PATCH ANTENNA AT 3.65GHZ FOR 5G COMMUNICATION WITH HARMONIC SUPPRESSION

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

Faculty of Electronic and Computer Engineering
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2020

DECLARATION

I declare that this report entitled "Patch Antenna at 3.65GHz for 5G Communication with Harmonic Suppression" is the result of my own work except for quotes as cited in the references.

Signature :

Author : Samuel Chieng Hoe Sing

Date : 25/6/2020

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

Signature :

Supervisor Name : MOHAMAD HARRIS MISRAN ………………………………….

Date : 26/6/2020 ………………………………….

DEDICATION

I would like to dedicate my project that I had done with sincere to my beloved family.

ABSTRACT

Mobile technology is an important part in our life that connects individuals with one another. The evolution of mobile technology started from 1 Generation, 2 Generation, 3 Generation, 4 Generation and currently, 5 Generation technology. The need for 5G technology is brought about by the needs to accommodate various technologies such as the advent of Industrial Revolution (IR) 4.0. Due to the high needs of 5G technology, various mobile company in Malaysia has started to do their own research and trials to prepare for 5G technology using the frequency mid-band of 3.3 – 3.8GHz. Which is why there is a need to research an antenna that can work within the mid-band frequency for 5G in Malaysia. This research focus on designing a patch antenna at 3.65GHz using harmonic suppression for 5G communication. To make sure that the antenna can work at 3.65GHz, harmonic suppression techniques are needed to suppress the higher modes of harmonic. Harmonic suppression technique can be used to control the surface current distribution on the antenna, thus effectively reducing the higher modes of harmonic. By controlling the length and width of the structured used for harmonic suppression, the degree of suppression will also be varied. To design this antenna, Computer Simulation Technology (CST) was used as the simulator to simulate the designed antenna.

ABSTRAK

Teknologi telefon mudah alih merupakan suatu bahagian yang penting dalam hidup kita dengan menyambungkan setiap individu antara satu sama lain. Evolusi ini bermula Generasi 1, Generasi 2, Generasi 3, Generasi 4 dan sekarang Generasi 5. Oleh disebabkan oleh fenomena Revolusi Industri 4.0 (IR 4.0), teknologi 5G amat diperlukan untuk menampung teknologi yang dibawa oleh IR 4.0. Justeru itu, pelbagai syarikat telekomunikasi di Malaysia telah memulakan untuk membuat penyedilikan dan percubaan bagi menyediakan teknologi 5G dengan menggunakan frekuensi dalam jarak 3.3 hingga 3.8GHz. Hal ini meyebabkan ada keperluannya untuk membuat kajian bagi antena yang boleh berfungsi dalam jarak frekuensi 3.3GHz hingga 3.8GHz untuk teknologi 5G di Malaysia. Kajian ini menumpukan dalam mereka bentuk 'patch antenna' pada 3.65GHz menggunakan teknik penekanan harmonik untuk tujuan komunikasi 5G. Bagi memastikan 'patch antenna' boleh berfungsi pada 3.65GHz, penekanan harmonik diperlukan untuk menekan harmonik-harmonik pada frekuensi yang lebih tinggi. Ini adalah kerana teknik penekanan harmonik boleh mengawal distribusi arus elektrik pada permukaan antena dan keadaan ini membawa kepada pengawalan harmonik-harmonik pada frekuensi yang tinggi. Apabila panjang dan lebar bagi bentuk yang digunakan untuk penekanan harmonik diubahkan, tahap

penekanan harmonik turut diubah berdasarkan dimensi bentuk tersebut. “Computer Simulation Technology” (CST) merupakan perisian yang digunakan untuk membuat simulasi dan reka bentuk antena.

ACKNOWLEDGEMENTS

Foremost of all, I would like to thank my parents for supporting me financially and giving me moral support throughout the long four years in my years of studying. Not to forget also my siblings that listened to me and give advices and feedback throughout the duration of my final year project.

Next, I would also like to thank my supervisor, Dr Mohamad Harris Bin Misran for accepting me as his student and giving me guidance and suggestions to complete this project.

Furthermore, not to forget my friends who had also given their own share of advices to me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

5G	:	5 Generation
CST	:	Computer Simulation Technology
VNA	:	Vector Network Analyzer
IoT	:	Internet of Things
IR	:	Industrial Revolution
AR	:	Augmented Reality
GSMA	:	Global System for Mobile Communications Association
DGS	:	Defected Ground Structure
CP	:	Circular Polarization
FR4	:	Flame Retardant 4
EM	:	Electromagnetic
RFID	:	Radio Frequency Identification
RF	:	Radio Frequency
DMS	:	Defected Microstrip Structure

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Project Background

In the recent years, 5G technologies had been the hot topics amongst the engineers to research and design. This is due to many advantages of implementing 5G technologies worldwide such as faster data transfer speed of more than 10GBps, allow new applications such as autonomous car and low latency for IoT (Internet of Things) usage [1] and to answer towards the components of Industrial Revolution (IR) 4.0 such as autonomous robots and Internet of Things (IoT). An antenna is an important component in 5G technologies as it serves to convert radio frequency fields to into alternating current or versa. Which is why a research is needed for the antenna for the usage of mid-band of 5G (3.3 – 3.8GHz) in order to serve as a basis for future 5G communications.

Therefore, like many other countries, Malaysia also aimed to implement 5G technologies to use in broadband, Smart Home, Augmented Reality (AR), industry automation and others [2]. Furthermore, the new spectrum bands that were proposed by the task force for 5G deployment in Malaysia are 3.5GHz and 28GHz bands [2].

3.5GHz band (range of 3.3GHz to 4.2GHz) was chosen due to the coverage of the signal, ideal balance of high amount of traffic supported and low latency. Next, Global System for Mobile Communications Association (GSMA) reported that majority of the countries in the world had been assigned to that frequency band such as Austria, Saudi Arabia, and Switzerland [3].

A microstrip patch antenna was widely used due to its thin size, easy to fabricate and flexible patch shape design [4]. However, since unwanted frequencies exist especially when the antenna is designed to operate at higher modes of frequency, harmonic suppression techniques need to be applied to suppress those frequencies.

Harmonic suppression is important to reject unwanted signals and various techniques can be applied to the antenna design to achieve it. Inserting slots, add stubs or slits and applying defected ground structure (DGS) to the antenna patch [5]. Filter can also be added to antenna allowing it to improve the S_{11} parameter [6].

1.2 Problem Statement

The demand for antenna for 5G communications has risen over the recent years due to the low latency, high speed data transfer and able to support high amount of traffic. This leads to various companies doing 5G trials such as Celcom, TM Net and Umobile in Malaysia. Furthermore, the usual demand for antenna designed for communications is that the antenna must be compact and has small profile to integrate it into electronic devices. Next, the generic antenna usually has a fixed directional radiation pattern. However, for mobile communication, an antenna needs to have a circular polarization (CP) characteristic to deter the multipath effect by using the characteristic of a CP antenna that can transmit signal in every plane. Therefore, to overcome this problem, a circularly polarized (CP) microstrip patch antenna at 3.65GHz with harmonic suppression techniques was proposed.

1.3 Objectives

I. To design a CP microstrip patch antenna at 3.65GHz with harmonic suppression technique using DGS.

II. To fabricate the microstrip patch antenna using Flame Retardant 4 (FR4) substrate.

III. To measure and analyze the parameters of microstrip patch antenna using lab measurement setups.

1.4 Scope of Work

The scope of work for this project can be divided into 4 parts: Which is the literature review, design and simulation, fabrication, and analysis and measurement. For literature review, studies will be done on various papers regarding patch antenna with harmonic suppression techniques will be used as reference to find out the desired outcomes such as the return loss, gain, and radiation pattern.

For the design and simulation part, microstrip patch antenna at 3.65GHz with DGS for 5G communications is designed and simulated using CST software. Next, for the fabrication, photo lithographic technique will be used to fabricate the final design of microstrip patch antenna onto FR4 substrate. Finally, in analysis and measurement, vector network analyser will be used to measure the S_{11} parameter (return loss), gain and polarization of the fabricated antenna and comparison will be done between the simulation and the measured results.

CHAPTER 2

BACKGROUND STUDY

2.1 Introduction

In this chapter, a few related projects that were similar were reviewed and compared. Literature review’s section is an important part to show the significance of this project as well as to show the expected results upon completing this project. Moreover, those projects that were reviewed can also be used as references to improve the performances of the patch antenna such as the S_{11} parameter (return loss), gain and other parameters that were important towards the performances of the patch antenna.

2.2 Antenna and history

Antenna is used to transmit or receive electromagnetic (EM) waves. It can convert currents into EM waves when using transmitter antenna and vice versa for a receiver antenna [7].

Antenna was first introduced back in the year 1901 when an antenna was used by Marconi to relay a signal between two locations that were about 3,500 kilometres apart from each other [8]. Then in the year 1940s, Harold A. Wheeler introduced small and compact antenna with high Q values which bring about to the narrow band features. Fast forward to year 1970s, microstrip patch antenna became well received due to it being flexible and uncomplicated designs.

Even though antenna were generally implied as a device used to send and receive signals, however it comes in different types and each type has their own specific applications. Some of the types of antenna that are available are the wire antenna, travelling wave antenna, reflector antenna, microstrip antenna, aperture antenna and others [9].

Due to the many advantages that microstrip patch antenna has, it was widely applied across many applications such as radio frequency identification (RFID), mobile phones, monitoring system and satellites usage [10].

