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

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Contents

1 Introduction

The advances of technologies now ahead through now wouldn't be happened without a communication systems. In such today, wireless communication is covering almost everywhere in the world. One of the most important thing in the communication system is the antenna. Because it could be able to radiate or receive power into the air. With these abilities, we may use it to send or receive those infomation that we want to. As we know, just a wire could be used as an antenna technically. However, its property may not be good for every requirement or application.

The freedom of using frequency bands bring us to the world of technologies. Back to 1947, in the International Telecommunications Conference of the ITU in Atlantic City established the first lot of ISM(Industrial, Scientific and Medical) bands which allows us to use those frequency without asking for a permission. For example, the microwave oven, we never have to ask for any government's allowance to use the microwave which radiates the electromagnetic wave at the frequency of 2.45 GHz to our food because this frequency is in ISM bands.

There are many methods to increase the range of the antenna. The easiest one is increasing more power. However, if we just want to send a message from a station to another station, there will be a huge power loss on the air at the direction that we don't really need to send to. In a good practical, engineers design antennas that their property is focusing on only one direction which is called Directivity. Therefore, a high directivity antenna can be able to send more distance than the ordinary one.

Considering a droplet drops on the surface of the 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 depends on location and it'll reform like a seacoast wave. So this will make a more powerful wave from 2 sources. Moreover, the direction can also be changed by controling how droplets fall onto the surface. The same as the array of antennas, if we can control each element's phase so we will be able to control antenna's directivity upon our desire.

If we want to make a device that everyone agrees on carrying to everywhere, basically, it must be small, thin and cheap. To response to this demand, there is a flat composite material which composed of woven fiberglass cloth available in the market. It's 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 could be any type of microwave circuits including antennas.

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

2 Objectives

The main objective of this project is to study about the analysis of the microstrip phased array antenna, and compare whether the physical test result is the same to the theories. This project is consist of several tasks combining together.

- Review past lituratures
- Compare techniques
- Design the antennas and circuits
- Simulate the antennas
- Test and find its result
- Compare the antenna results with the analysis method

for the full procedure flowchart it'll be shown in the methodology section.

3 Methodology

This is the project procedure flowchart

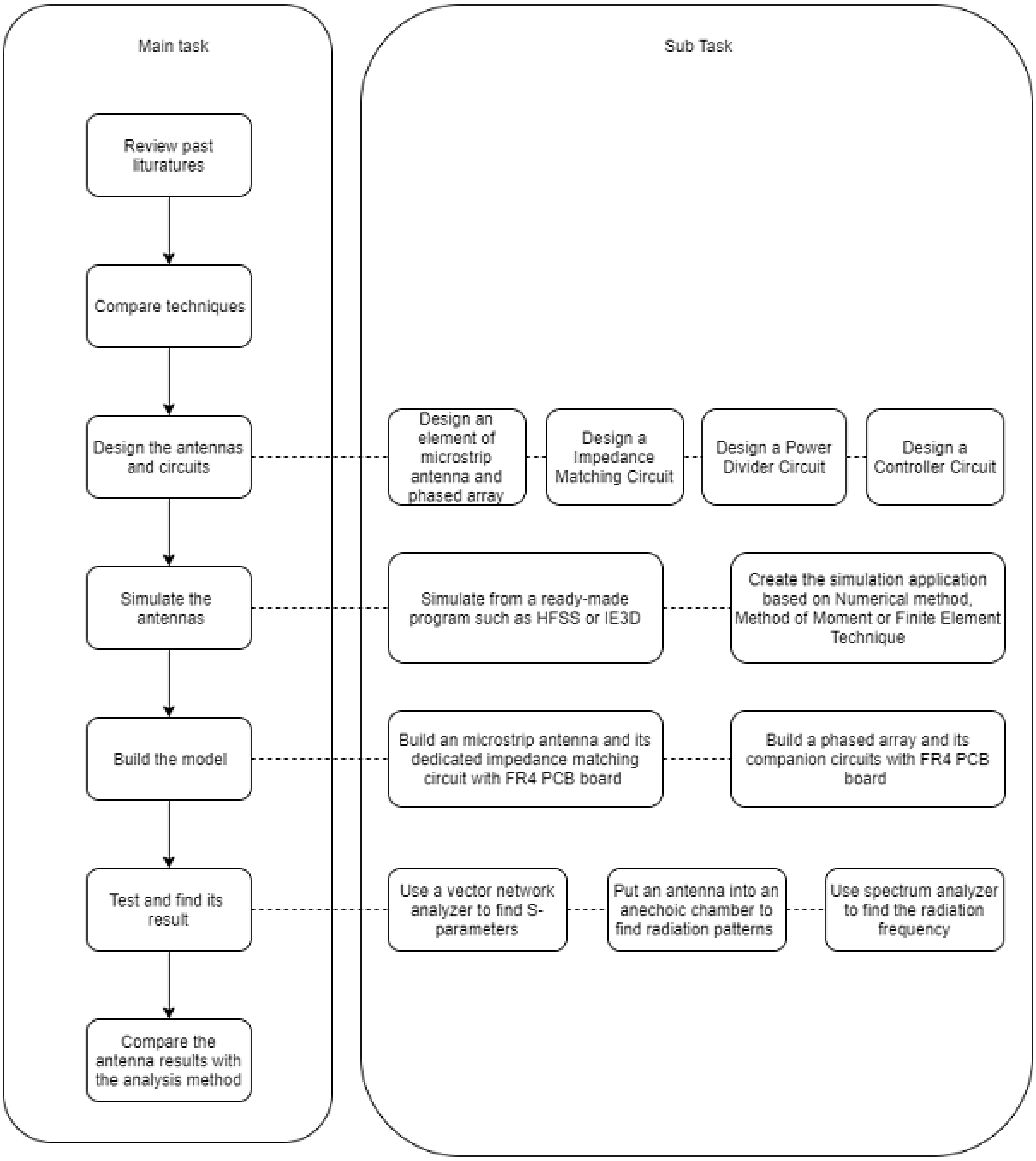

Figure 1: The project procedure flowchart is shown above.

