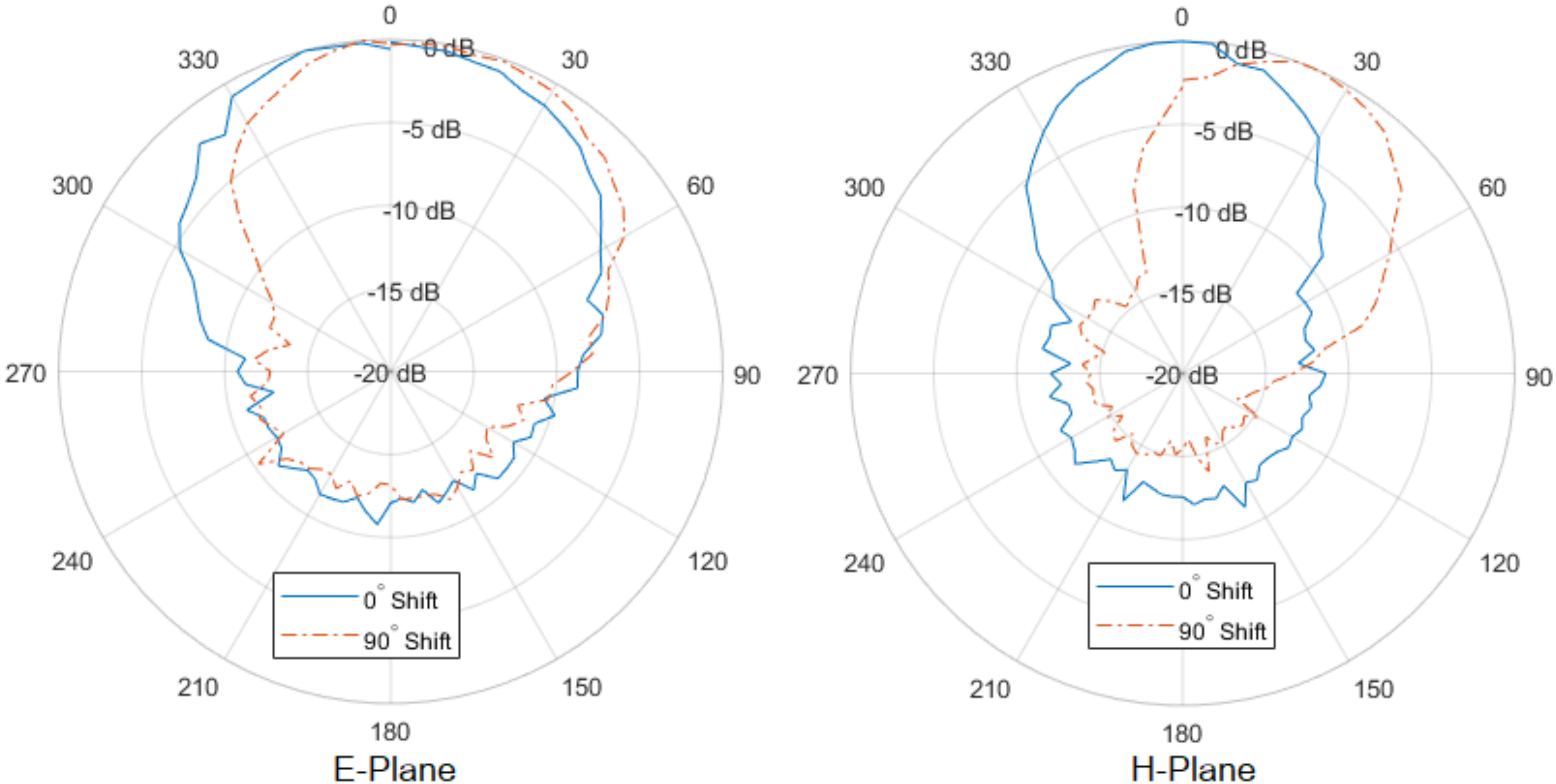






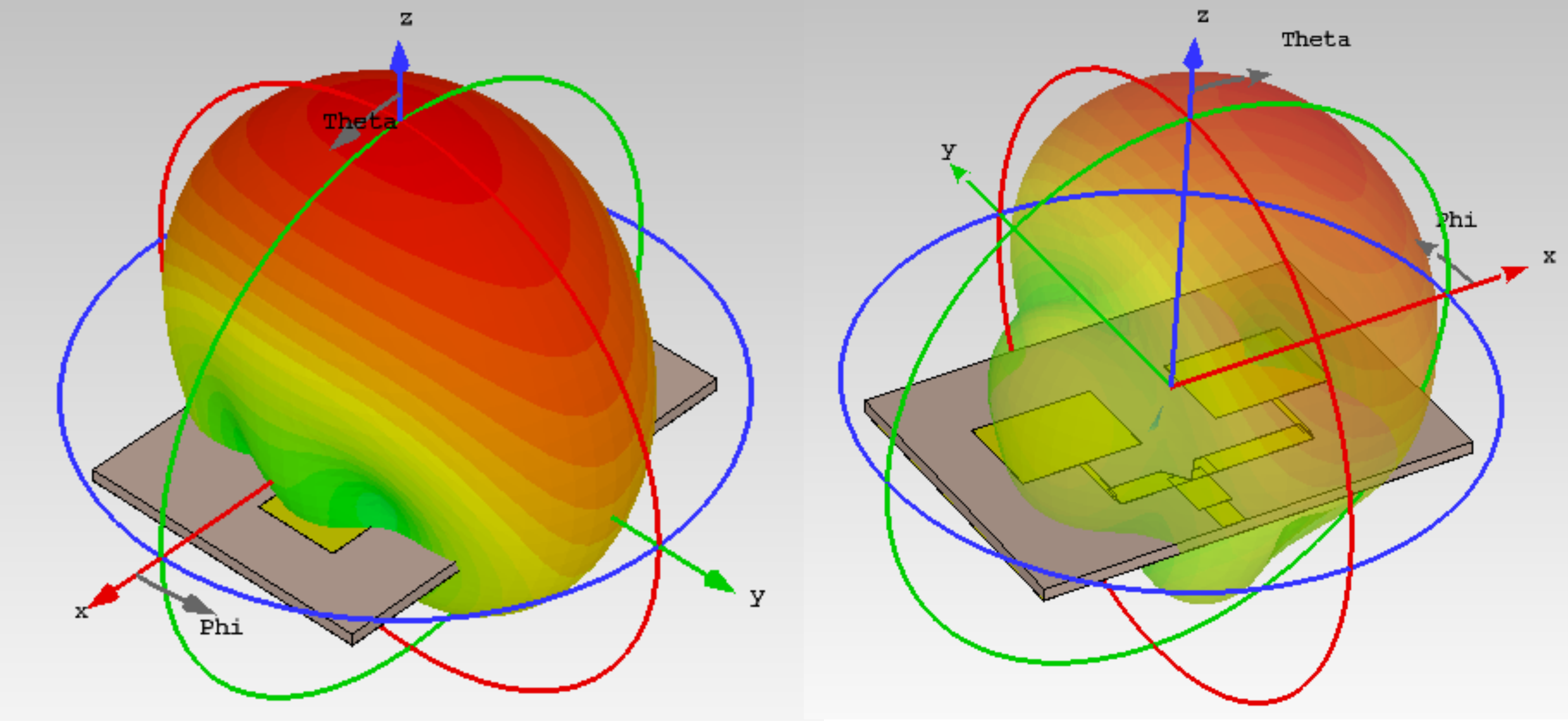
1x2