2.3 Microstrip patch antenna

Before any additional designs are done onto the microstrip patch antenna, it can be said that the antenna has four basic components to it, which are the patch, microstrip feed, ground plane and the dielectric substrate as shown in Figure 2.1 below.

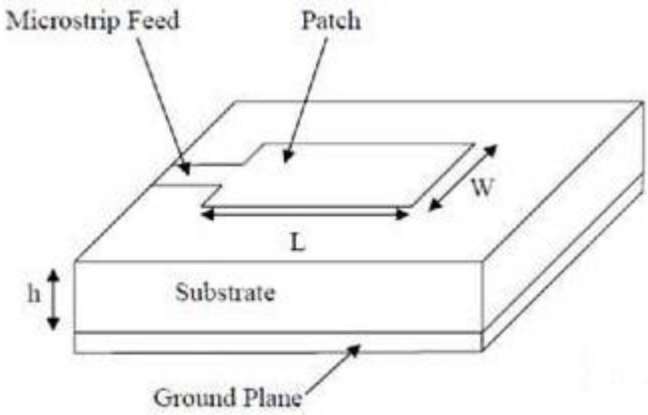


Figure 2.1: Microstrip patch antenna

Figure 2.1 shows *W*, *L* and *h* where *W* is the width of the patch of the antenna, *L* is the length of the patch and h is the height of the dielectric substrate. In order to obtain the length and width of the patch, calculations using formula can be done [11]. *W* (width) can be expressed as

$$W = \frac{c}{2f\sqrt{\frac{(\varepsilon r+1)}{2}}} \tag{2.1}$$

where *W* is the width of patch

c is the speed of light (3 x 10^8 ms^{-1})

f is the resonance frequency of the desired antenna

ε_r is the dielectric constant of the substrate

L (length) can be expressed as

$$L = Leff - \Delta L \tag{2.2}$$

where L is the length of patch

L_{eff} is where $Leff = \frac{c}{2f\sqrt{\varepsilon eff}}$ (2.3)

$$\Delta L = 0.412h\frac{(\varepsilon eff+0.3)(\frac{W}{h}+0.264)}{(\varepsilon eff-0.258)(\frac{W}{h}+0.8)} \quad (2.4)$$

$$\varepsilon_{eff} = (\varepsilon r + 1)/2 + (\varepsilon r - 1)/2[1 + 12\, h/W]^{-\frac{1}{2}} \quad (2.5)$$

h is the height of the substrate chosen for the microstrip patch antenna

For a circular patch antenna, the radius of the patch can be calculated by using the formula of [12],

$$a = \frac{F}{\sqrt{1+(\frac{2h}{\pi\varepsilon rF})(\ln\left(\frac{\pi F}{2h}\right)+1.7726)}} \quad (2.6)$$

where $F = \frac{8.791 \times 10^9}{f\sqrt{\varepsilon r}}$ (2.7)

a is the radius of the circular patch

2.4 Types of feeding techniques

Feeding techniques is essential for microstrip patch antenna as it fed the radio frequency (RF) through the feed line towards the patch. Feeding techniques can be classified into two types which are the contact type and non-contact type. Further branching down from these two classifications are the techniques such as coaxial probe, microstrip line, aperture coupling and proximity coupling [13].

2.4.1 Microstrip line

Microstrip line feed is a type of contact techniques. It is a line of conductor that connects from the patch to the port. The benefit of this technique is that it makes it easier to be designed along with the patch and fabrication of the microstrip line feed can be done in one step along with the patch antenna [13].

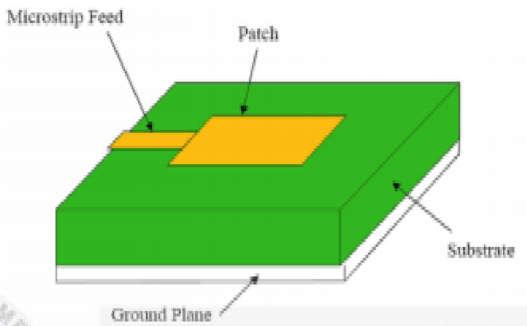


Figure 2.2: Microstrip feed line

2.4.2 Coaxial probe

Coaxial probe is also another one of the contact types of feeding technique. The apparent benefit of this technique is that it allows any positioning of the feed as long as it touches the patch to acquire the impedance matching as shown in Figure 2.3. Next, it is also simple to be fabricated and causes low undesired frequency. However, the major drawbacks of this technique are that it can be difficult to design it in the software as a hole is needed to be opened through the ground plane towards the patch and provides small bandwidth [13]. The position for the coaxial probe can be calculated by the formula of [12],

$$X_f = \frac{L}{\sqrt{\varepsilon\text{eff}}} \tag{2.8}$$

$$Y_f = \frac{w}{2} \tag{2.9}$$

where X_f and Y_f is the x, y coordinates of the coaxial probe feed

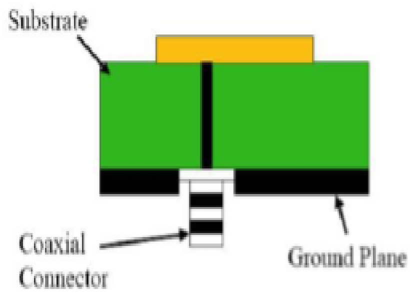


Figure 2.3: Coaxial probe feed line

2.4.3 Aperture Coupled Feed

This technique is a type non-contact feed technique. It is similar to the microstrip feed technique in that it also involves both microstrip feed line and a patch element. However, the difference is that it was to be placed below the feed substrate as shown in Figure 2.4. Since it has two layers of substrates, both the parameters of the dielectric constants along with the thickness of the substrates can be designed separately to obtain a more efficient antenna. Since both feed line and patch element were separated by the ground plane, it minimizes the effect of unwanted frequencies. Moreover, it also brought a relatively high bandwidth of 21%. However, the major drawback is that it is hard to be fabricated due to the two layers of substrates [13].

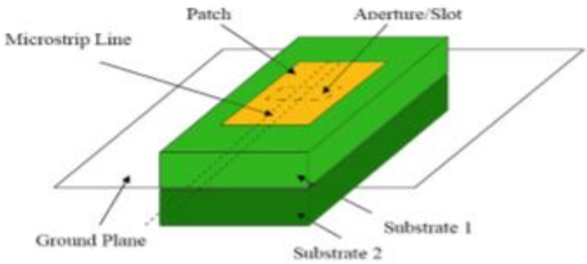


Figure 2.4: Aperture coupled feed line

2.4.4 Proximity Coupled Feed

Proximity coupled feed is also a type non-contact feed technique. It is similar to aperture coupled feed where two layers of substrates are also required. This technique can bring about a relatively high bandwidth of 13% by having a thicker microstrip patch antenna. Furthermore, unwanted frequencies can also be eliminated through this method. By using this technique, it also allows the user to have two different substrates, for the patch and the feed line each respectively. The drawbacks of this method are that the entire antenna will have a thicker appearance and hard to fabricate due to two dielectric substrates that requires a right arrangement as shown in Figure 2.5 [13].

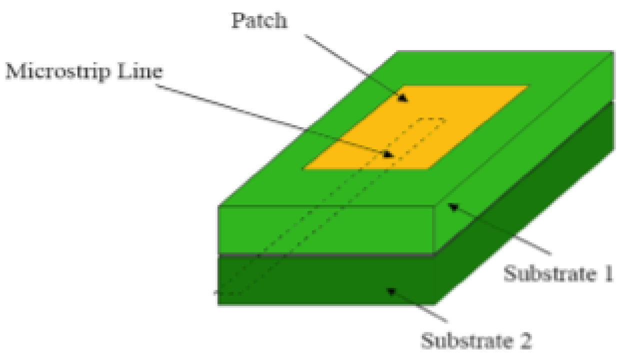


Figure 2.5: Proximity coupled feed line

2.4.5 Summary of different feeding techniques

The techniques for antenna feed line can summarised in the Table 2.1 [13]:

Table 2.1: Summary of different feed line techniques

Characteristics	Feed line techniques			
	Microstrip	Coaxial	Aperture	Proximity
Unwanted frequencies	High	High	Low	Minimum
Fabricating	Simple	An opening and soldering are needed on the bottom	Right arrangement required	Right arrangement required
Impedance matching	Easy	Easy	Easy	Easy
Bandwidth	2 – 5%	2 – 5%	21%	13%

2.5 Antenna Parameters

The efficiency of an antenna can be determined by observing several parameters which are return loss (S_{11}), gain, bandwidth, input impedance and polarization.

2.5.1 Return Loss (S_{11})

Return loss can be defined as the reflecting power of a signal when it went into a transmission line. Since an antenna can be said to be working when the operating frequency is below -10dB of S_{11}. This happens when at least 90% of the power is transferred to the antenna and a maximum of 10% power is reflected back. This can be summarized into an equation where [13]:

$$S_{11} = 10 \log \left(\frac{reflected\ power}{power\ in}\right) \tag{2.10}$$

2.5.2 Gain

Gain can be said to be one of the most understood parameters among the antenna parameters and a measurement that includes the efficiency of antenna and the capabilities of the directional parameter [14]. Generally, the value of gain is lower than directivity. This is because gain can be defined as the ratio of radiation intensity to the input power where it is expressed as [15]:

$$\text{Gain} = 4\pi \left(\frac{radiation\ intensity}{input\ power}\right) \tag{2.11}$$

2.5.3 Bandwidth

An antenna's bandwidth is the span of frequencies which an antenna can properly work. By identifying the maximum frequency of a certain band, minimum frequency and center frequency, the bandwidth can be determined as:

$$BW = 100 \text{ x } (f_H - f_L) / f_C \tag{2.12}$$

where BW is the antenna's bandwidth

f_H is the maximum frequency

f_L is the minimum frequency

f_C is the center frequency

Bandwidth is the percentage of difference in frequency divided by the bandwidth's center frequency. Bandwidth has no distinguishable characterization, due to the polarization, gain, input impedance and other parameters does not vary in the same way. Which is why the parameters are determined and set beforehand according to the antenna’s application [14].