3.1 Structure of the Microstrip Patch Antenna

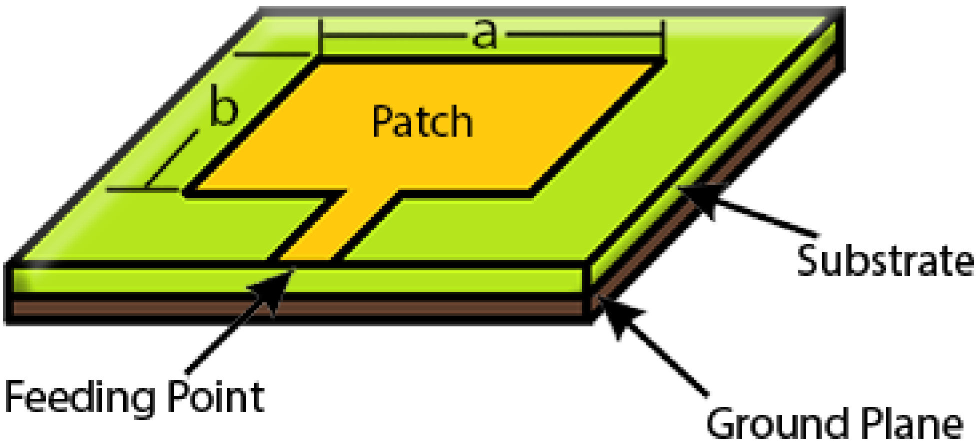

Figure 2: The structure of a microstrip patch antenna

Generally, the structure of a microstrip patch antenna is an antenna that was fabribated using microstrip technique on a printed circuit board(PCB)[1]. It consists 3 layer, a conducting plate, substrate and a ground plane. The plate and ground plane is made of conductors but the substrate is made of a glass-reinforced epoxy(for an FR4 plate). With this structure, a patch antenna can be made easily by using a cutter.

3.2 Radiation pattern of Rectangular Microstrip Patch Antenna

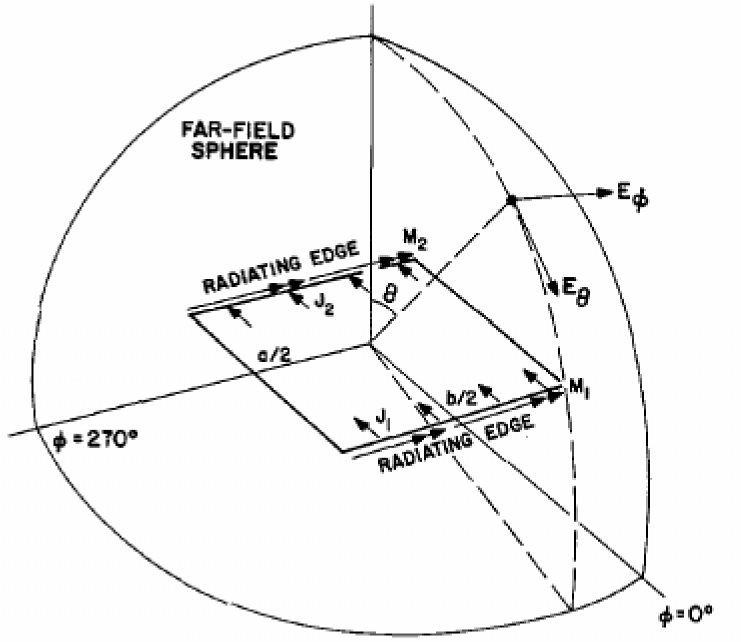

Figure 3: Geometry Far-field pattern of a rectangular microstrip [2]

The figure aboves show the far field radiation pattern of a rectangular microstrip patch on TM_{10} mode at the radiating edge[2] for the the corresponding rectangular microstrip equation.

$$E_\theta = -\frac{jV_0k_0ae^{-jk_0r}}{\pi r}\cos(kt\cos\theta)\frac{\sin[k_0\frac{a}{2}\sin\theta\sin\phi]}{k_0\frac{a}{2}\sin\theta\sin\phi}\cos(k_0\frac{b}{2}\sin\theta\cos\phi)\cos\phi, (0 \leq \theta \leq \frac{\pi}{2}) \quad (1)$$

$$E_\phi = \frac{jV_0k_0ae^{-jk_0r}}{\pi r}\cos(kt\cos\theta)\frac{\sin[k_0\frac{a}{2}\sin\theta\sin\phi]}{k_0\frac{a}{2}\sin\theta\sin\phi}\cos(k_0\frac{b}{2}\sin\theta\cos\phi)\cos\theta\sin\phi, (0 \leq \theta \leq \frac{\pi}{2}) \quad (2)$$

From these equation, we could see that the antenna directivity is directional. Furthermore, these graphical figure below indicate that the microstrip antenna is directional.