& 1x2 with Phase Shift

S11



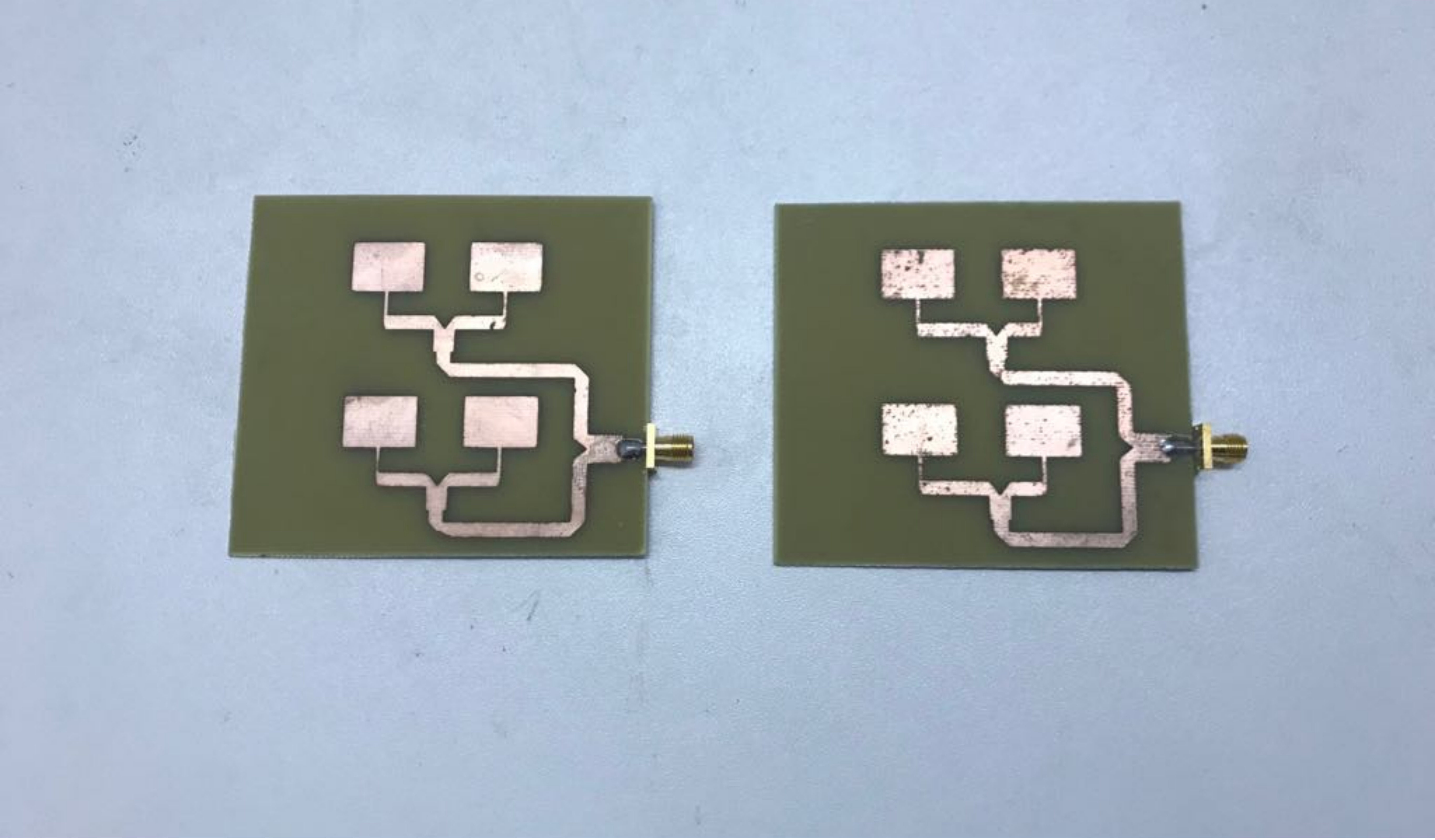
1x2
& 1x2 with Phase Shift

