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

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Abstract

The purpose of this report is mainly studying on both the analysis and design of the 2x2 phased array antenna which each element of the arrays are a rectangular microstrip antenna. The phased array are analyzed with multiple phased difference in order to understand the phased array behavior. A comparison between the physical and the simulation model is included.

Keywords: phased array, microstrip, array antenna

Contents

1 Introduction

The recent advances of technologies would not have happened without communication systems. Today, wireless communication is available almost everywhere in the world. One of the most important things in communication systems is the antenna, because it is able to radiate or receive electromagnetic wave from the air. With these abilities, we may use it to send or receive the information that we want instantly and cheaply. As we know, just a wire could technically be used as an antenna, however, its properties may not be good for every requirement or application.

The freedom of using frequency bands bring us to the world of technology. Back in 1947 at the International Telecommunications Conference of the ITU (International Telecommunication Union) in Atlantic City the first ISM (Industrial, Scientific and Medical) bands were established, which allowed us to use individual frequencies without asking for permission. For example, the microwave oven, we never have to ask for any government's permission to use microwaves which radiate the electromagnetic wave at the frequency of 2.45 GHz to our food because this frequency is in the ISM bands.

There are many methods to increase the gain of an antenna, the easiest one is to increase the power. However, if we just want to send a message from one station to another there will be a huge power loss to the air in directions that we do not really need to transmit. A good practical engineer designs antennas that have the property of focusing in only one direction which is called directivity. Therefore, a high directivity antenna can be able to send the signal greater distances than a non-high directivity antenna.

Considering a water droplet dropping onto the surface of water, there will be a circular wave spreading out from the origin. If there are multiple droplets in a row, those wave will be constructed and destructed depending on the location and it will reform like a seacoast wave. So this will make a more powerful wave from two sources. Moreover, the direction can also be changed by controlling how the droplets fall onto the surface. The same as an array of antennas, if we can control each element's phase we will be able to control antenna's directivity as desired.

If we want to make a device that everyone agrees to carry everywhere they go, basically, it must be small, thin and cheap. To response to this demand, there is a flat composite material which is composed of woven fiberglass cloth available on the market, it is termed FR4 (a grade designation assigned to glass-reinforced epoxy laminate sheets, tubes, rods and printed circuit boards). Engineers usually uses FR4 as a microstrip. It can be used in any type of microwave circuit including antennas.

Therefore, there are a lot of constraints depending on which application we want to use. As from the title of this proposal, Analysis and Design of Planar Phased Array Antenna for 5 GHz Applications, this project consists of reviewing past literature, derived formula, empirical formula and try to using all of this knowledge to design an array of antenna with phase-shift at the ISM band (5.8 GHz).

2 Project Overview

2.1 Objectives

The main objectives of this project is to study about the analysis and design of the microstrip phased array with the variety of phase difference and observe the gain improvement when the number of patches are increased from a single patch to 2 patches and 2 patches to 4 patches. Comparing with the theories, simulations and the physical models altogether.

2.2 Scope of Work

- Study the design and the analysis of microstrip and phased array theory
- Design the antennas and microstrip transmission line
- Analysis the antenna prototypes by using computer and software
- Shift array antennas with some phases
- Craft the printed antenna
- Test the antennas

2.3 Expected Outcomes

- 2x2 Microstrip phased array antennas.
- Simulation results
- Measurement results

3 Methodology

3.1 Microstrip Antenna

3.1.1 Overview

Microstrip patch antenna is considered as the greatest achievement of antenna technology. Because of their lightweight, easy to fabricate, low cost and very versatile. But its drawback is that the bandwidth is quite narrow and low efficiency.[8] However, this technology is picked for this project because these advantages.

Figure 1: Microstrip patch antenna that is fabricated for this project

3.1.2 Transmission Line Model

This model is the easiest way to describe the microstrip patch antenna. Because it makes use of transmission line theory and describe radiating slots as admittance.[4] Though, the slot admittance is defined as

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

where: λ_0 = Free space wavelength
W = Width of the patch
η_0 = Impedance of free space
k_0 = Wavenumber
h = Substrate thickness

And, the characteristic admittance is defined as

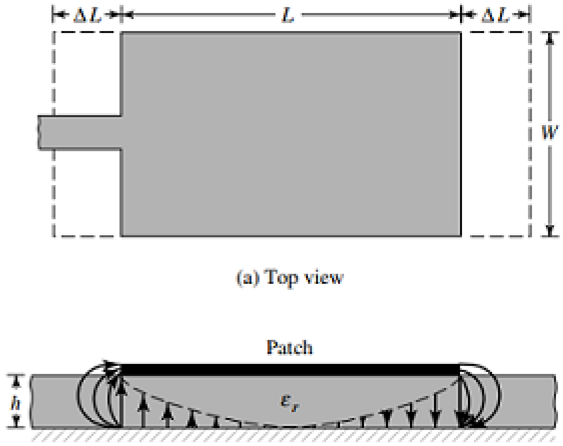
$$Y_0 = \frac{W\sqrt{\epsilon_r}}{h\eta_0} \tag{2}$$

where: ϵ_r = Relative dielectric constant

Even though, the transmission line equation and the slot admittance are given but the equation is not really useful because it doesn't count on the power that radiate nor the mutual coupling at all. It just help us for understanding the insight of the microstrip patch antenna.

3.1.3 Fringing Effect

Fringing effect causes an extra length of the microstrip patch. Therefore, a length subtraction will be required at the process of calculating the length of the patch[3]



(a) Top view

(b) Side view

Figure 2: The fringing effect that cause an extra length (adapted from [3])

Electric field spreading at both sides of the edges causes to adding the extra length followed as this expression[3]

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{r(eff)} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{r(eff)} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{3}$$

where: ΔL = Extra length of the patch
h = Substrate thickness
$\epsilon_{r(eff)}$ = Effective relative dielective constant(See Appendix)
W = Width of the patch

3.1.4 Preliminary Dimension

With a given frequency, the dimension of microstrip patch can be easily designed with these expressions[3, 6].

$$L = \frac{c}{2f_r\sqrt{\epsilon_r \mu_r}} - 2\Delta L \tag{4}$$

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{5}$$

where: L = Length of the patch
W = Width of the patch
c = Speed of light
f_r = Resonant frequency
ϵ_r = Relative dielective constant of the substrate
μ_r = Magnetic permeability of the substrate
ΔL = Extra length of the patch

3.1.5 Input Impedance

According to the transmission line model, there are 2 edges(slots) and the transmission line wire them as a parallel circuit. The derivation from cavity model represents both slots as admittance Y but the transmission line model represents the transmission line as characteristic admittance.[3] Howsoever, the characteristic impedance may not need to be considered because the when we rotate the smith chart at around $\frac{\lambda_g}{2}$, the smith chart will be around at the same point.