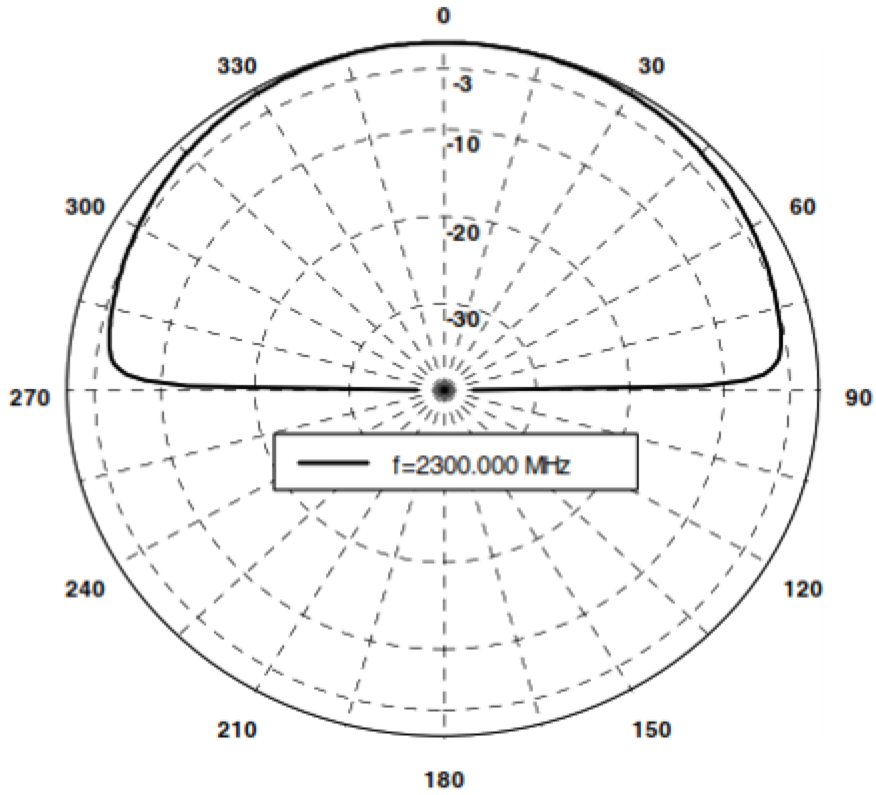

Figure 4: Normalized E-plane far-field radiation pattern E_θ of the microstrip patch at f = 2,300 MHz ($\phi = 0°, -90° < \theta < 90°$) [3]

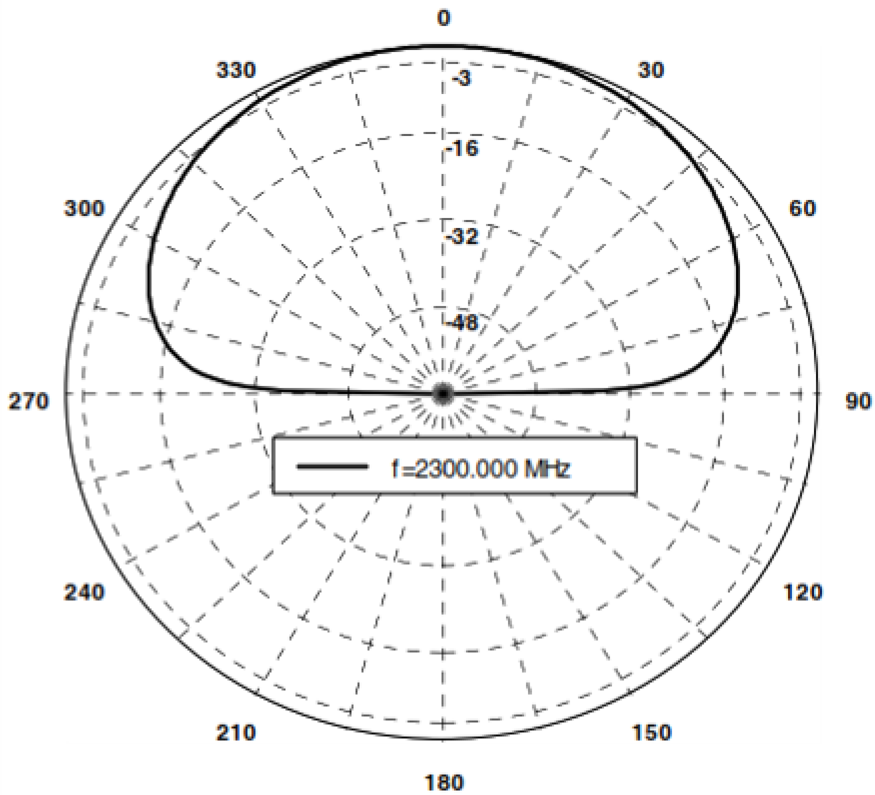

Figure 5: Normalized H-plane far-field radiation pattern E_ϕ of the microstrip patch at f = 2,300 MHz ($\phi = 0°, -90° < \theta < 90°$) [3]