Farfield

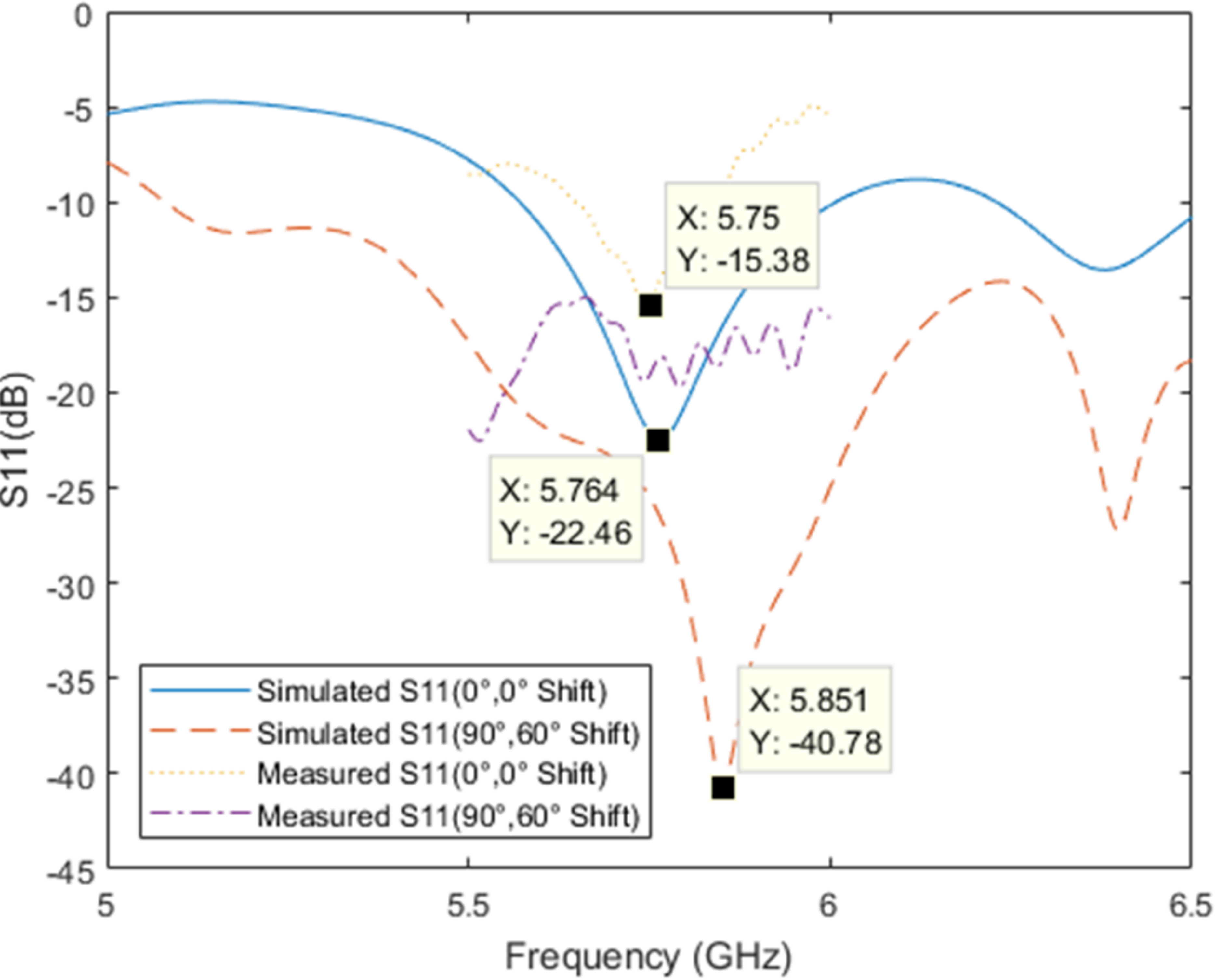


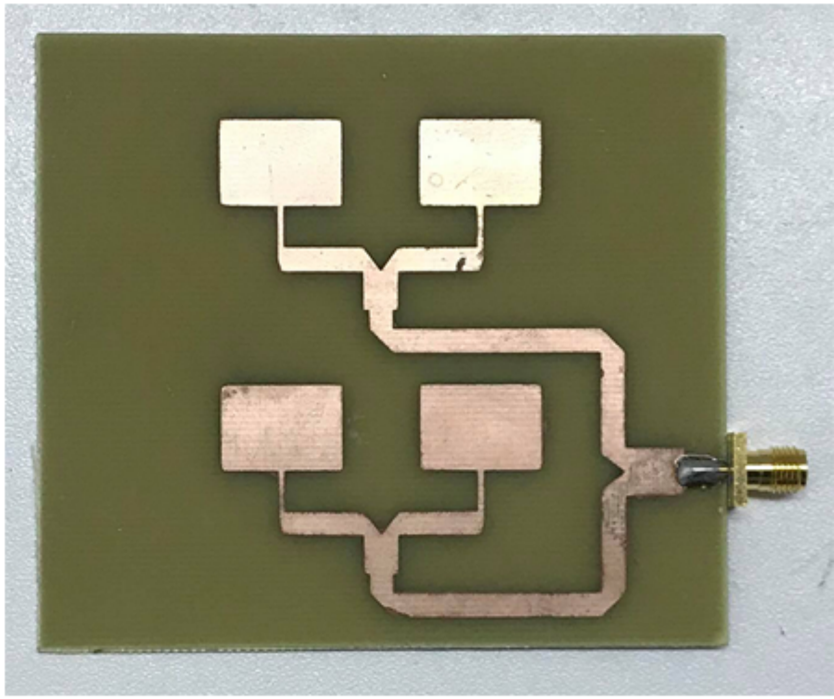