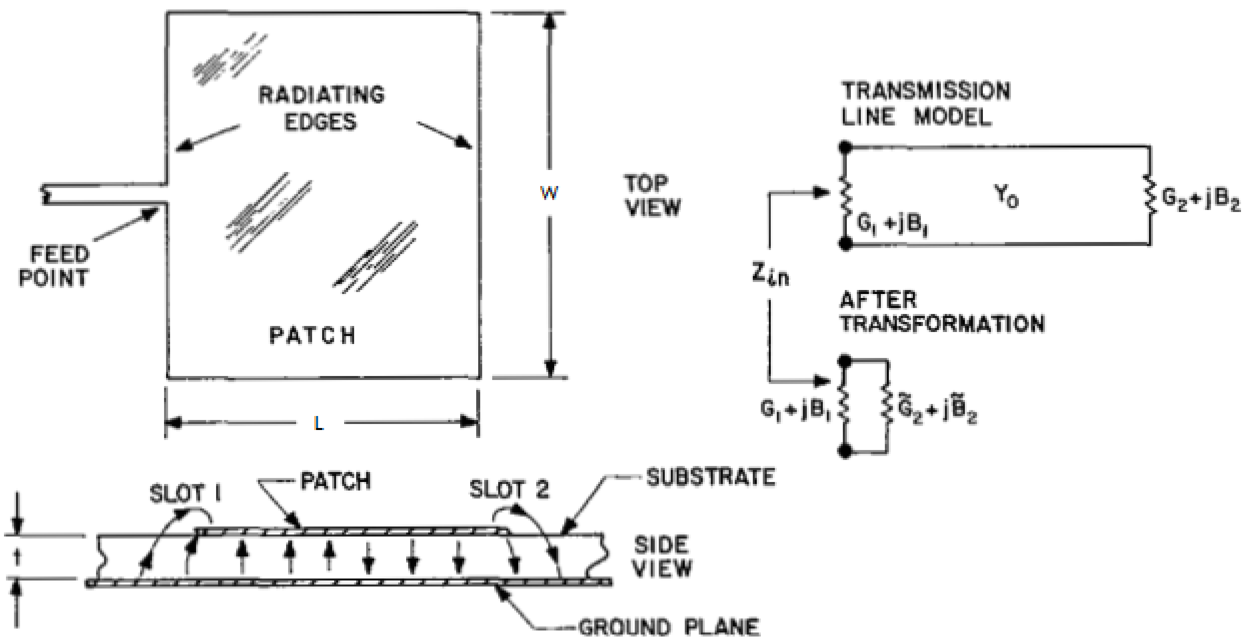


Figure 3: Transmission line model (adapted from [4])

The slot admittance can be represent as $Y_1 = G_1 + jB_1$. As mentioned before, G_1, slot conductance, expressed by the cavity model is[3]

$$G_1 = \frac{2P_{rad}}{|V_0|^2} = \frac{I_1}{120\pi^2} \tag{6}$$

$$I_1 = \int_0^{\pi} \left[\frac{\sin\left(\frac{X}{2}\cos\theta\right)}{\cos\theta} \right]^2 \sin^3\theta d\theta = -2 + \cos(X) + XSi(X) + \frac{\sin(X)}{X} \tag{7}$$

$$X = k_0 W$$

by

$$P_{rad} = \frac{|V_0|^2}{2\pi\eta_0} \int_0^{\pi} \left[\frac{\sin\left(\frac{X}{2}\cos\theta\right)}{\cos\theta} \right]^2 \sin^3\theta d\theta \tag{8}$$

where: G_1 = Slot conductance
P_{rad} = Radiation power
V_0 = Input voltage
k_0 = Wavenumber
η_0 = Impedance of free space
$Si(x)$ = Sine integral(See Appendix)

The component B_1 could be neglected if the slot distance is separated by the distance around $\frac{\lambda_g}{2}$ which caused $B_2 \approx -B_1$. But for G_2, due to the slots have almost the same width, then its value is the same to G_1 and it could be also written as $G_2 \approx G_1$. Therefore, the total admittance would be

$$Y_{in} = Y_1 + Y_2 = G_1 + jB_1 + G_2 - jB_2 \approx 2G_1 \tag{9}$$

And, the input impedance is surely be

$$Z_{in} = \frac{1}{Y_{in}} = \frac{1}{2G_1} \tag{10}$$

However, this equation doesn't take mutual effects into account. So, G_{12} is introduced as a mutual conductance and the impedance equation must be altered to[3]

$$Z_{in} = \frac{1}{2(G_1 \pm G_{12})} \tag{11}$$

If it's odd resonant mode, the plus sign(+) will be used, the minus(-) sign will be used instead[3]. According to the preliminary design, the length of the antenna is around $\frac{\lambda_g}{2}$ so it could be easily guess that the mode is TM_{010}. Therefore, the mode is odd.

by

$$G_{12} = \frac{1}{|V_0|^2}\mathrm{Re}\int\int_S \vec{E_1} \times \vec{H_2^*} \cdot d\vec{s} = \frac{1}{120\pi^2}\int_0^\pi \left[\frac{\sin\left(\frac{X}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0(Y\sin\theta)\sin^3\theta d\theta \tag{12}$$

$$X = k_0 W$$

$$Y = k_0 L$$

where:
G_{12} = Mutual conductance
V_0 = Input voltage
$\vec{E_1}$ = Electric field radiated by the slot #1
$\vec{H_2}$ = Magnetic field radiated by the slot #2
$\vec{s}$ = Area vector
J_0 = Zero order Bessel function
k_0 = Wavenumber
W = Width of the patch
L = Length of the patch

3.1.6 Matching Technique

There are many several technique to perform matching a single microstrip patch antenna such as[1]

- Quarter Wave Impedance Transformer (See Appendix)
- Inset Feed
- Coupled(Indirect) Feed
- Aperture Feed
- Coaxial Feed

In this project, quarter wave impedance transformer will be used because this technique is the most basic one and the patch will not be suffered from trimming at the feed point. Consequently, it's more versatile to build an array antenna comparing to the coaxial feed.

3.1.7 Radiation Pattern

Derived from the cavity model[7], at TM_{010} mode, the radiation field is

$$E_\phi = j\frac{k_0 W V_0}{\pi r}e^{-jk_0 r}\left(\cos\theta\sin\phi\frac{\sin X}{X}\frac{\sin Y}{Y}\right)\times\cos(Z) \tag{13}$$

$$E_\theta = j\frac{k_0 W V_0}{\pi r}e^{-jk_0 r}\left(\cos\phi\frac{\sin X}{X}\frac{\sin Y}{Y}\right)\times\cos(Z) \tag{14}$$

$$f(\theta,\phi) = \sqrt{\vec{E}_\phi^2+\vec{E}_\theta^2} = \sqrt{1-\sin^2\phi\sin^2\theta}\cdot\frac{\sin X}{X}\frac{\sin Y}{Y}\cos Z \tag{15}$$

by

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

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

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

where: E_ϕ = Electric field at coordinate
E_θ = Electric field at coordinate
$f(\theta,\phi)$ = Normalized field pattern
k_0 = Wavenumber
W = Width of the patch
L = Length of the patch
h = Height of the patch's substrate

3.1.8 Design Procedure

First, use (5) to design the the width of the patch by replace the frequency, f_r, of 5.8 GHz and assume that, ϵ_r, the dielectric constant of FR-4 is 4.3

$$\begin{aligned} W &= \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \\ &= \frac{3\times10^8}{2\times5.8\times10^9}\sqrt{\frac{2}{4.3+1}} \\ &= 15.8\text{ mm} \end{aligned}$$

Second, substitute the equation (30) with the calculated W(because $W = 15.8\text{mm} > h = 1.6\text{mm}$) to find the effective dielectric constant.

$$\begin{aligned} \epsilon_{r(eff)} &= \frac{\epsilon_r+1}{2}+\frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \\ &= \frac{4.3+1}{2}+\frac{4.3-1}{2}\left[1+12\times\frac{1.6\times10^{-3}}{15.8\times10^{-3}}\right]^{-1/2} \\ &= 3.76 \end{aligned}$$

Third, use the effective dielectric constant to find the extra length that caused from fringing effect in (3)

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

Therefore,

$$\begin{aligned}\Delta L &= 0.454 \times h \\ &= 0.454 \times 1.6 \text{ mm} \\ &= 0.726 \text{ mm}\end{aligned}$$

Fourth, substitute both effective dielectric constant and the extra length to the equation (4)

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

Now, the antenna's dimension are calculated with the width and the length equal to 15.8 mm and 11.9 mm respectively. Next, for the fifth step, use equation (7), (6), (12) and (11) to find the input impedance(See Appendix for $Si(x)$ and J_0 function).