2.5.4 Input Impedance

Input impedance for an antenna can be defined as a voltage to current ratio at a set of terminals. When the maximum power transfer between a transmission line and the antenna were determined the input impedance can also be determined. To achieve the highest power transfer, the transmission line, antenna and the input impedance must be matched. On the account that these three elements were not matched, a wave will be reflected from the antenna’s terminal and send back towards the power source which will cause the efficiency of the antenna to be reduced [14].

2.5.5 Polarization

Polarization for antenna in a certain direction can be defined as the polarization of radiated wave by an antenna. A wave’s polarization can then be said to be a wave sent or received by the antenna in certain direction. Radiated wave at any given point of an antenna’s far field can be said to be represented by a plane wave which its electric-field force is similar as the wave which its course of propagation coincides with the radial direction of the antenna.

Polarization can be categorized into three type, linear, circular and elliptical. The field is linearly polarized if the vector of an electric field of a point is always being directed along a course of line. If the electric field runs along an ellipse shaped course, then it is polarized elliptically. Finally, if the ellipse became a circle or line, the polarization then becomes circular or linear each respectively [14].

2.6 Harmonic Suppression Techniques

Harmonic suppression is important in antenna design as it can be used to control the current distribution on the patch element of the antenna. By controlling the current distribution, the efficiency of the antenna can be improved as the higher modes of unwanted frequencies can be suppressed [16]. Some techniques that can be used to suppress the harmonics are slot, notch, slit, stubs and defected ground structure (DGS).

By using a simple structure, DGS can improve the parameters of an antenna. When doing harmonic suppression such as slot or slit onto the ground plane of the antenna, it is referred to as DGS. It has been known that when DGS is implemented into a conventional microstrip antenna design it can induce a band-stop property, suppressing higher harmonics, improve bandwidth and antenna's gain [17].

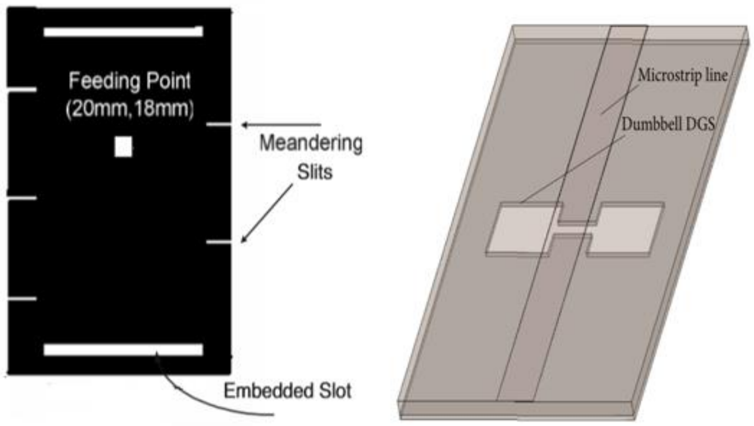


Figure 2.6: Slot, Slit and DGS

2.7 Comparing previous works

In this section, various previous work that were done before were being compared. To ensure that the work compared were eligible to be used for comparing and references, databases such as Institute of Electrical and Electronics Engineers (IEEE), ResearchGate, International Advanced Research Journal in Science, Engineering and Technology (IARJSET) and Google Scholar were used as the platform to search and cite papers from. The criteria that were used to select works done were based on the harmonic suppression techniques and the design used.

In a work done by Sabran, M. I et al. [18], a square patch antenna at 2.45GHz fed by proximity coupling using FR-4 substrate was proposed. In the initial design of the patch antenna was done and has two higher order harmonics. To suppress the higher order harmonics (4.75GHz and 6.85GHz) as shown in Figure 2.9, U-slot and double U-slot were introduced to the feed line of the antenna to create a filtenna.

After that, the patch antenna was simulated to observe the S_{11} parameters of the proposed patch antenna as shown in Figure 2.9. By referring to Figure 2.9, the initial S_{11} has two higher order harmonics at 4.75GHz and 6.85GHz. The addition of the U-slot on the antenna suppress the harmonic at 6.85GHz and by adding double U-slots, the harmonics at 4.75GHz was also suppressed.

Then, farfield monitor was used to measure the radiation efficiency and gain of the patch antenna. The results were that the radiation efficiency of the antenna is at 83.55% with the total efficiency of the antenna at 83.54%. Finally, the gain of the antenna was measured as 5.5dBi for simulated antenna and 5.3dBi for the fabricated antenna.

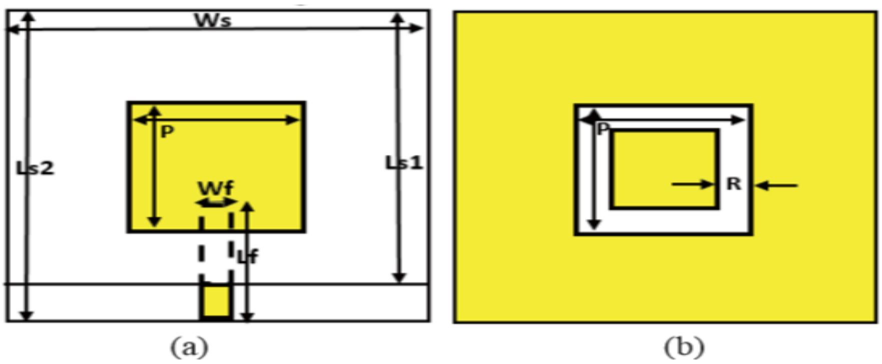


Figure 2.7: Proposed antenna (a) Front (b) Back

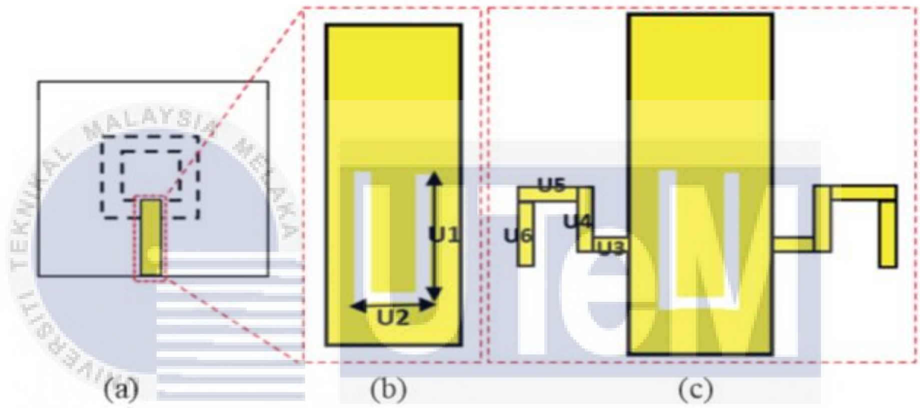


Figure 2.8: Feedline (a) Feed (b) U-slot (c) Double U-slot stubs

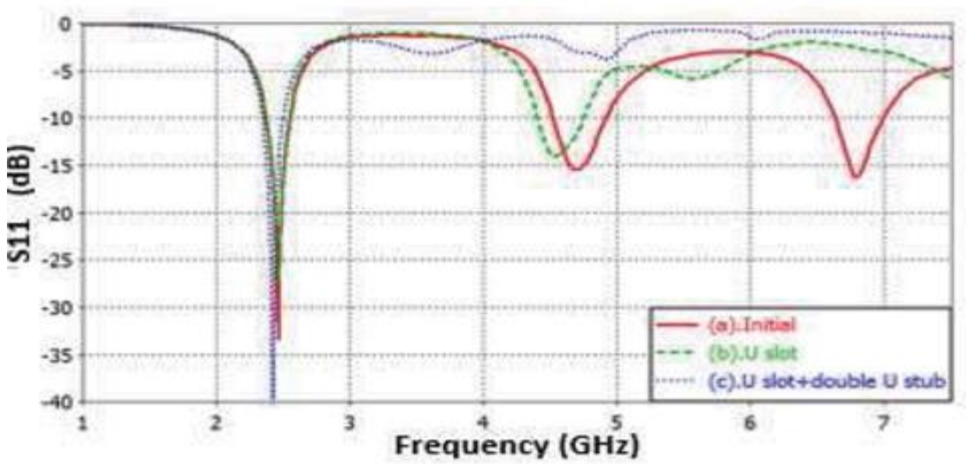


Figure 2.9: S11 parameter of antenna

In this work, R.A. Rahim et al. proposed a circular patch antenna for 2.45GHz circular patch antenna with FR-4 substrate [19]. In the initial simulation of S_{11} for the initial design of the antenna, there were three higher mode harmonics. Slits, stub and DGS were introduced to the circular patch antenna to disrupt the current flow of the higher mode harmonics as shown in Figure 2.10.

When the DGS were introduced to the partial ground of the antenna, the S_{11} of the frequencies shifted to the left. The S_{11} after applying the harmonic suppression techniques then have the resonant frequency of 2.45GHz with a return loss of -35.703dB and the higher mode harmonics were suppressed below -10dB as shown in Figure 2.11.