1x2
& 1x2 with Phase Shift

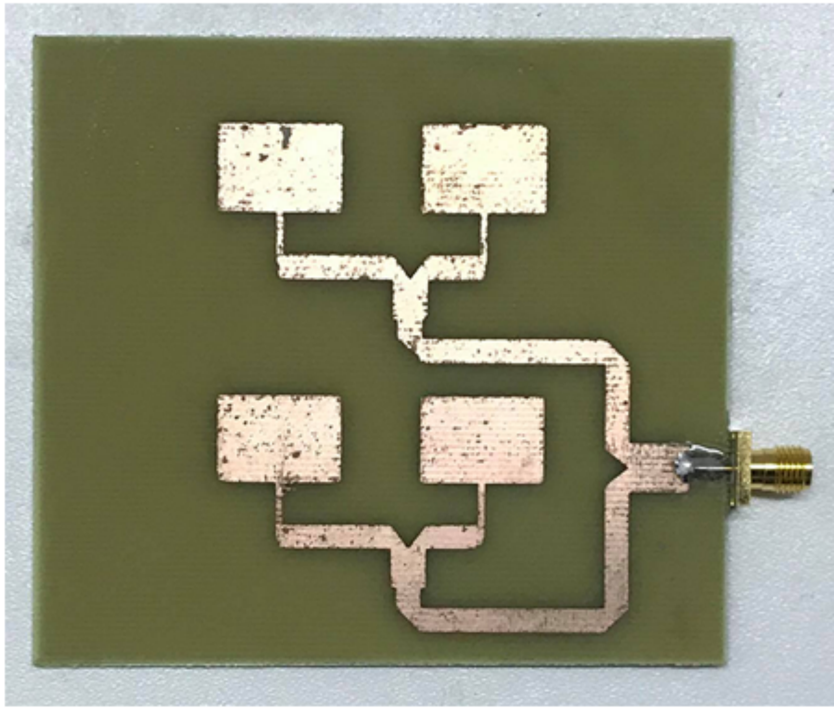
Simulated(for comparison)