$$\begin{aligned}X &= k_0W = \frac{2\pi f_0}{c} \times W \\ &= \frac{2\pi \times 5.8 \times 10^9}{3 \times 10^8} \times 15.8 \times 10^{-3} \\ &= 1.92 \\ I_1 &= -2 + \cos(X) + XSi(X) + \frac{\sin(X)}{X} \\ &= -2 + \cos(1.92) + 1.92 \times 15.8 \times 10^{-3} \times Si(1.92) + \frac{\sin(1.92)}{1.92} \\ &= 1.17 \\ G_1 &= \frac{I_1}{120\pi^2} \\ &= \frac{1.17}{120\pi^2} \\ &= 0.988 \ mS \\ Y &= k_0L = \frac{2\pi f_0}{c} \times L \\ &= \frac{2\pi \times 5.8 \times 10^9}{3 \times 10^8} \times 11.9 \times 10^{-3} \\ &= 1.45 \\ G_{12} &= \frac{1}{120\pi^2}\int_0^\pi \left[\frac{\sin\left(\frac{X}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0(Y\sin\theta)\sin^3\theta d\theta \\ &= \frac{1}{120\pi^2}\int_0^\pi \left[\frac{\sin\left(\frac{1.92}{2}\cos\theta\right)}{\cos\theta}\right]^2 J_0(1.45\sin\theta)\sin^3\theta d\theta \\ &= 0.613 \ mS \\ Z_{in} &= \frac{1}{2(G_1 \pm G_{12})} \\ &= \frac{1}{2(0.988 \times 10^{-3} + 0.613 \times 10^{-3})} \\ &= 312.6 \ \Omega\end{aligned}$$

Sixth, it is very important to match the impedance to 50 Ω because 50 Ω is the most common transmission line standard. Therefore, a matching circuit is required. In this step, a quarter wave impedance transformer from equation (32) will be used(See Appendix).

$$\begin{aligned} Z_{QWT} &= \sqrt{Z_{in} Z_L} \\ &= \sqrt{50 \times 312.6} \\ &= 125\ \Omega \end{aligned}$$

Seventh, use Hammerstad's characteristic impedance synthesis equation to calculate the width for the microstrip line(See Appendix). Therefore, the dimension of the quarter wave impedance transformer is

$$\begin{aligned} L_{QWT} &= 7.6 \text{ mm} \\ W_{QWT} &= 0.37 \text{ mm} \end{aligned}$$

Eighth, the length of the input 50 Ω microstrip is approximately $\frac{\lambda_g}{2}$ and the Width is 3.1 mm.

Ninth, the length of the ground plane is approximately the 2 times of distance from the feeding input to the center of the antenna. But the width of the ground plane is approximate 3 times of width of the antenna.

Finally, all the required dimension are set but the S_{11} response is not accurate, by using optimization-technique and set L, L_{QWT}, W_{QWT} as configurable parameters in CST STUDIO SUITE Software, the dimension will be as the figure below.(see result for S_{11} and field pattern)

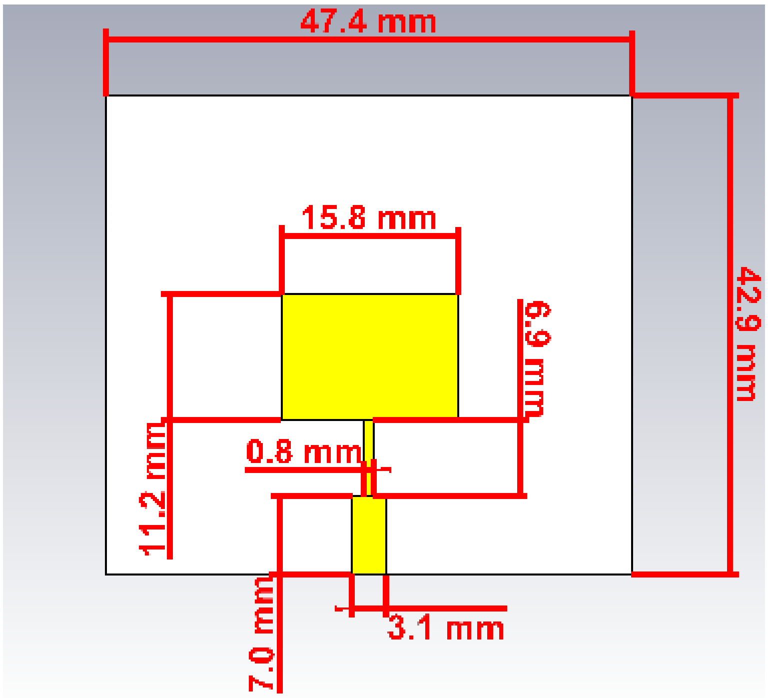


Figure 4: The optimized microstrip patch antenna

3.2 Array Theory

Sometimes, a standalone antenna's specification could not meet the application's requirement. By connecting it as an array, it could increase the gain or transform its characteristics.

To understand the array theory, 2 infinitesimal horizontal dipoles placed along z-axis are used as foundation because it's one the most basic antenna. Each of these antennas are counted as 'element'. Assuming that there is no coupling effect between the elements.[3] Therefore, the total field is given by

$$\vec{E}_t = \vec{E}_1 + \vec{E}_2 = \hat{a}_\theta j\eta \frac{kI_0 l}{4\pi} \left\{ \frac{e^{-j[kr_1-(\beta/2)]}}{r_1} \cos\theta_1 + \frac{e^{-j[kr_2-(\beta/2)]}}{r_2} \cos\theta_2 \right\} \tag{16}$$

where: k = Wavenumber
I_0 = Current in the infinitesimal dipole
l = Length of the infinitesimal dipole
β = Phase difference between the elements

For farfield observation,[3]

$$\theta_1 \simeq \theta_2 \simeq \theta \tag{17}$$

$$\left.\begin{aligned} r_1 &\simeq r - \frac{d}{2}\cos\theta \\ r_2 &\simeq r + \frac{d}{2}\cos\theta \end{aligned}\right\} \text{for phase variation} \tag{18}$$

$$r_1 \simeq r_2 \simeq r \quad \text{for amplitude variation} \tag{19}$$

Therefore, the total radiation field of the array is

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

$$\vec{E}_t = \hat{a}_\theta j\eta \frac{kI_0 l}{4\pi r} \cos\theta \left[2\cos\left(\frac{kd\cos\theta+\beta}{2} \right) \right] \tag{20}$$

It could be observed that the array antenna could be divided as 2 main factors. First, the element factor, E and the array factor, AF