After that, the farfield simulation was done to measure the efficiency of the antenna and the gain. The radiation efficiency of the circular patch antenna was measure at 72.33% and overall efficiency is 72.32%. The gain of the antenna is measured at 2.229dBi.

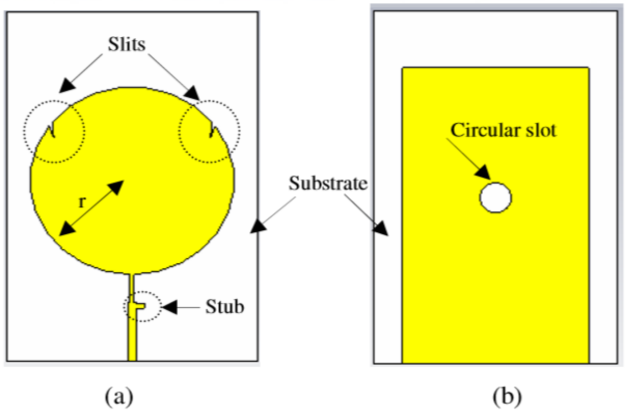
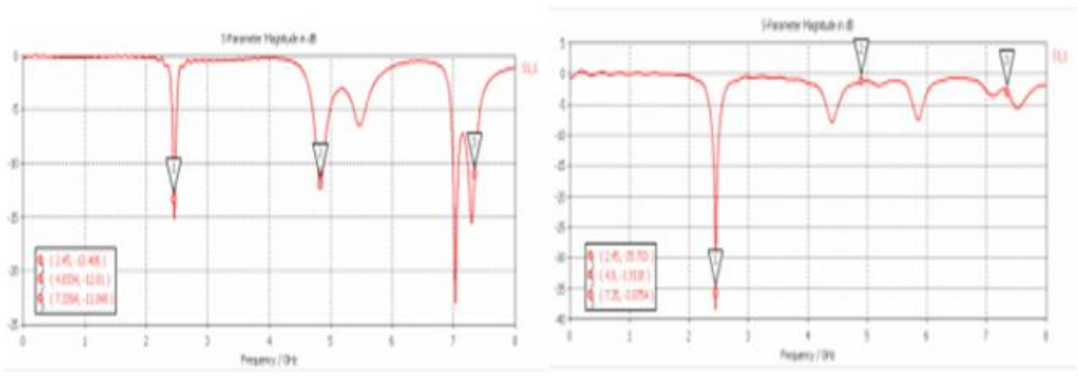


Figure 2.10: Proposed antenna (a) Front (b) Back



(a) (b)

Figure 2.11: S_{11} (a) DGS (b) Stub and slits

Eltouh H. et al., has proposed a design of microstrip rectangular patch antenna using FR-4 substrate with inset feed at 5.5GHz [20]. The initial design of the rectangular patch as shown in Figure 2.12 has the S_{11} with 5.5GHz and the unwanted harmonic, 7.6GHz as shown in Figure 2.13.

Other than DGS, Defected Microstrip Structure (DMS) also was used to suppress the unwanted harmonics. DMS on the microstrip line can disrupt the surface current distribution. This is due to the DMS property where it can provide a longer path for electromagnetic (EM) wave for the antenna which will raise the impedance of the transmission line.

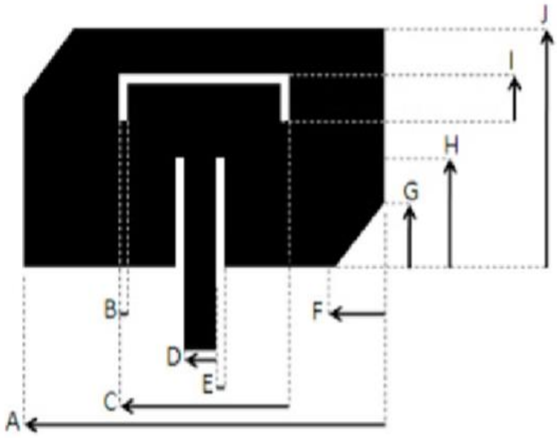


Figure 2.12: Proposed antenna

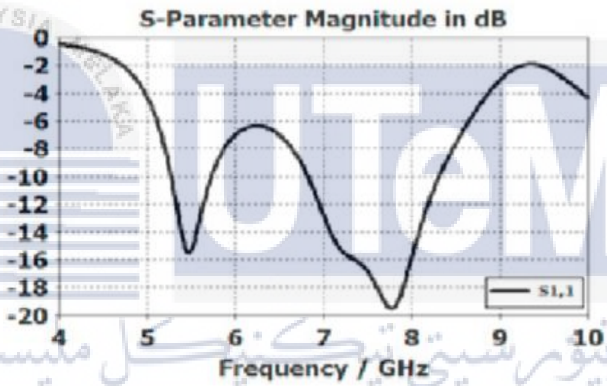
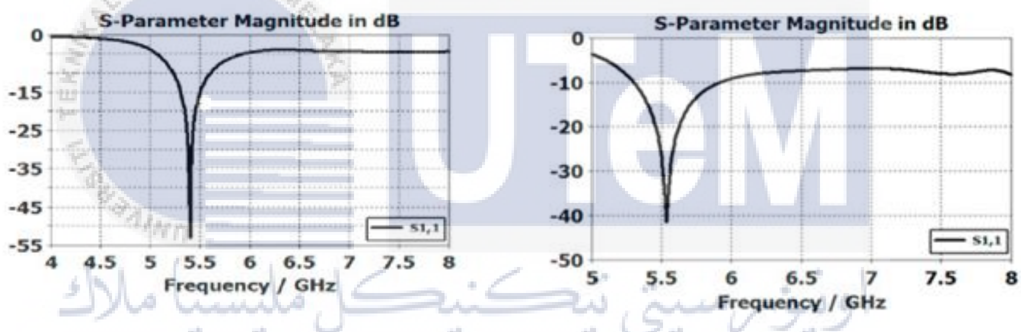


Figure 2.13: S_{11} of proposed antenna

To further suppress the harmonic at 7.7GHz, DGS and Defected Microstrip Structure (DMS) were used on two different antennas. For the DGS, a dumbbell structure was used at the ground. By designing the DGS structure to have the properties of 5.4GHz cut-off frequency and 7.6GHz stopband, this structure when combined with the designed antenna can be used to suppress the harmonic at 7.6GHz.

(a) (b)

Figure 2.14: Proposed antenna (a) DGS (b) DMS



(a) (b)

Figure 2.15: Simulated S_{11} (a) DGS (b) DMS

Chopra, R. et al [21] has proposed a microstrip patch antenna at 2.25GHz using harmonic suppression. In this design, superstrate effect was applied to improve the bandwidth of the antenna. The patch of the antenna was then applied with slots to suppress the higher order of harmonics and then fabricated using foam substrate and the Teflon for the superstrate effect. The antenna was then measured for its gain which is a maximum of 7dBi.

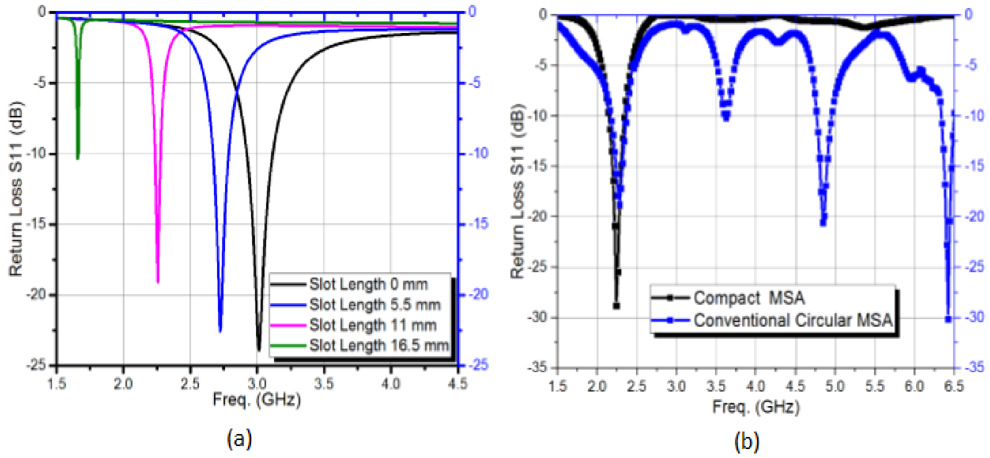


Figure 2.16: Simulated S11 (a) Initial (b) Final

Figure 2.17: Final design of antenna

Verma, S. et al has proposed a rectangular patch antenna using FR-4 substrate at 9.7GHz for 5G applications [22]. The proposed antenna was fed using a microstrip line and uses a rectangular slot to suppress the higher mode of harmonics.

The antenna was then simulated using the farfield monitor to determine the gain of the patch antenna which is 4.46dBi. The proposed antenna was then fabricated and measured using a VNA to determine the measured S_{11} of the fabricated antenna as shown in Figure 2.20.