2x2 Array Antennas | Actual

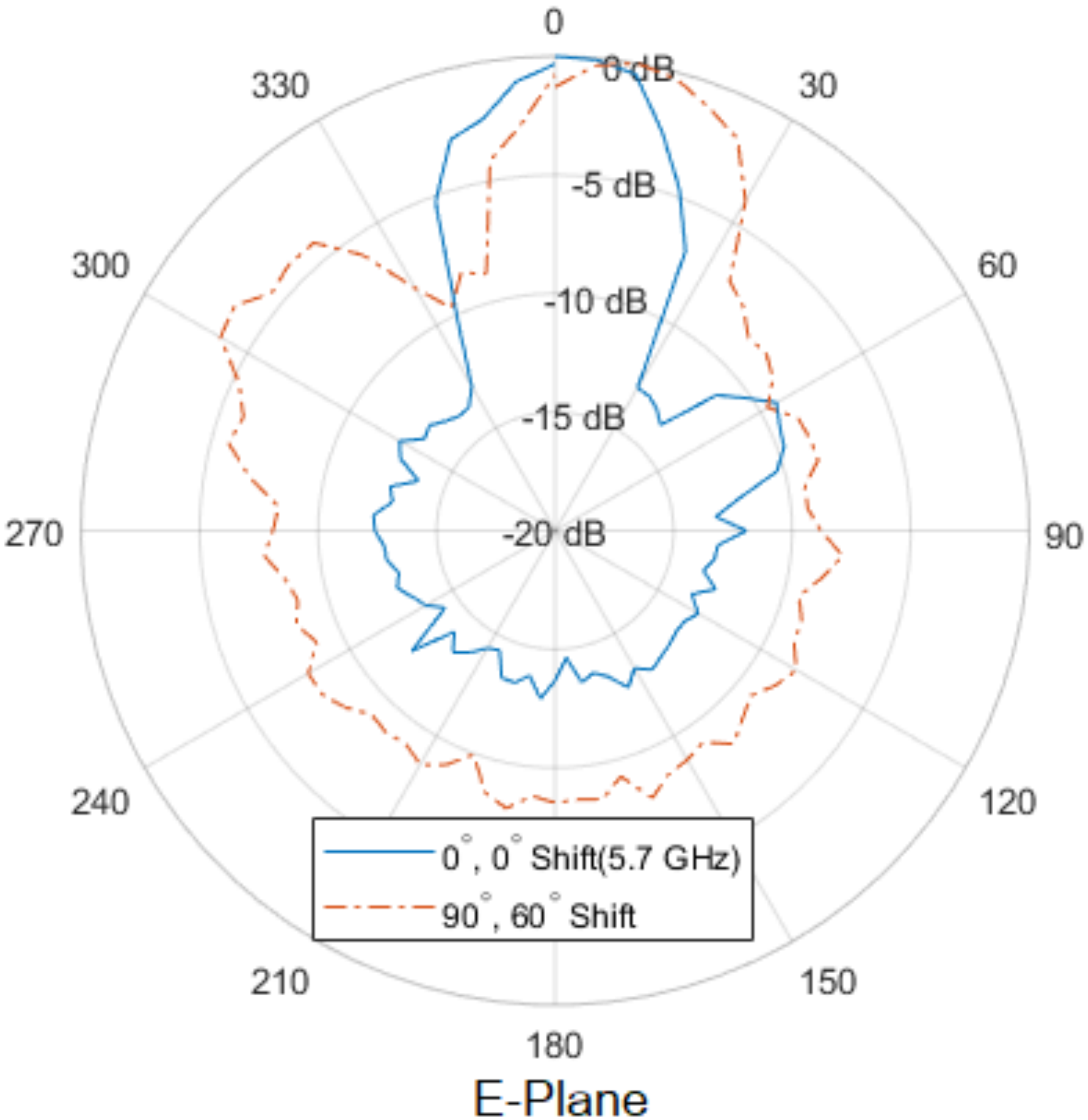


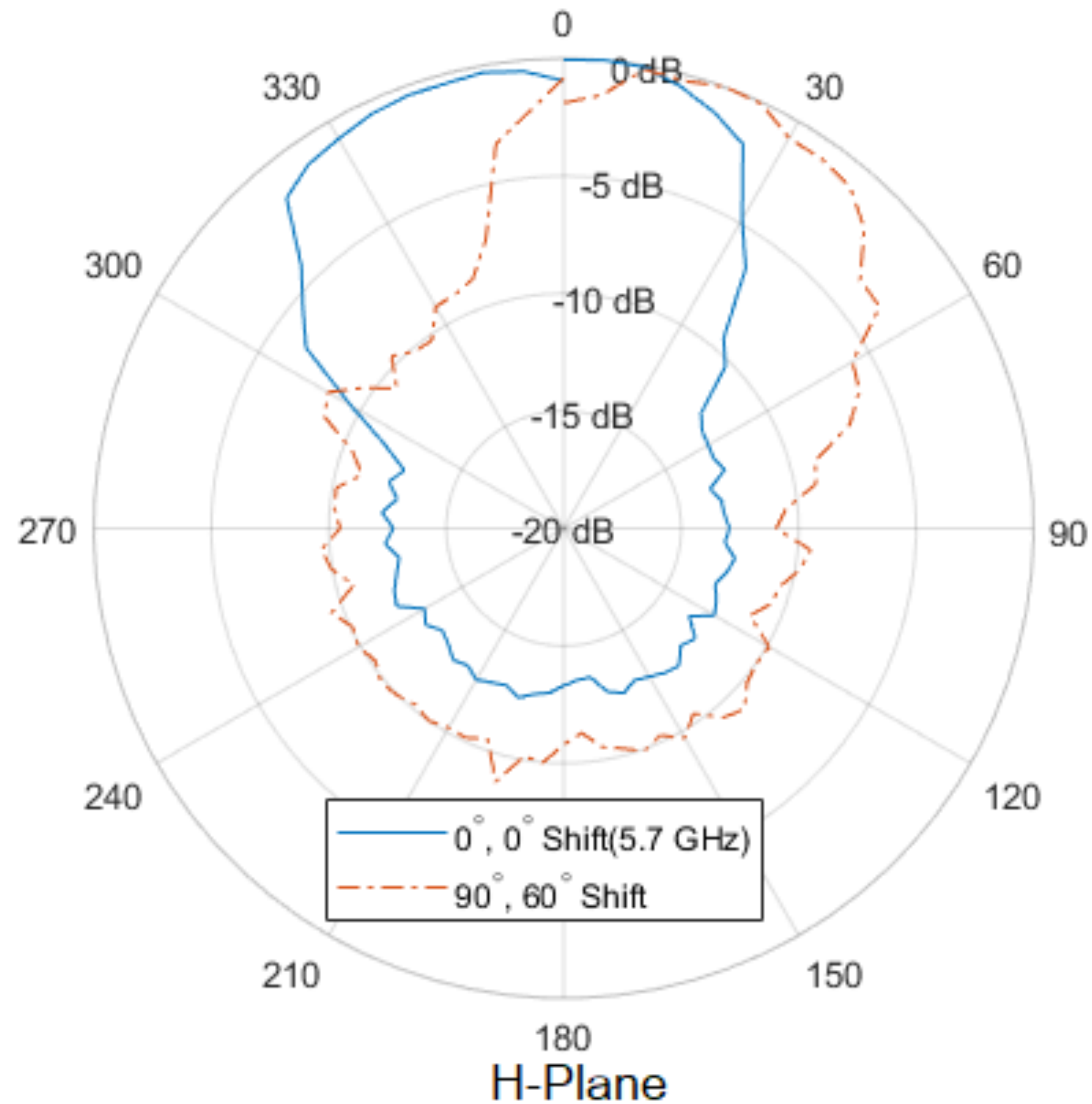