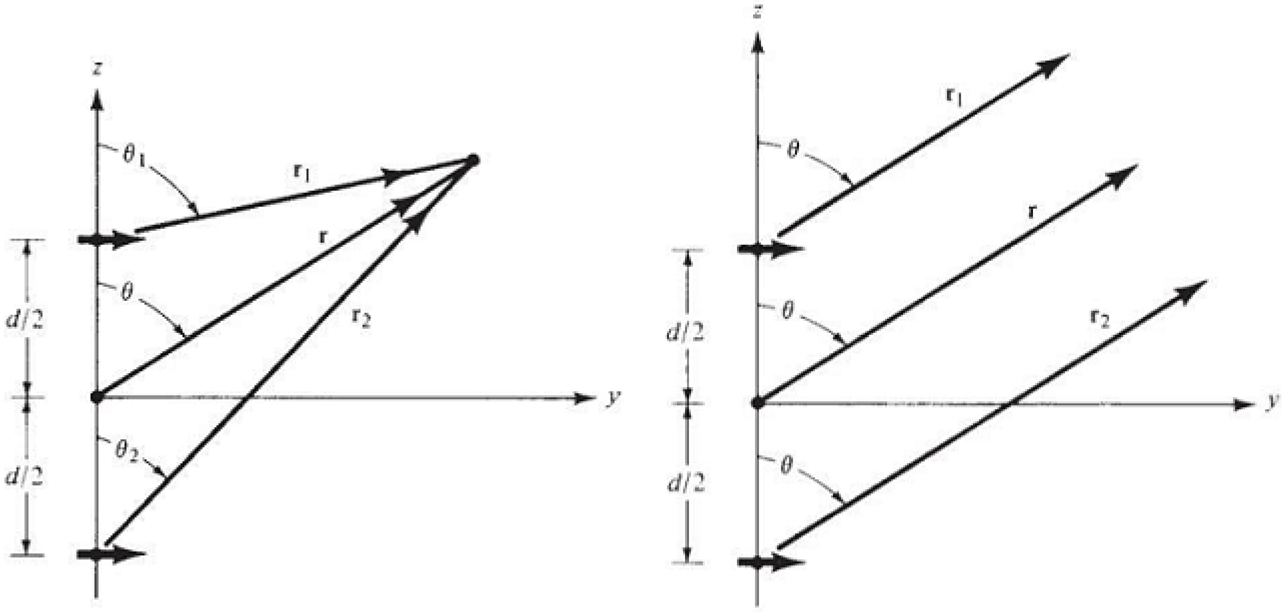
$$f(\theta,\phi) = E(\theta,\phi) \times AF(\theta,\phi) \tag{21}$$

where: $f(\theta,\phi)$ = Total radiation field pattern
$E(\theta,\phi)$ = Element's radiation pattern
$AF(\theta,\phi)$ = Array Factor

The array factor(AF) has an important role on defining how radiation pattern be. For this project, the array factor with 2 elements is enough.

$$AF = 2\cos\left(\frac{kd\cos\theta+\beta}{2} \right) \tag{22}$$

where: k = Wavenumber
d = Distance between the patches
β = Phase difference between the patches



(a) Two infinitesimal dipoles (b) Far-field observations

Figure 5: Array of 2 horizontal dipole lying on the z-axis[3]

3.3 Power Divider with 50 Ω Matching

The power divider used in this project is a T-junction power divider combined with matching circuit to 50 Ω on all three ports. The middle impedance transformer use the concept of the quarter wave impedance transformer which its impedance can be calculated with this equation.

$$Z_{QWT} = \sqrt{Z_{in} \times \frac{Z_{o1} \times Z_{o2}}{Z_{o1} + Z_{o2}}} \tag{23}$$

where: Z_{QWT} = Impedance of quarter wave impedance transformer
Z_{in} = Impedance of the input port
Z_{o1} = Impedance of the first output port
Z_{o2} = Impedance of the second output port

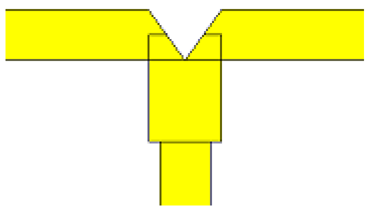


Figure 6: T-junction power divider with matching circuit

For the dimension of this impedance transformer, the length is $\frac{\lambda_{g(QWT)}}{4}$ and the width can be calculated using the Hammerstad's equation(See Appendix).

This design is good for moving the feed point, because the traditional one have the quarter wave impedance transformer at both output ports.

It could be seen that the power from the bottom port will be divided to both left and right port equally because of their symmetry property.

The edge is advised to get chamfered because it will make it harder to transmit the microwave from first output to the other output. Also, the input port will be tend to be more matched.

3.4 Microstrip Array Antenna

3.4.1 1x2 Array Antenna

The array antenna is just the combination of the patch antennas and the power divider. The proper x-coordinate distance of this array antenna is $\frac{\lambda_0}{2}$. Assuming that the microstrip patch is highly matched already, but in order to add more degree of freedom to get the better matching antenna, the optimization of the quarter wave transformer is required.

It could be seen that this project tries to conserve the parameters from the previous calculation to make the procedure clear.

For the ground plane tuning, see on discussion.

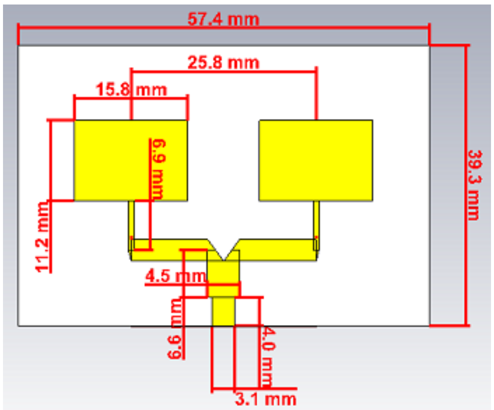


Figure 7: The optimized 1x2 microstrip patch array antenna

3.4.2 2x2 Array Antenna

The 2x2 array antenna procedure have the same approach as the 2x1 antenna. Assume that the 1x2 optimized array antenna is highly matched, just translate and copy to the top and the bottom of the FR-4 plane. This design is designed to make the travelling wave go through microstrip transmission and reach all antennas with the same clock cycle. Another advantage of this design is the ease of approaching the project objective, to delay the phase to the antenna, by just moving the feeding point.

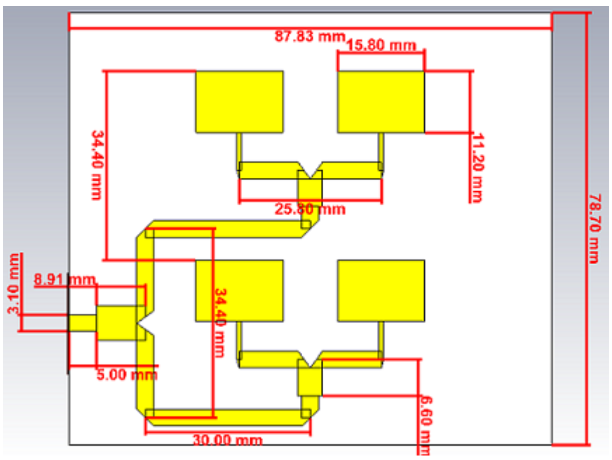


Figure 8: The optimized 2x2 microstrip patch array antenna

3.5 Phased Array Theory

According to the array factor equation, (22), if we change β value to be something else instead of 0. The array pattern could be changed. The figure below shows that how the variety of β can affect the array pattern when $d = \frac{\lambda_0}{2}$

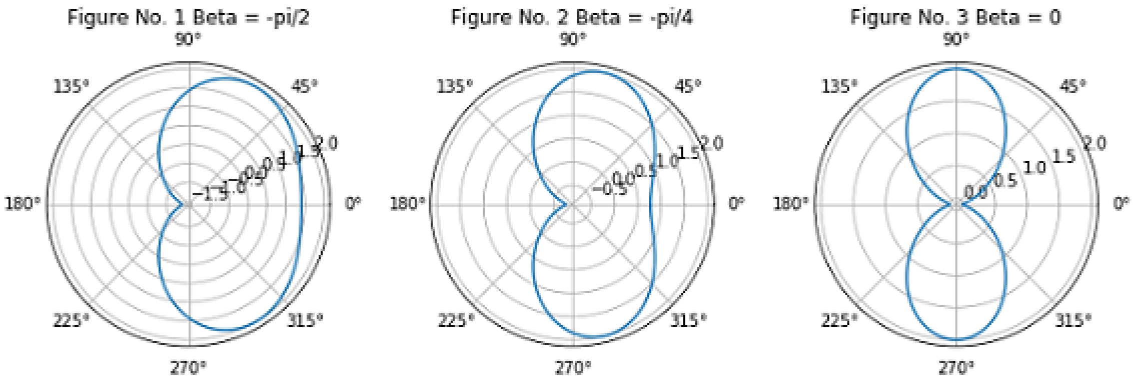


Figure 9: Array pattern varying on difference phases

3.6 Phase Shift by Translating Feed Point

For this design, there is no need to add distance to make the phase shift. Just using the translating feed point concept. The equation is very easy as below,

$$x_0 + x_1 = d_x \tag{24}$$

$$x_0 - x_1 = \Delta\phi_x \tag{25}$$

$$y_0 + y_1 = d_y \tag{26}$$

$$y_0 - y_1 = \Delta\phi_y \tag{27}$$

where: x_0, x_1 = Left and right distance according to the feed point
d_x = Distance between the patch in X-direction
x_0, x_1 = Top and bottom distance according to the feed point
d_y = Distance between the patch in Y-direction