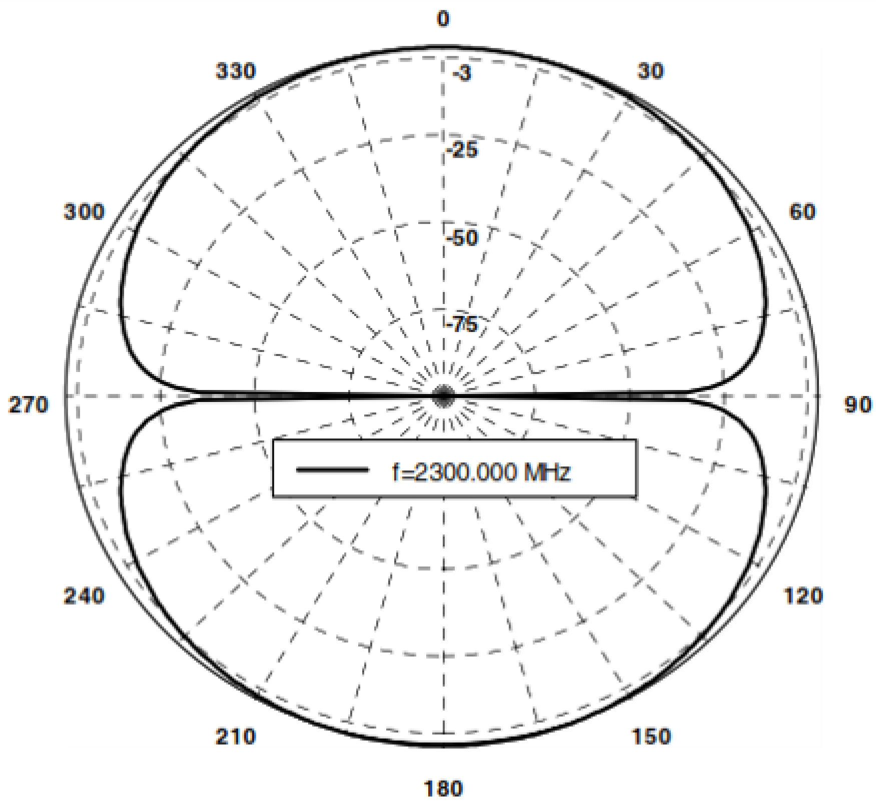

Figure 6: Normalized far-field radiation pattern E_θ of the microstrip patch at f = 2,300 MHz ($\theta = 0°, -180° < \phi < 180°$) [3]

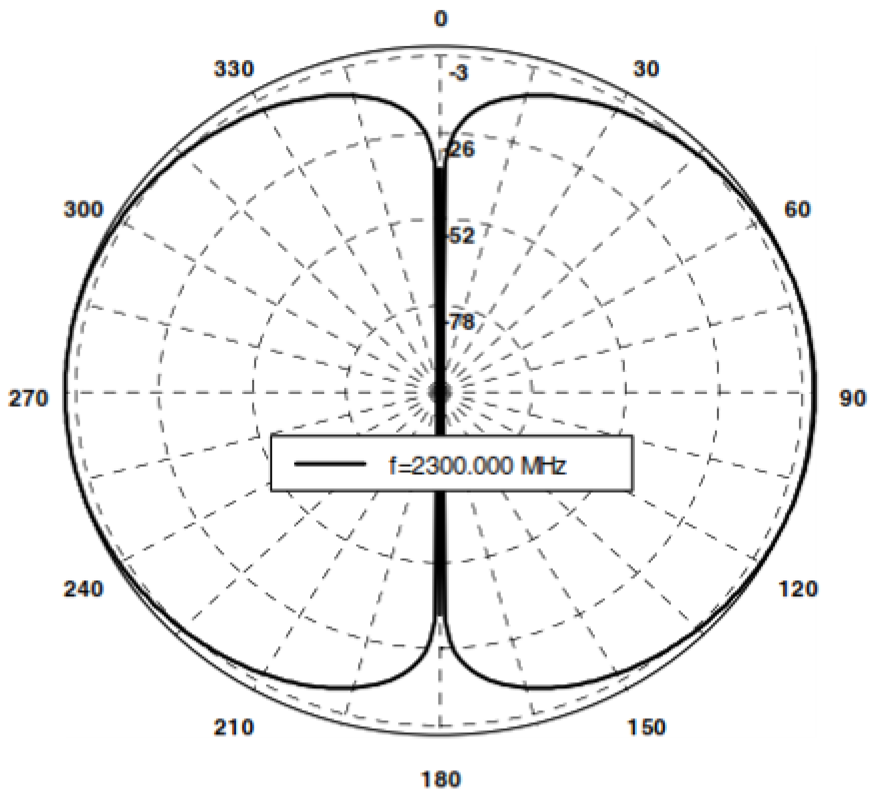

Figure 7: Normalized far-field radiation pattern E_ϕ of the microstrip patch at f = 2,300 MHz ($\theta = 90°, -180° < \theta < 180°$) [3]

3.3 Basic Dimension Design of The Microstrip Antenna

In order to determine a dimension of microstrip antenna for a given frequency can be designed easily with this expressions[3].