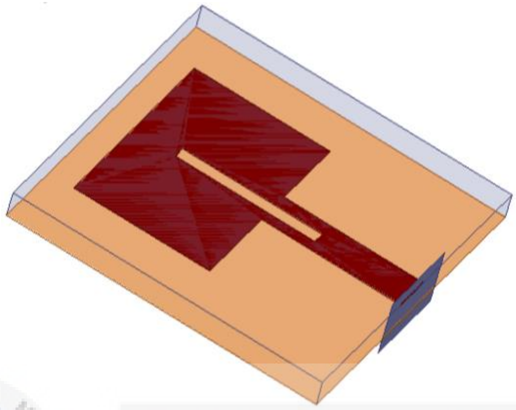


Figure 2.18: Proposed antenna design

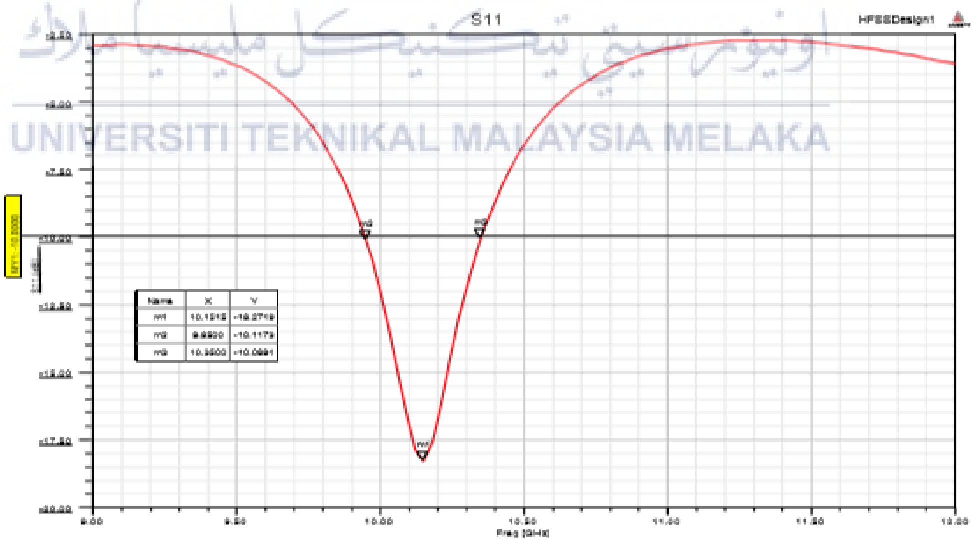


Figure 2.19: Simulated S_{11} of proposed antenna

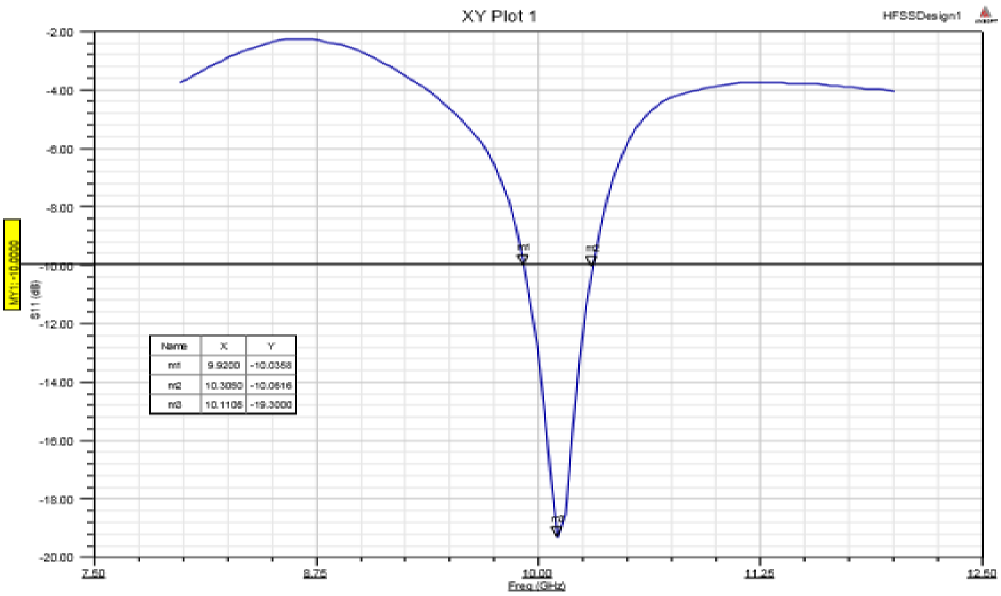


Figure 2.20: Measured S_{11} of fabricated antenna

Zainol, N. et al has proposed a patch antenna with rectangular shape at 2.45GHz with circularly polarized characteristic using proximity coupling feeding technique [23]. The design uses U-stub that is inverted and U-slot onto the microstrip line for harmonic suppression effect. Then, to obtain the circular polarisation characteristic, the corner of the patch is then truncated and applied with U-slot. The designed antenna was then simulated with the higher order harmonics suppressed and has gain of 4.61dB with axial ratio (AR) of 1.48.

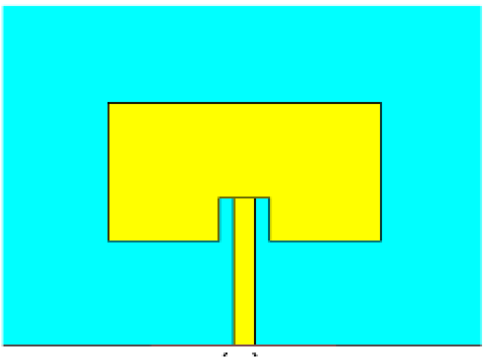


Figure 2.21: Patch design

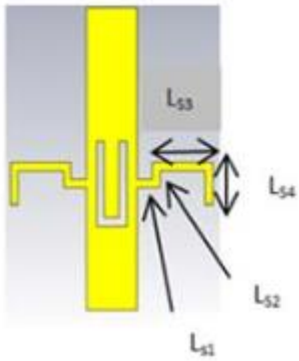


Figure 2.22: Transmission line with stub and slot

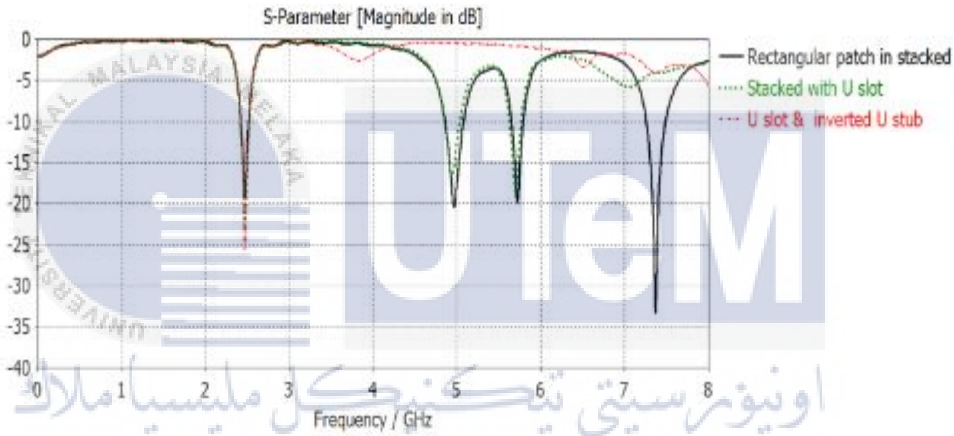


Figure 2.23: S_{11} of the antenna

2.7.1 Summary of previous work

Table 2.2: Summary of previous works

Author	Shape of patch	Feeding method	Resonant frequency (GHz)	Harmonic suppression technique	Substrate	Gain (dBi)
Sabran, M. I. et al	Square	Proximity coupling	2.45	- Slot - Stub	FR-4	5.5

R.A. Rahim et al	Circle	Microstrip	2.45	- Slit - Stub	FR-4	2.229
Eltouh H. et al.	Rectangle	Microstrip	5.5	- DGS - DMS - Slot	FR-4	6.41
Chopra, R. et al	Circle	Microstrip	2.25	- Slot	Foam	7.0
Verma, S. et al	Rectangle	Microstrip	9.7	- Slot	FR-4	4.46
Zainol, N. et al	Rectangle	Proximity coupling	4.61	- Slot	FR-4	4.61

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, it will discuss about the methods and procedures taken to properly design a microstrip patch antenna at 3.65GHz using harmonic suppression technique. This chapter also shows the parametric study that was done to design the patch antenna.

3.2 Procedures of the project development

When doing this project, the project must be planned appropriately so that the objectives and scope of work can be achieved in time. This is also to ensure that the flow of progress will be smooth. Before starting the designing of the antenna, various data were collected from technical reports, journals and articles from reputable sources to ensure that the data collected were reliable and can be trusted. Which is why a flowchart is used to plan and use as a guideline during the project duration as shown in Figure 3.1.