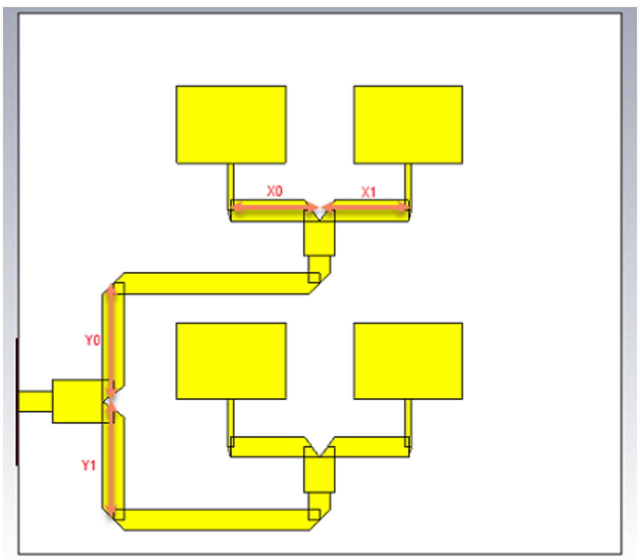


Figure 10: Explanation figure on phase shift by using translate feed point

4 Results

4.1 Experiment Setup for Antenna Testing

The field pattern results were taken from Microwave Anechoic Chamber in King Mongkut's Institute of Technology Ladkrabang (KMITL).

Figure 11: Microwave Anechoic Chamber from KMITL

Return loss, S_{11}, were measured with N9912A FieldFox Handheld RF Analyzer in Telecommunication Laboratory of KMITL.

Figure 12: N9912A FieldFox Handheld RF Analyzer and UUTs

4.2 Return Loss, S_{11}

4.2.1 Single Patch Antenna

The single patch antenna was designed and optimized for 5.8 GHz.

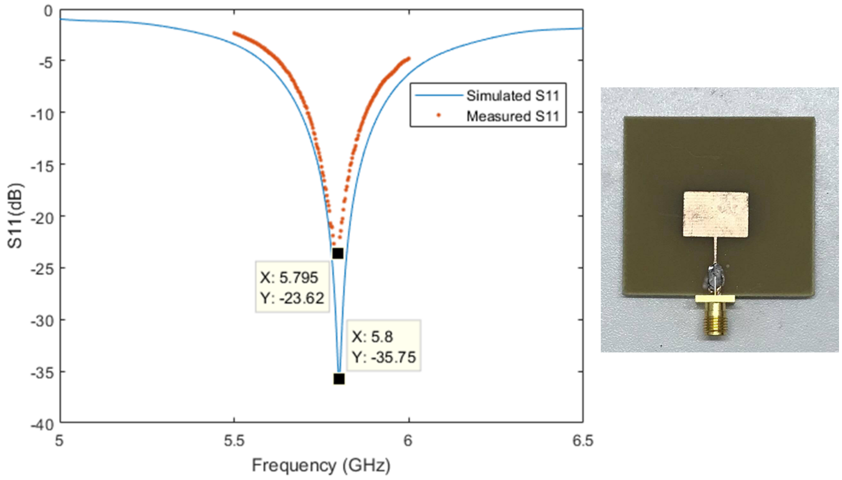


Figure 13: Simulated and measured S_{11} results of dedicated antenna

4.2.2 1x2 Array Antenna

The top 1x2 microstrip array antenna was in-phase and designed for 5.8 GHz. The bottom, 1x2 phased array was designed as quadrature phase.

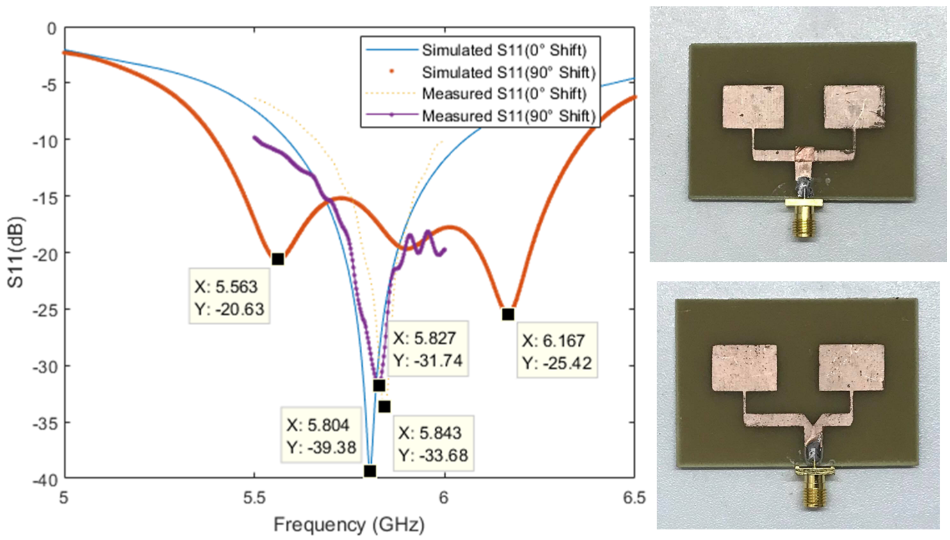


Figure 14: Simulated and measured S_{11} results of dedicated antennas (The bottom one has phase shift)

4.2.3 2x2 Array Antenna

The top 2x2 microstrip array antenna was in-phase and designed for 5.8 GHz. The bottom, 2x2 phased array was designed for 2 axis phased shift. By top-right is the baseline, top-left is phased by 90°, bottom-right is phased by 60°, bottom-left is phased by 150°.

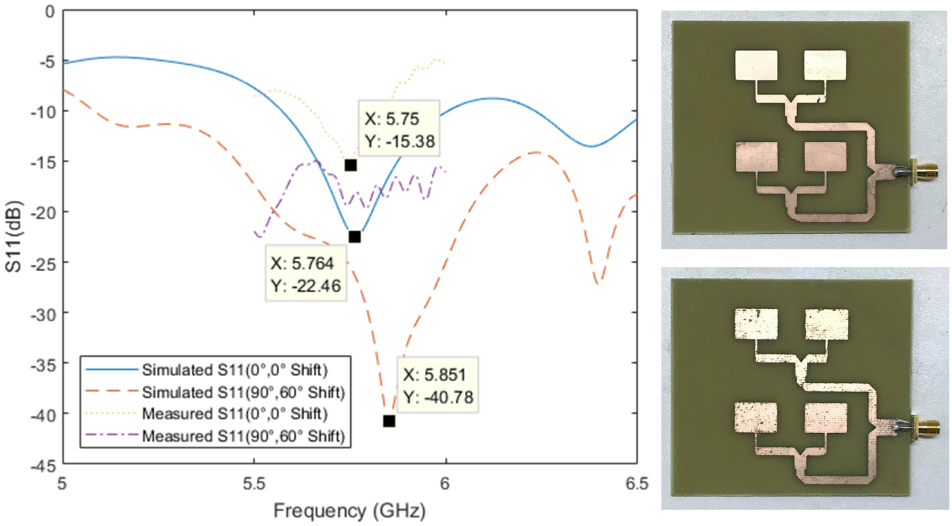


Figure 15: Simulated and measured S_{11} results of dedicated antennas (The bottom one has phase shift)

4.3 3D Simulated Farfield in Linear Scale

4.3.1 Single Patch Antenna

The main beam was at $\phi = 270°$ and $\theta = 3°$.