$$a = \frac{c}{2f_0\sqrt{\epsilon_r \mu_r}} - 2\Delta l \tag{3}$$

$$b = \frac{c}{2f_0} \tag{4}$$

where a and b are the dimensions of an antenna

f_0 is the resonance frequency

ϵ_r is the relative dielectric constant

μ_r is the relative magnetic constant

c is the speed of light in free space

Δl is the fringing effect at the edge of the antenna*

However from [4] the best width should be

$$b = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{5}$$

where v_0 is the free-space velocity of light

3.3.1 Example

If we want to build a 5.8 GHz of microstrip patch antenna with $\epsilon_r = 4.5$ and $\mu_r = 1$ The length of the antenna would be without fringing effect and let

$$a = \frac{3 \times 10^8}{2 \times 5.8 \times 10^9 \times \sqrt{4.5}} = 12cm \tag{6}$$

$$b = \frac{3 \times 10^8}{2 \times 5.8 \times 10^9} = 25cm \tag{7}$$

*Note that the fringing effect will be refered to at the Fringing Effect of the Microstrip Antenna section

3.4 Transmission Line Model

Transmission Line Model is considered as the easiest way to analyze the description of the rectangular microstrip patch.

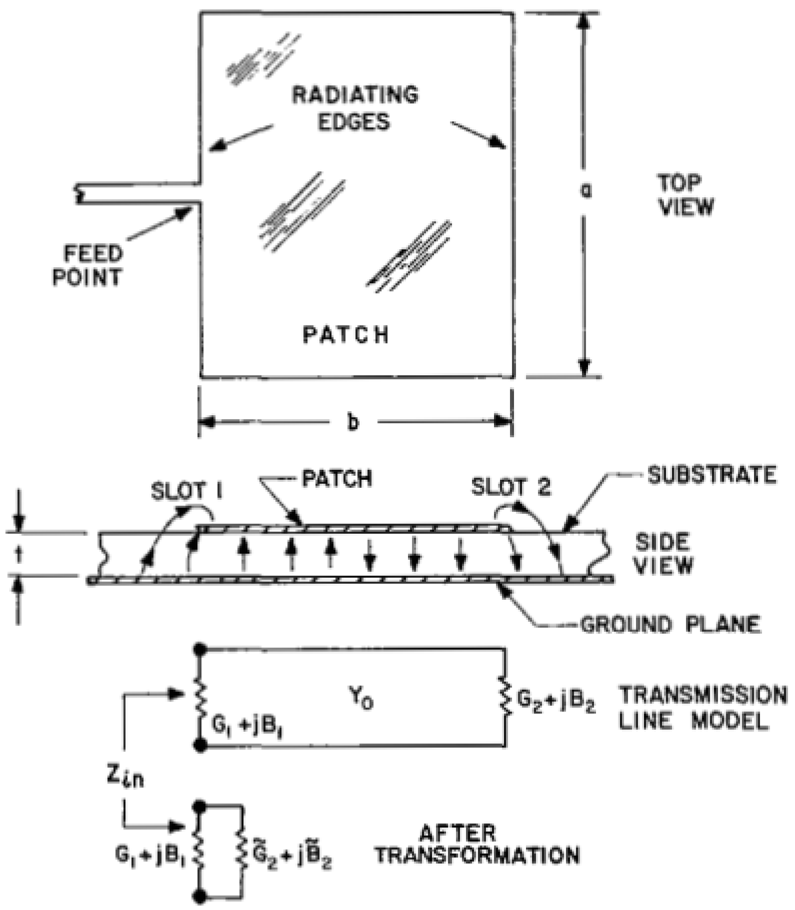

Figure 8: The antenna at top view, side view, and its transmission line model[2]

3.4.1 Slot admittance

The slot admittance is given by [2]

$$G_1 + jB_1 \cong \frac{\pi a}{\lambda_0 z_0}[1 + j(1 - 0.636 \ln k_0 w)] \tag{8}$$

where a is the length of the patch antenna, λ_0 is free space wavelength, $k_0 = frac2\pi\lambda_0$, and w is the slot width which is approximately equals to the thickness of the substrate t

3.4.2 Characteristic admittance

Assume that there is no field variation along the edge of plate, so the characteristic admittance is given by [2]

$$Y_0 = \frac{a\sqrt{\epsilon_r}}{tz_0} \tag{9}$$

where t is the substrate thickness and the impedance of free space which is $\sqrt{\frac{\mu_0}{\epsilon_0}}$

3.4.3 Total Admittance & Resistance at Resonance frequency

By using Smith chart to get the length that will reflute out the imaginary part. Then, the total impedance would be

$$Y_{in} = 2G_1 \tag{10}$$

Typically, b should be at $0.48\lambda_d$ to $0.49\lambda_d$ because of the imaginary part reflution and the compensation of the fringing effect that cause an extra effective length. Also, a should be around $0.5\lambda_0$ as well to get the best power radiation.