2x2
& 2x2 with Phase Shift

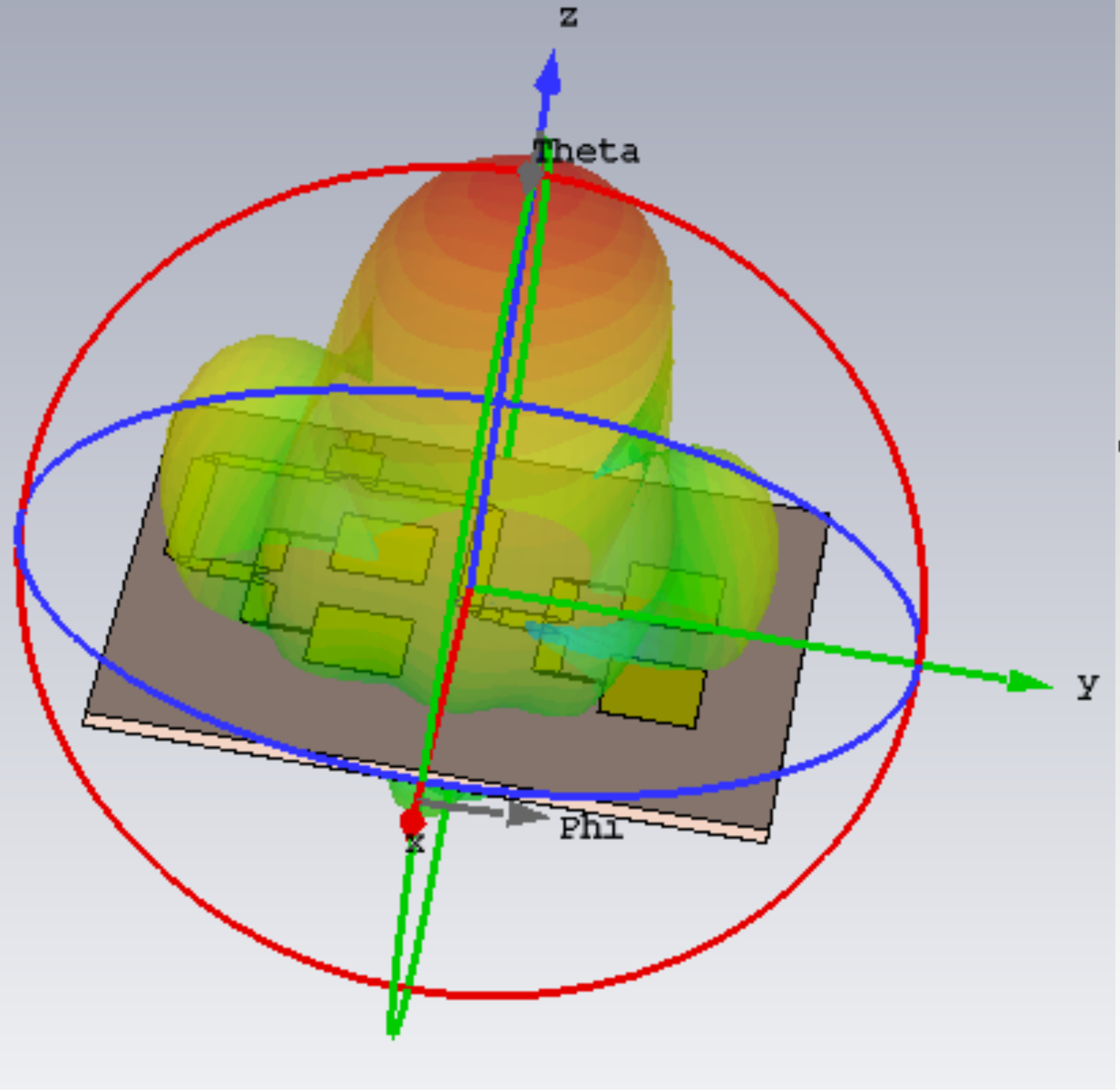
S11