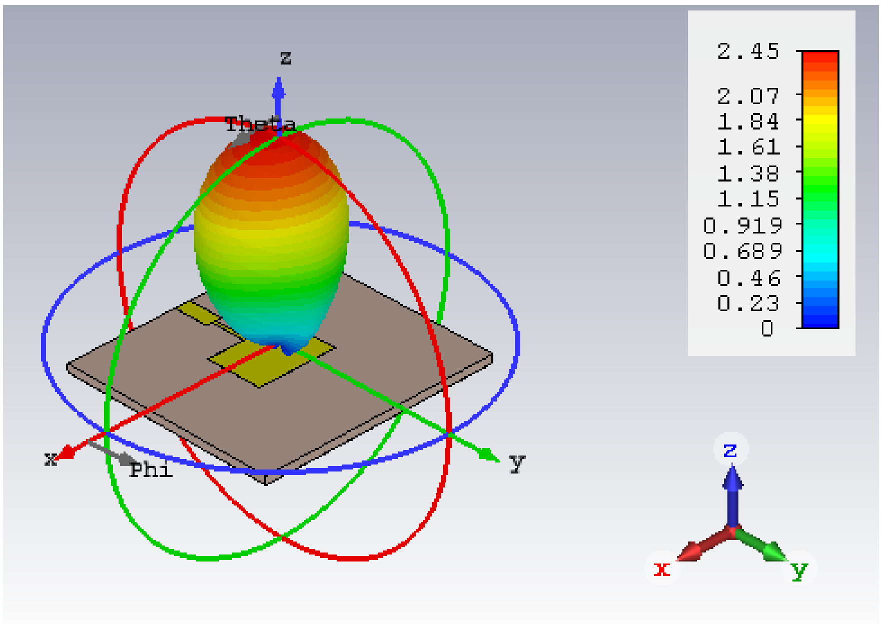


Figure 16: Farfield of Single Patch Antenna

4.3.2 In-phase 1x2 Array Antenna

The main beam was perfectly at $\theta = 0°$.

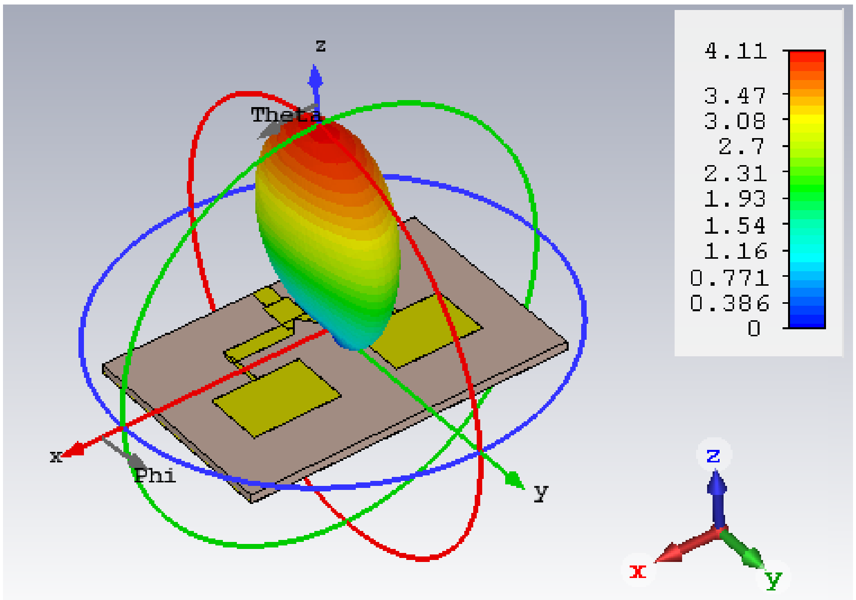


Figure 17: Farfield of 1x2 Array Antenna with 0° Phase Shift

4.3.3 Quadrature Phase 1x2 Array Antenna

The main beam was at $\phi = 180°$ and $\theta = 18°$.

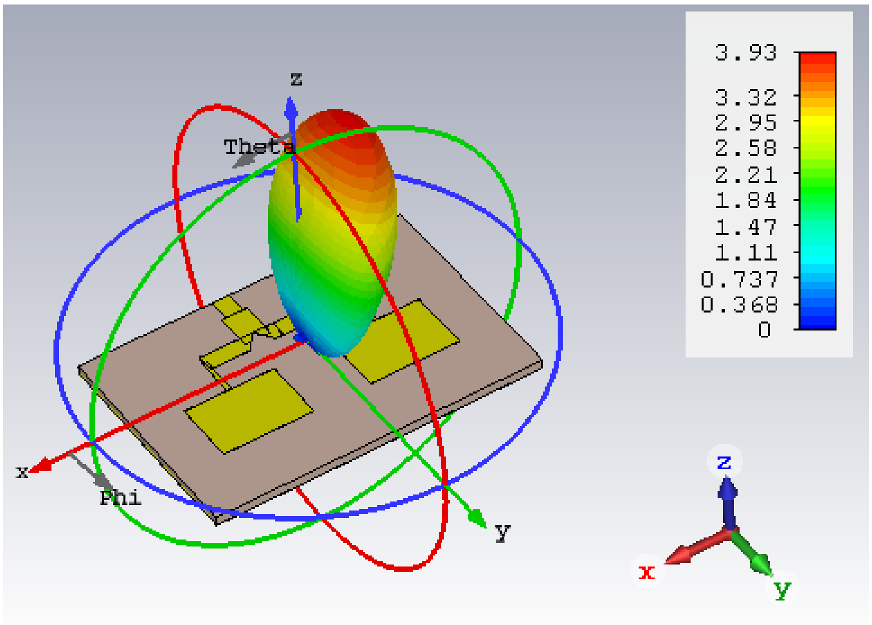


Figure 18: Farfield of 1x2 Array Antenna with 90° Phase Shift

4.3.4 In-phase 2x2 Array Antenna

The main beam was perfectly at $\theta = 0°$.

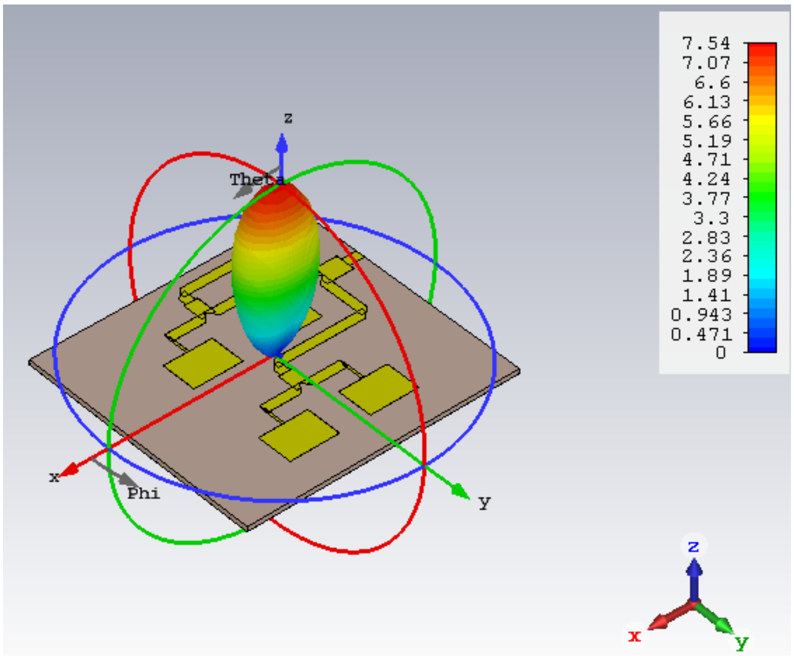


Figure 19: Farfield of the 2x2 Array Antenna with 0°, 0° Phase Shift

4.3.5 Quadrature & Hexature 2x2 Array Antenna

The main beam was at $\phi = 221°$ and $\theta = 22°$.