After complete the calculation of the admittance from the above parameters, so that the admittance $G_1 = 0.00417$ mhos. Then the input impedance of the antenna would be

$$Z_{in} = \frac{1}{2G_1} = 120 \quad \Omega \tag{11}$$

3.4.4 Resonance frequency

The resonant frequency is found from

$$f_r = \frac{c}{\lambda_d\sqrt{\epsilon_r}} = q\frac{c}{2b\sqrt{\epsilon_r}} \tag{12}$$

where q is the accurary of the resonant frequency and could easily determined by measuring f_r [2]

3.4.5 Summary

The transmission line model is very easy to design and calculate parameters. However, the transmission line model is hardly to adapt with the other shape of the patch or. Also, this model is lack of accurate data. In order to find more precise infomation about the antenna, the Cavity model will be introduced in the next section which is much more accurate than this one.[2, 3]

3.5 Fringing Effect of the Microstrip Antenna

Because of fringing effect, this will cause many phenomenas such as Effective length extension, dielectric constant distortion and resonance frequency distortion[4]

3.5.1 Effective Length Extension

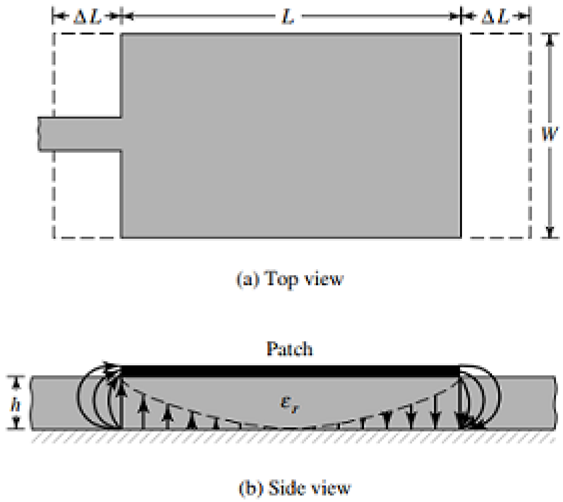

Figure 9: The fringing effect that cause to length extension

The length is extended because of fringing effect, that spreading at the edge of all sides so $L_{eff} = L + 2\Delta L$[4]

$$\frac{\Delta l}{h} = 0.412\frac{(\epsilon_{r(eff)} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{r(eff)} - 0.258)(\frac{W}{h} + 0.8)} \tag{13}$$

3.5.2 Dielectric Constant Distortion

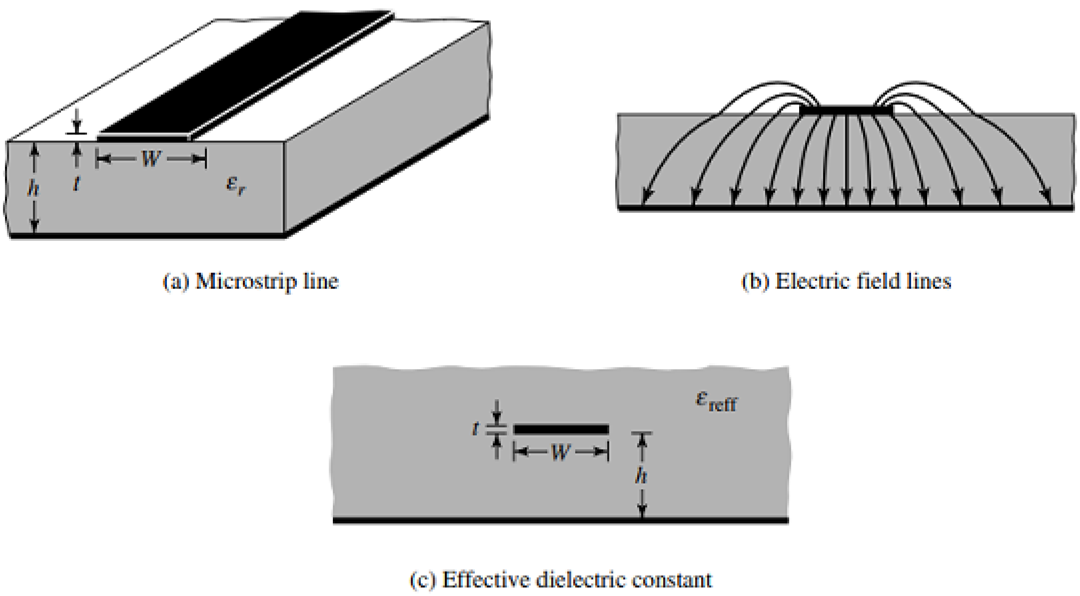

Figure 10: The fringing effect that cause to length extension

Due to the electric field is not only happened inside the microstrip line, there's a leakage electric field in the air, so the dielectric that will be used for calculating will need to be reconsidered as follow[4]

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}[1 + 12\frac{h}{W}]^{-0.5} \tag{14}$$

3.5.3 Resonance frequency distortion

In TM_{010} mode, the resonant frequency is given by

$$f_{r(010)} = \frac{1}{2L\sqrt{\epsilon_r}\sqrt{\epsilon_{\mu_0\epsilon_0}}} = \frac{v_0}{2L\sqrt{\epsilon_r}} \tag{15}$$

With fringing effect, the equation will be given by

$$f_{r(010)} = \frac{1}{2L_{eff}\sqrt{\epsilon_{r(eff))}}\sqrt{\epsilon_{\mu_0\epsilon_0}}} = \frac{1}{2(L + 2\Delta L)\sqrt{\epsilon_{r(eff)}}\sqrt{\epsilon_{\mu_0\epsilon_0}}} \tag{16}$$

3.6 Phased Array Antena

In phased array antenna principle, there are 2 main factor in the equations. First one is an element factor which is the factor that come from only one antenna itself and the another factor is called array factor which is come from the effect of multiple antennas combining together.