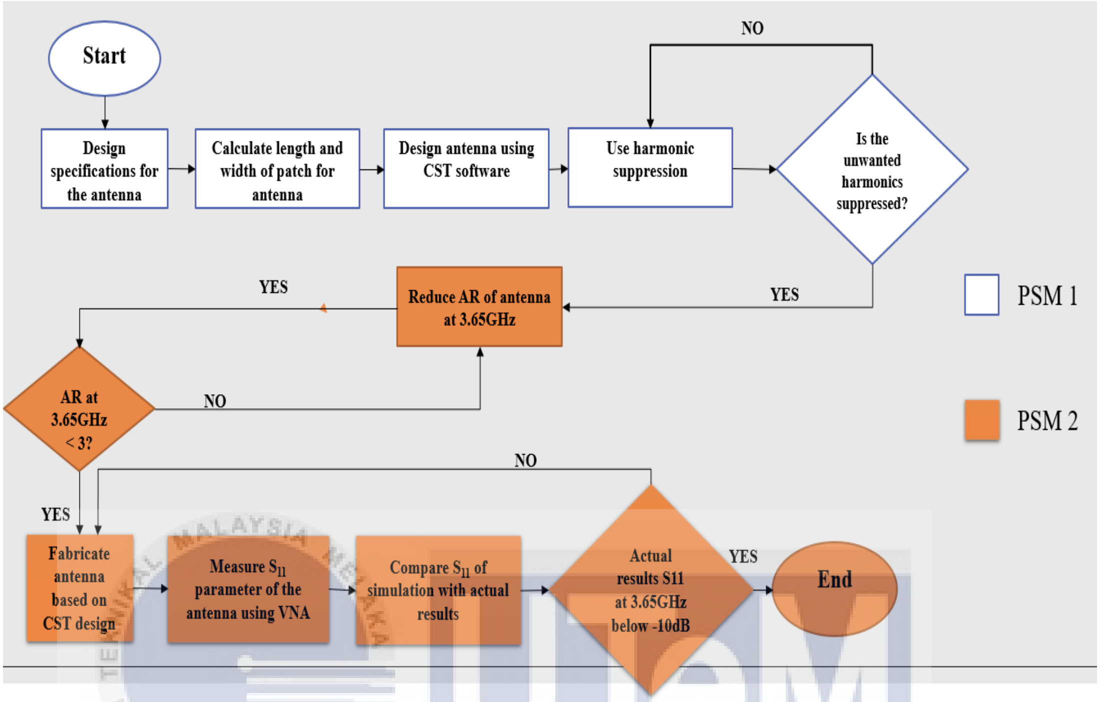


Figure 3.1: Project flowchart

When designing the antenna, the ease of fabrication and the parameters of the antenna that will be brought about by the methods chosen were considered after comparing and referring to various related journals and articles. To choose the best design for the antenna, parametric studies were done for each of the slots that were on the antenna. Then, after taking into considerations of the return loss, gain and the radiation pattern, the design chosen was then used for antenna fabrication.

3.2.1 Process for fabrication

When doing fabrication, there are few procedures that need to be followed to ensure that the fabricated antenna is acceptable. If the specifications of the antenna do not match the requirement, the fabrication process needs to be re-do so that the measured antenna parameters from the fabricated antenna matches the parameters wanted.

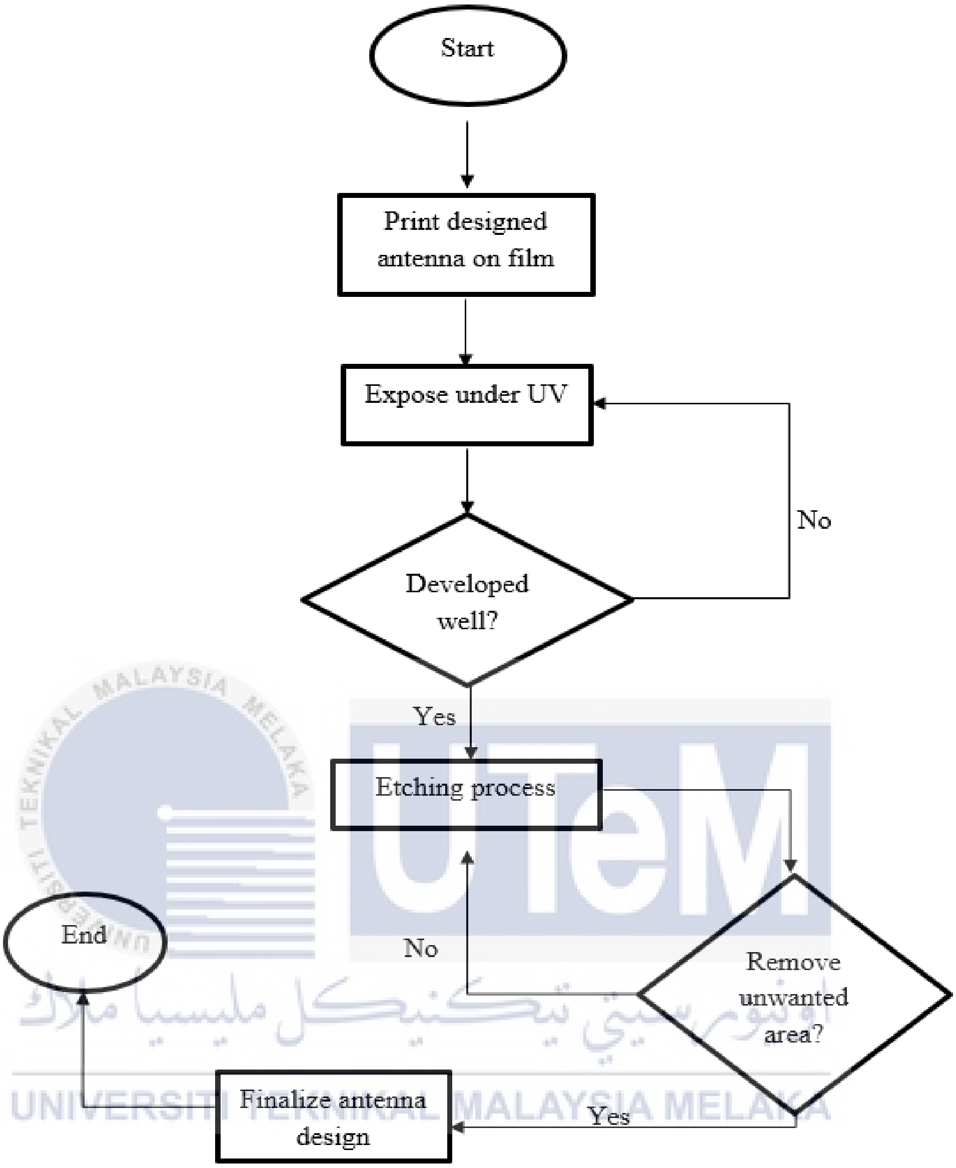


Figure 3.2: Fabrication process flowchart

3.3 Design Specification

Before designing the antenna, researches were done to determine the minimum specifications for the antenna. The parameters consist of gain, resonant frequency, efficiency, return loss, dielectric constant of the substrate and axial ratio as shown in Table 3.1.

Table 3.1: Specifications of patch antenna

Antenna parameters	Value
Resonant frequency	3.65GHz
Gain	≥ 2dB
Return loss	≤ -10dB
Efficiency	> 50%
Dielectric constant	4.4
Axial ratio	≤ 3

3.4 Design Process for Patch Antenna

To design the patch antenna, Computer Simulation Technology (CST) software was used as the simulation tool because it can do a fast and precise analyzing of devices of high frequency such as antenna, filters and others. Then, by utilizing the various solvers in CST such as the Time Domain and Frequency Domain solver, the parameters in Table 3.1 can be analyzed and simulations can be done.

3.4.1 Design of antenna

When designing the patch of the antenna, the types of shape had to be determined first. The shape of the antenna was chosen as a square shape patch using the copper (lossy) material. Copper (lossy) was chosen to take into consider of the losses during the fabrication part. Then, equation 2.1 and 2.2 were used to determine the width and length of the patch. By substituting the values into equation 2.1 and 2.2, the width and length of the patch is 24.99mm and 19.12mm.

Then, the substrate and ground of the antenna were chosen the dimension of width of 50mm and length of 40mm using the FR4 substrate and copper (lossy) for the ground plane. The dimensions for the substrate and ground are determined so that the length of the antenna can be adjusted with enough space to spare as the resonant frequency of the antenna in S_{11} graph will change as adjustments were made to the patch or ground. The ground plane for the antenna is a full ground plane. It acts as a plane to reflect the radio waves. The diameter of the patch, ground and substrate is summarized in Table 3.2.

The microstrip line which is the feeding line for the patch can be calculated by using the function in the CST software as shown in Figure 3.3. The calculated impedance of the microstrip line is near to 50Ω because it is the standard transmission line impedance used. When the impedance line matches between the transmitter antenna and receiver antenna, it minimizes the reflection of the signal and return loss. Thus, reducing the loss of the signal during transmission.

The initial design of the patch, substrate, ground and microstrip line is then shown in Figure 3.4. The antenna is then simulated to determine the initial S_{11} parameters as shown in Figure 3.5.