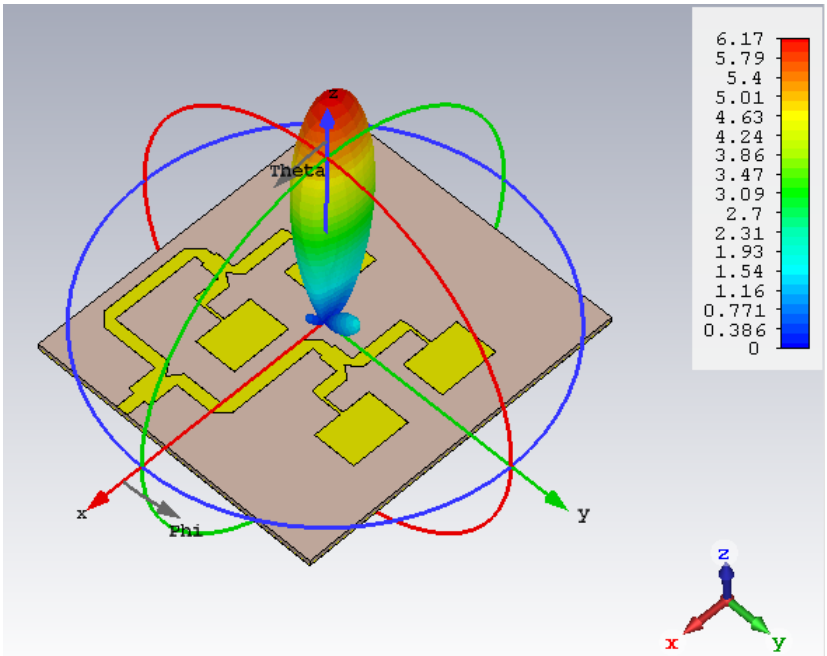


Figure 20: Farfield of 2x2 Array Antenna with 90°, 60° Phase Shift

4.4 2D Measured Field Pattern

4.4.1 Single Patch Antenna

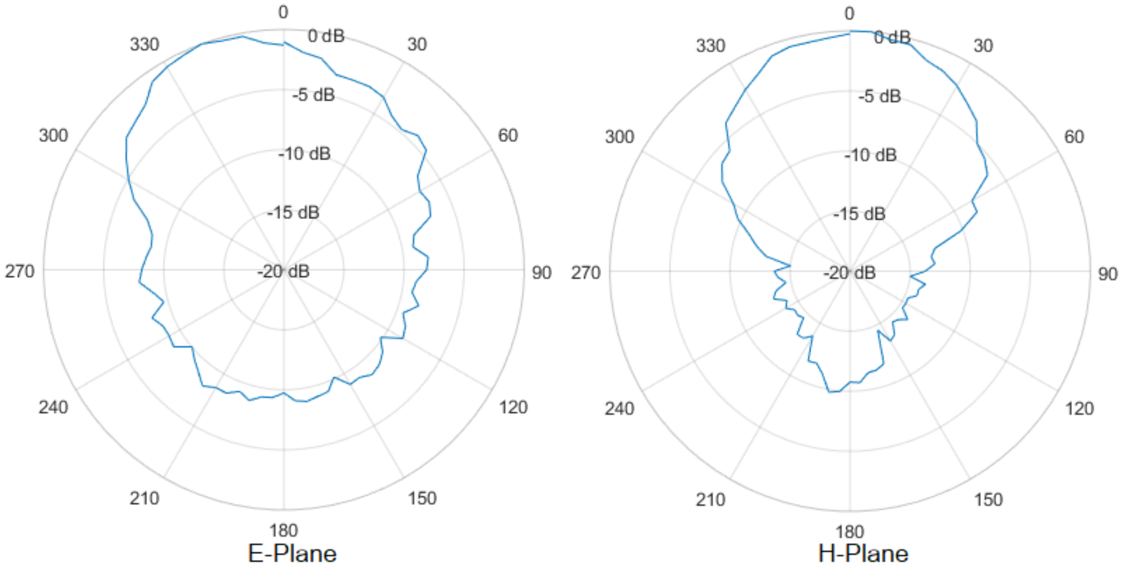


Figure 21: Measured E-Plane and H-Plane of Single Patch Antenna

4.4.2 1x2 Array Antennas

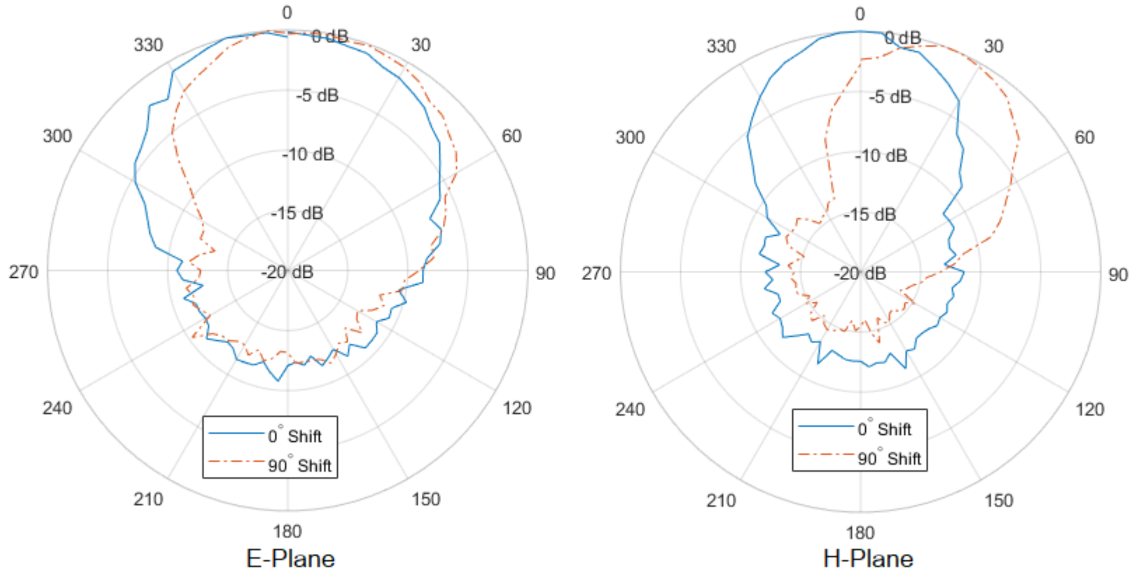


Figure 22: Measured E-Plane and H-Plane of 1x2 Array Antenna with and without phase shift