$$S(\vartheta) = S_e(\vartheta)S_a(\vartheta) \tag{17}$$

Whereas

S_e is a radiation pattern from only one element
S_a is a element factor with

$$S_a(\vartheta) = \sum_{i=1}^{K} a_i e^{jk(K-i)dsin(\vartheta)} \tag{18}$$

a_i is an amplitude taper.
K is a number of array antenna.
d is a distance of each antenna.
ϑ is a wavefront angle

4 Preliminary results

This project results will consist of 1) a simulation program that have ability to simulate a microstrip from the given parameters. 2) an phased antenna that could steer its direction to the desired point

4.1 Simulation Application

By using all the parameters that required to design the antenna, this simulation application will provide all the data from the algorithm that was proposed from the past. There are many techniques to simulate the antenna as Finite Element(FE), Method of Moments(MoM), or Numerical Method. However, the technique that will be used is one of those. In order to inspect on its correctness, the standard simulation application will be required to compare. Consequently, the antenna results is expected to have similar outcomes as well.

4.2 Microstrip Antenna

It's expected that a patch antenna should be have an impedance of zero Ohm at 5.6 GHz frequency

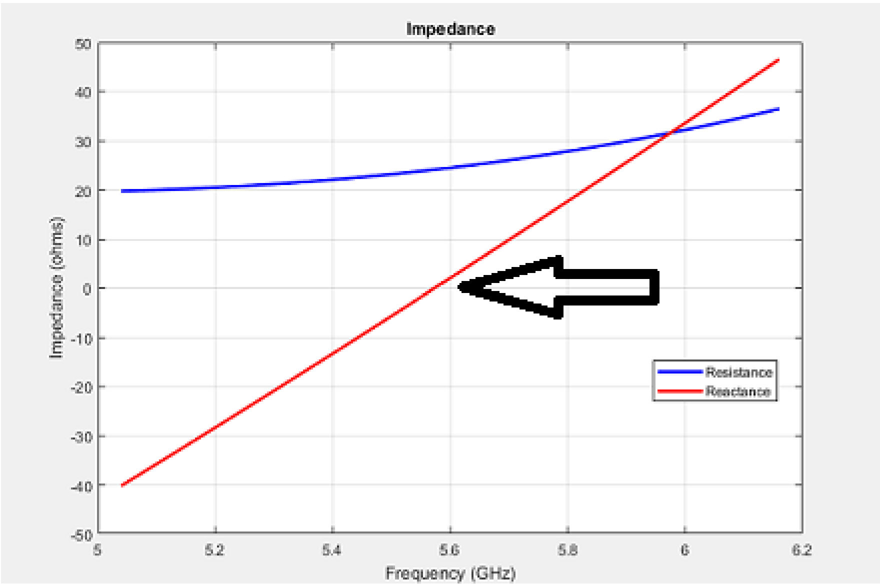

Figure 11: The designed antenna's impedance should have approximately 0 Ohm reactance at 5.6 GHz

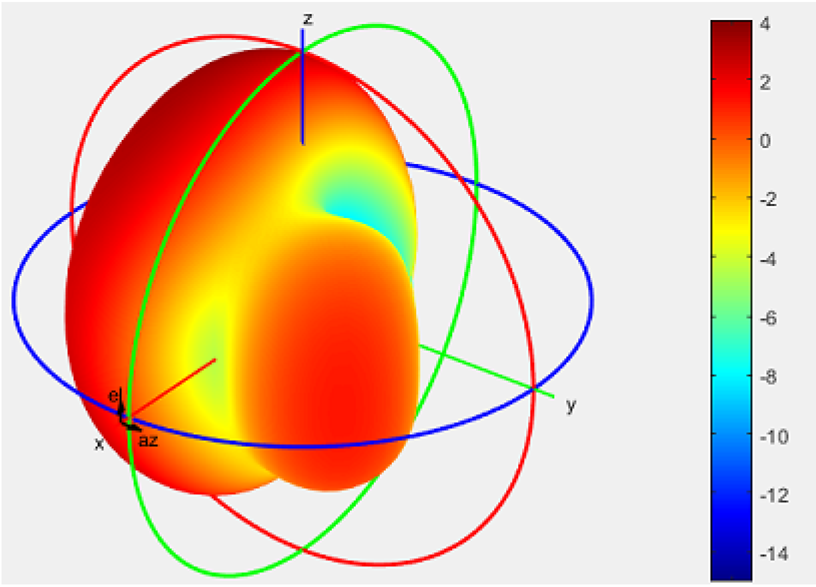

Figure 12: The designed antenna's radiation pattern like the analysis

4.3 Array Antenna Patern

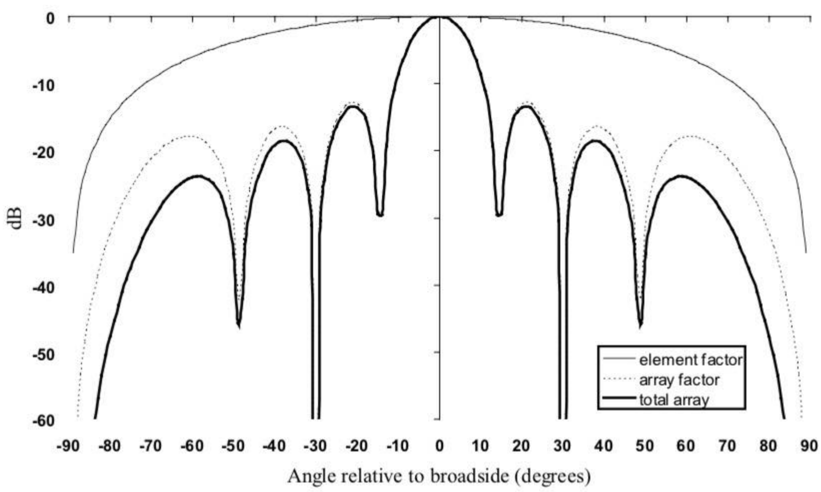

Figure 13: Power radiation pattern without amplitude taper aka. $\forall a_i = 1$