Table 3.2: Antenna initial dimensions

Antenna parts	Width (mm)	Length (mm)
Patch	24.99	19.12
Substrate	50.00	40.00
Ground	50.00	40.00
Microstrip line	3.25	10.40

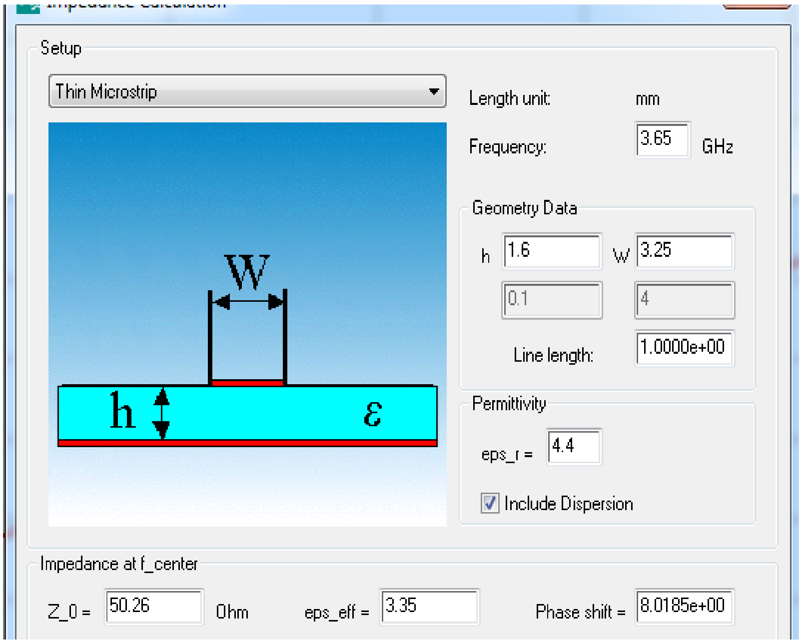
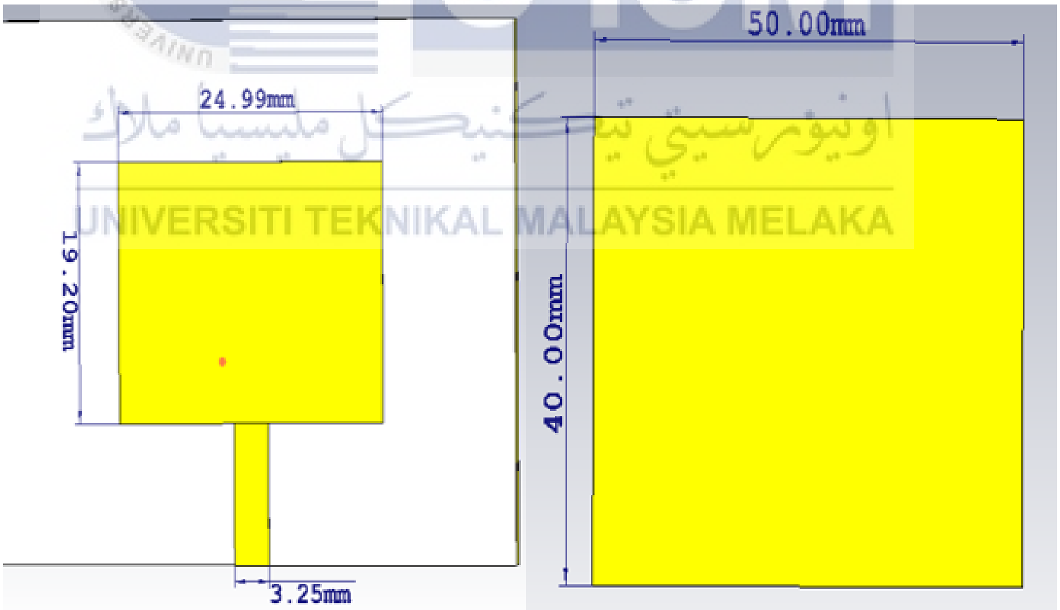


Figure 3.3: Microstrip feed line calculation



(a) (b)

Figure 3.4: Initial (a) Front (b) Back

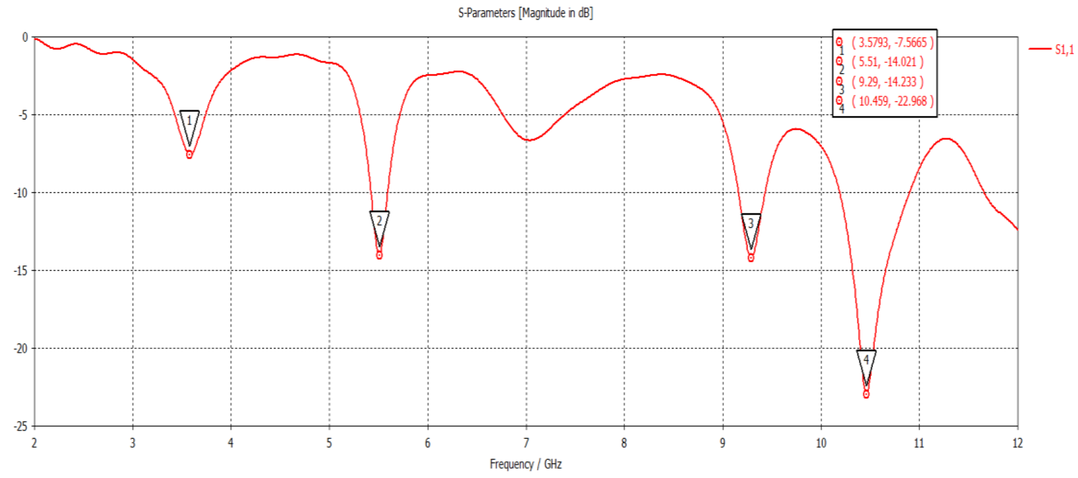


Figure 3.5: Initial S_{11}

As shown in Figure 3.5, there are 4 higher order of harmonics in the S_{11} parameters. However, the resonant frequency (3.65GHz) of the antenna is more than -10dB. To reduce the S_{11} at the resonant frequency, inset feed technique will be used.

3.4.2 Inset Feed

Inset feed is used to improve the bandwidth and the S_{11} of the antenna [24]. This is because inset feed can improve the impedance matching of the antenna, which lead to improvement of the S_{11}. To find out the best length of the inset feed that yields good S_{11} parameters, parametric study was done from 5.1mm to 4.1mm as shown in Figure 3.6. Then, by observing the S_{11} of each length, 4.6mm was chosen due to a better return loss at the resonant frequency and reduced of S_{11} of the higher modes of harmonics as shown in Figure 3.7. The final dimensions of the inset feed was then shown in Figure 3.8.

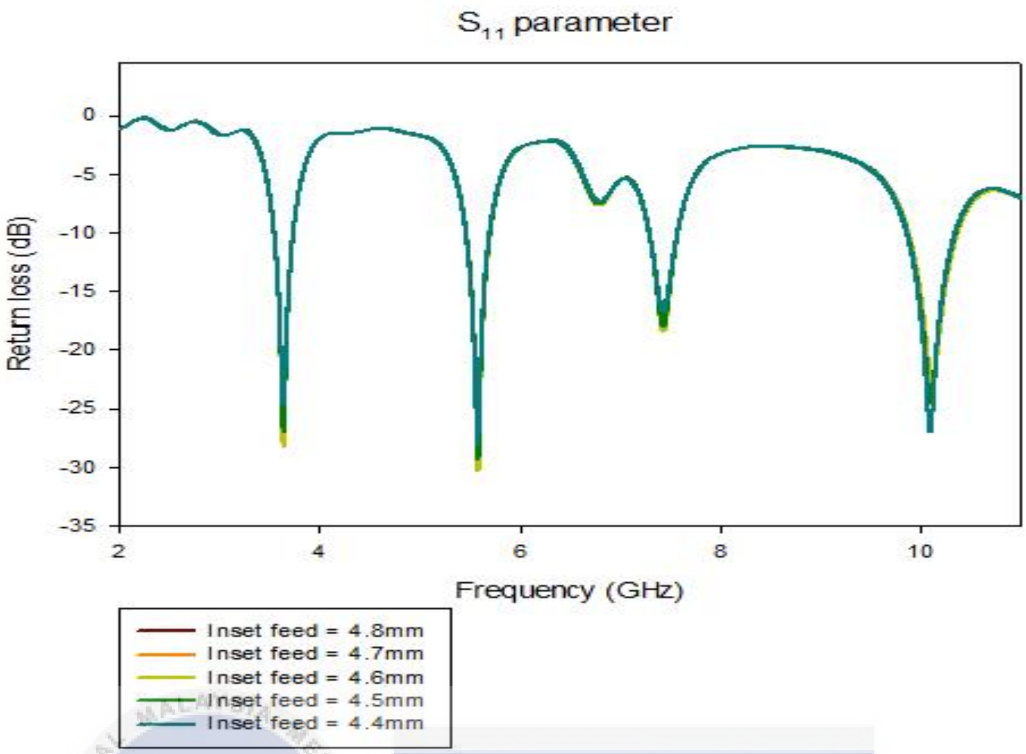


Figure 3.6: S_{11} of inset feed from 4.8mm to 4.4mm

Table 3.3: S_{11} of inset feed parametric study

Frequency (GHz)	Return loss (dB)				
	IF=4.8mm	IF=4.7mm	IF=4.6mm	IF= 4.5mm	IF=4.4mm
3.65	-26.87	-26.86	-28.12	-26.87	-24.57
5.50	-12.57	-12.59	-12.46	-12.57	-12.82
9.3	-3.76	-3.75	-3.79	-3.76	-3.73
10.5	-7.27	-7.28	-7.57	-7.27	-7.16