4.4.3 2x2 Array Antennas

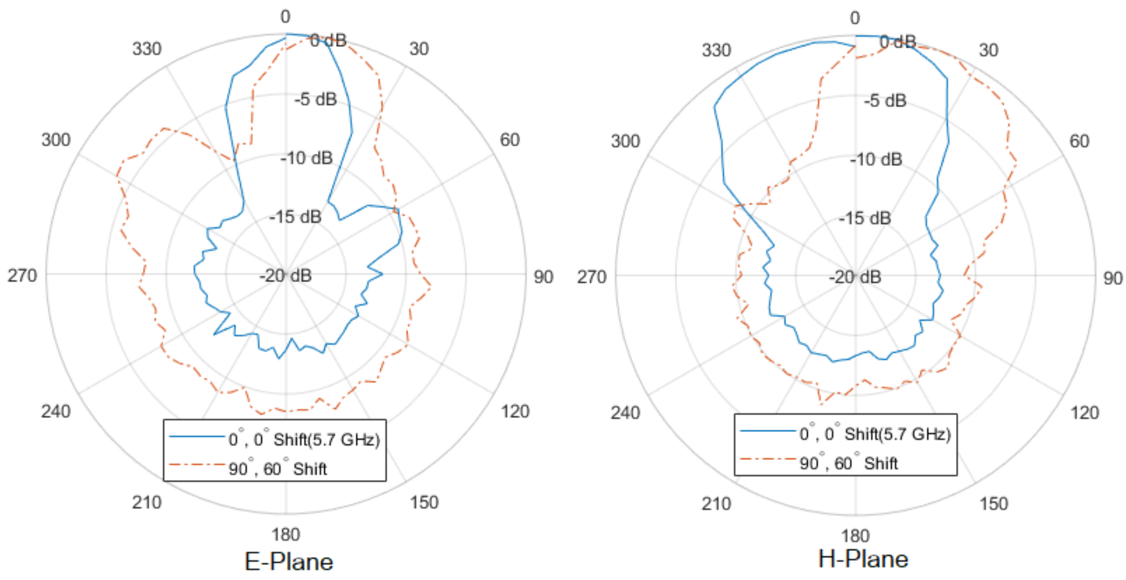


Figure 23: Measured E-Plane and H-Plane of 2x2 Array Antenna with and without phase shift

5 Discussion

5.1 Affect on the Ground Plane

The calculated radiation pattern of microstrip antenna is from the assumption that the antenna has infinite ground plane. Practically, the ground plane width is just 3 times by the patch width, and the ground plane length can be approximately equal to that width. From experiments by using CST Software, the beam may be tilted forward or backward depends on the ground plane length. To fix that, if the tilt beam is going forward, just decrease the ground plane only on the top side. Remarks that the antenna patch is not required to be balance in the middle of the plane.

5.2 Array Factor Usage

In order to the total radiation pattern, the array factor is must be used while taking absolute function. Because the negative value of array factor doesn't imply that the patch will be steered at the reverse direction.

6 Conclusions

This project accomplished on designing an optimized microstrip patch antenna and multiple phased array antennas with support of simulation tools. For both simulation and the physical results, the gain was increased as expected. Also, the directivity is altered as long as the feedline was translated.

7 Acknowledgement

I would like to express my deep gratitude to Assist. Prof. Tuptim Angkaew, my research advisor, for their patient guidance, enthusiastic encouragement and useful critiques of this senior project. I would also like to thank Assist. Prof. Suvit Nakpeerayuth, for his guideline on how to tune the antenna. My grateful thanks are also extended to Mr.Pisit Janpangngern from KMITL for his help in measuring the various parameters of the antenna, to Mr. Tanan Hongnara from KMUTNB, who offered me the resources and place to fabricate the microstrip antenna and to Mr. Sumeth Klomchitcharoen for his support in all of the processes from designing to realization.

Finally, I wish to thank my parents and my brother for their support and encouragement throughout my study.

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8 Appendices

8.1 Sine Integral, $S_i(x)$

$$S_i(x) = \int_0^x \frac{\sin\tau}{\tau} d\tau \tag{28}$$

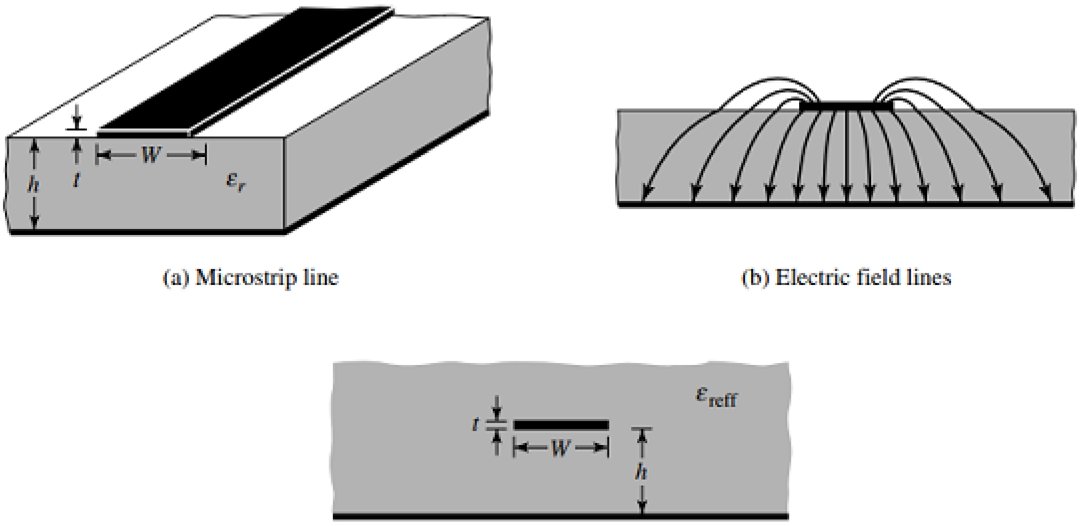
8.2 Bessel Function, J_n

For any integer values of n, the n-order representation of Bessel fuction is[9]

$$J_n(x) = \frac{1}{\pi} \int_0^\pi \cos(n\tau - x\sin\tau) d\tau \tag{29}$$

8.3 Effective Relative Dielective Constant of Microstrip Line

Since the electric field is not only happened below the substrate, but it's also existed in the air. Therefore, the dielectric constant would absolutely be altered.



(a) Microstrip line

(b) Electric field lines

(c) Effective dielectric constant

Figure 24: Electric field on microstrip line and its equivalent[3]

A simple, accurate and practical equation was derived for calculating it.[3, 2]

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

$$\epsilon_{r(eff)} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{30}$$

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

$$\epsilon_{r(eff)} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left\{\left[1 + 12\frac{h}{W}\right]^{-1/2} + 0.04\left[1 - \frac{W}{h}\right]^2\right\} \tag{31}$$

8.4 Quarter Wave Impedance Transformer

Quarter wave impedance transformer is the easiest impedance transformer circuit. The length of this transformer must be $\frac{\lambda_g}{4}$ and that's the reason why it's called "Quarter Wave Impedance Transformer"

$$Z_{QWT} = \sqrt{Z_{in} Z_L} \tag{32}$$

where: Z_{QWT} = Impedance of the impedance transformer
Z_{in} = Input Impedance
Z_L = Load Impedance

8.5 Hammerstad's Microstrip Characteristic Impedance Synthesis Equation

This synthesis equation could be used for calculating the width of the transmission line without calculating the effective dielectric constant first. This equation is also claimed that the error is not beyond than 2 % [5]

$$\frac{W}{h} = \begin{cases} \dfrac{8}{e^{A} - 2e^{-A}}, & \text{for } \dfrac{W}{h} \leqslant 2 \\ \dfrac{2}{\pi}\left\{B - 1 - ln(2B-1) + \dfrac{\epsilon_r - 1}{2\epsilon_r}\left[ln(B-1) + 0.39 - \dfrac{0.61}{\epsilon_r}\right]\right\}, & \text{for } \dfrac{W}{h} > 2 \end{cases} \tag{33}$$

by

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

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

where: W = Width of the transmission line
h = Height of the substrate
η_0 = Impedance of free space
ϵ_0 = Dielectric constant of the substrate

8.6 50 Ω Microstrip Line

The mircrostrip transmission line dimension for the standard 50 Ω characteristic impedance is pre-calculated using Hammerstad's equation for the ease of works.

$$W = 3.1 \text{ mm}$$
$$L = 14.3 \text{ mm per half-cycle}$$