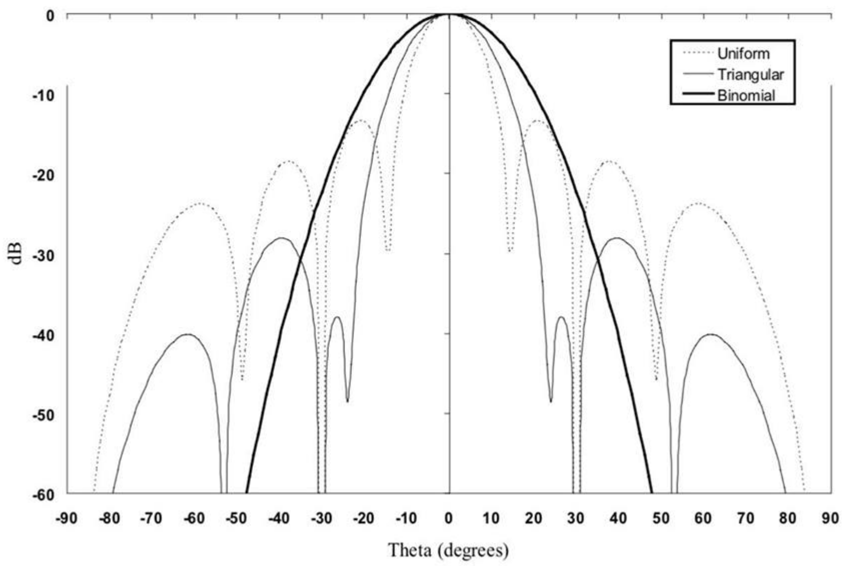

Figure 14: Power radiation pattern with amplitude taper of each type

5 Project overview

5.1 Scope of work

- An analysis of a microstrip antenna and phased array antenna
- A basic simulation application for finding antennas' radiation pattern
- A physical planar phased array microstrip patch antenna device with its test result.

5.2 Expected outcomes

It's expected that the physical device should have a preliminary result like those simulation applications, also, the simulation application and the application that come from other author will have similar results as well.

5.3 Project Plan

Name	Begin date	End date
Microstrip Antenna	9/1/17	4/29/18
Study past liturature	9/1/17	12/31/17
Design	12/1/17	1/30/18
Simulate	12/15/17	3/30/18
Test	1/1/18	4/29/18
Phased Array Antenna	11/1/17	3/31/18
Study past liturature	11/1/17	1/31/18
Design	2/1/18	2/27/18
Simulate	2/1/18	3/14/18
Test	2/15/18	3/31/18
Write a Simulation Program	1/1/18	4/28/18
Create layouts	1/1/18	2/28/18
Implements	2/1/18	3/30/18
Debug & Test	3/1/18	4/28/18

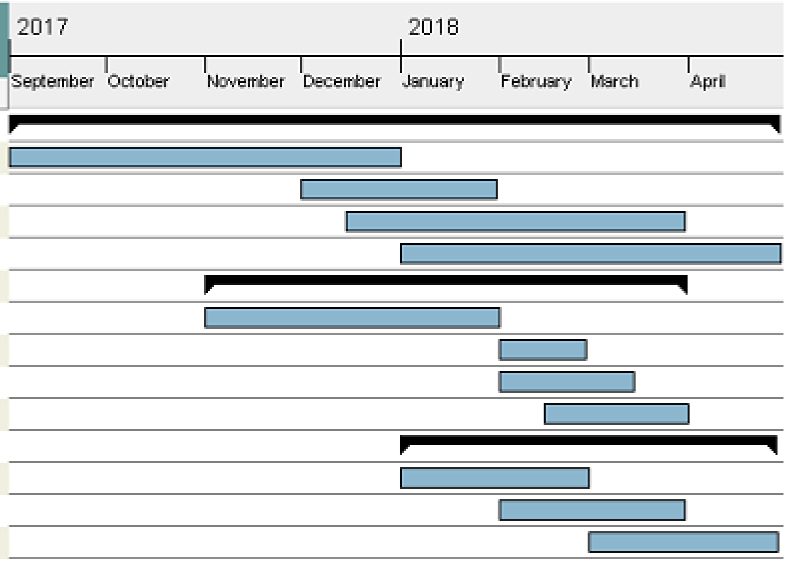

Figure 15: The project plan for the phased array antenna project

6 References

[1] K. M. L. Kai Fong Lee, *Microstrip Patch Antennas*. Imperial College Press, 2010.

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

[3] N. Kinayman, *Modern Microwave Circuits*. Artech House, 2005.

[4] C. A. Balanis, *Antenna Theory: Analysis and Design*. Wiley-Interscience, 2005.