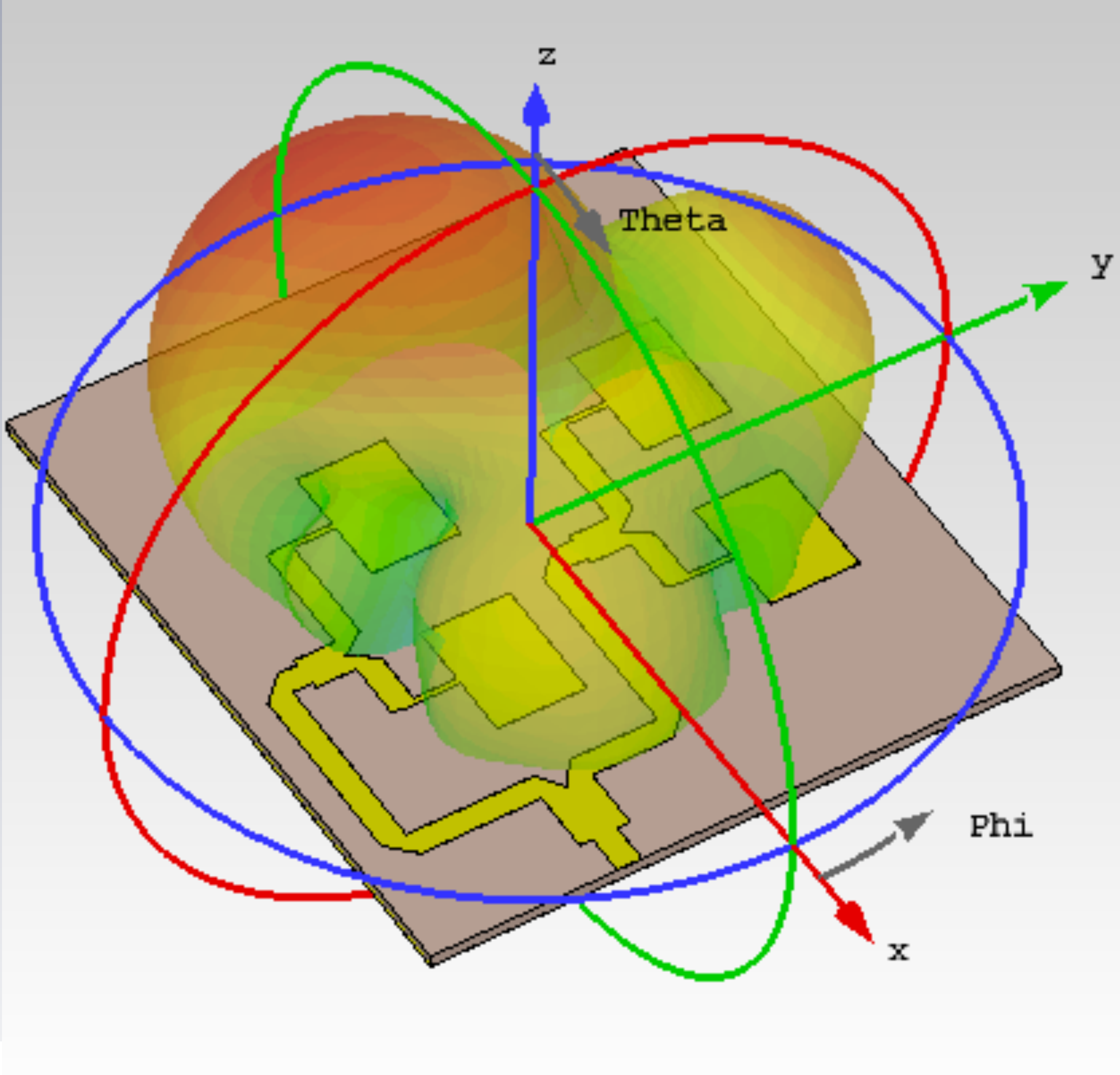




2x2
& 2x2 with Phase Shift

Farfield





2x2
& 2x2 with Phase Shift

Simulated(for comparison)

“Thank you for your kindness attention”

–Norawit Nangsue