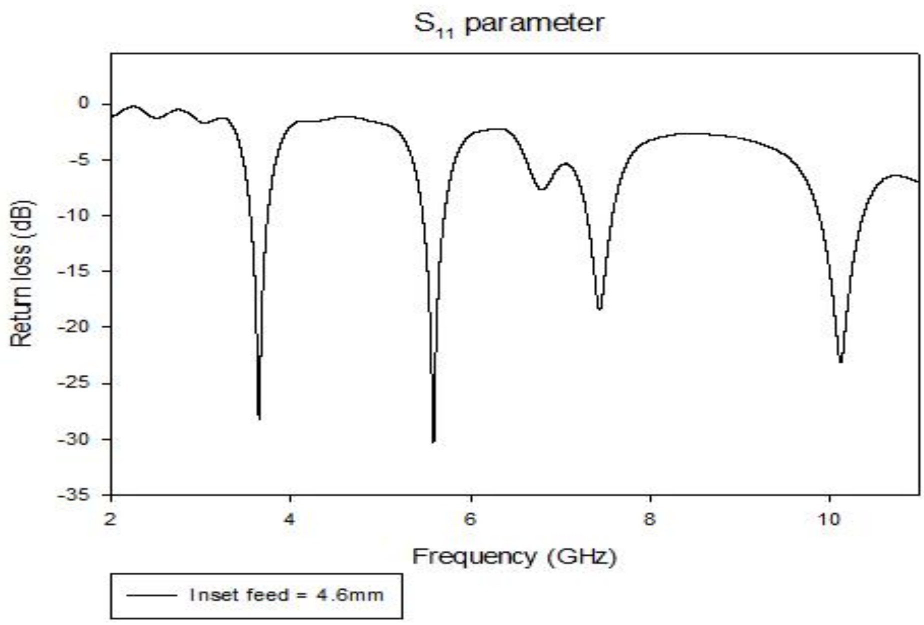


Figure 3.7: Inset feed 4.6mm length

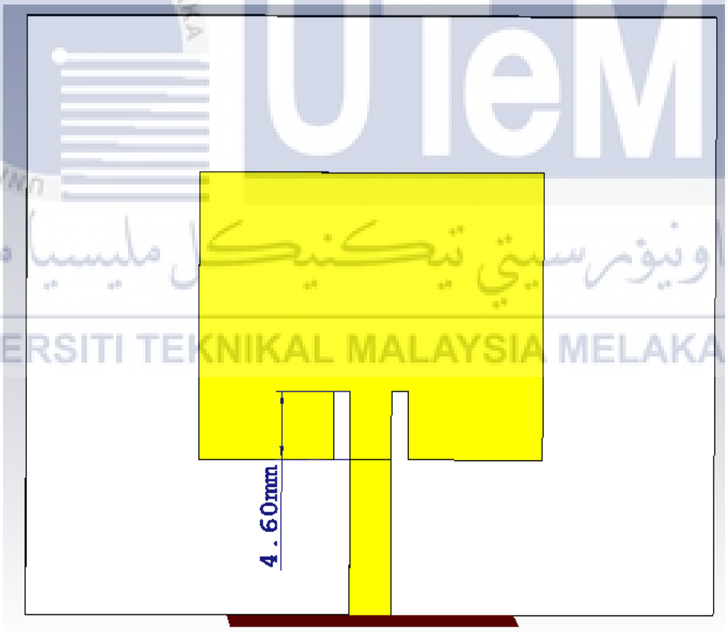


Figure 3.8: Final inset feed

3.4.3 Harmonic suppression

Harmonic suppression was done to suppress the higher modes of harmonics in the S_{11}. It is important to suppress those harmonics as it can deteriorate the performance of the antenna during transmission or receiving. Which is why DGS is proposed to suppress the higher modes of harmonics as DGS can suppress harmonics, acts like a filter, improve gain and bandwidth.

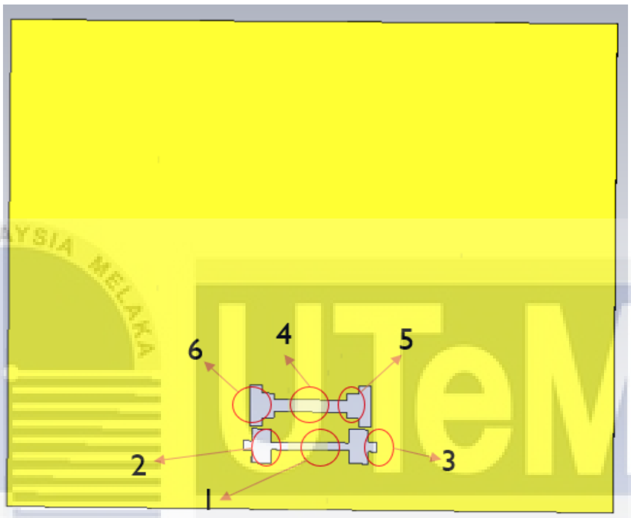


Figure 3.9: Back view of antenna

3.4.3.1 1st Slot

A slot was done to the ground plane on the back of the antenna. It was done on the same x and y-axis of the transmission line of the antenna. This is because it acts as a filter to block out the higher modes of harmonics in the S_{11} parameters. Parametric studies for the width of the slot was then done from 6.2mm to 7.0mm as shown in Figure 3.10. Then, the width of the 1st slot was chosen as 6.40mm as it yields a good S_{11} parameter. The length was chosen as 0.60mm as reducing or increasing it does not improve the S_{11} parameter. The final design of the 1st slot was then shown in Figure 3.12 and the S_{11} was shown in Figure 3.13.

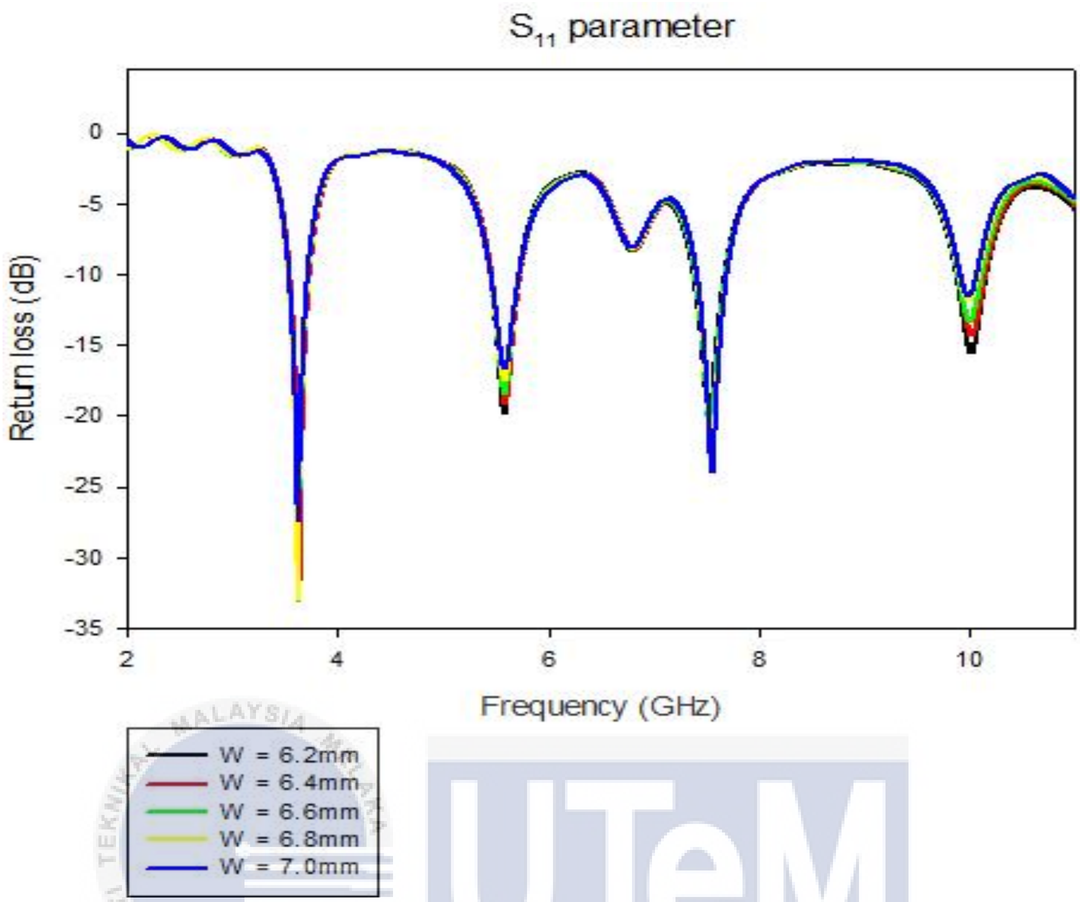


Figure 3.10: 6.2mm to 7.0mm

Table 3.4: S_{11} of DGS slot 1 width parametric study

Frequency (GHz)	Return loss (dB)				
	W=6.2mm	W=6.4mm	W=6.6mm	W= 6.8mm	W= 7.0mm
3.65	-23.49	-28.03	-22.63	-22.08	-21.07
5.59	-19.82	-19.05	-18.40	-17.47	-16.64
7.53	-20.00	-20.68	-21.21	-21.62	-21.08
10.0	-15.38	-14.10	-13.25	-11.80	-11.50

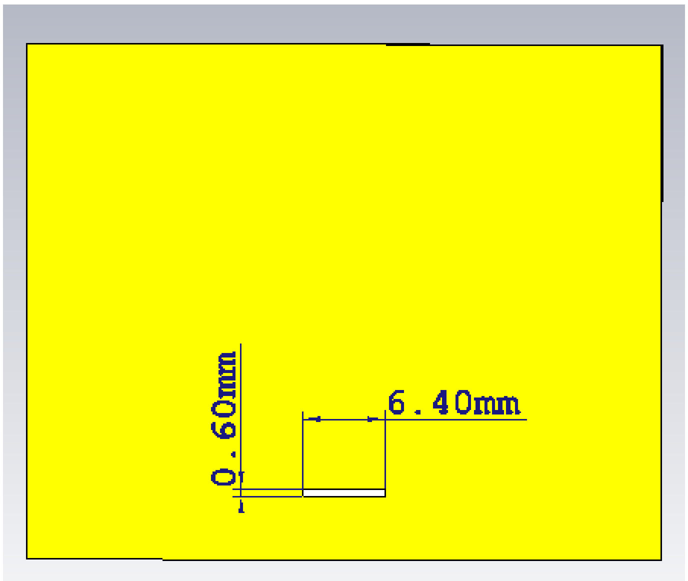


Figure 3.11: Final 1st slot

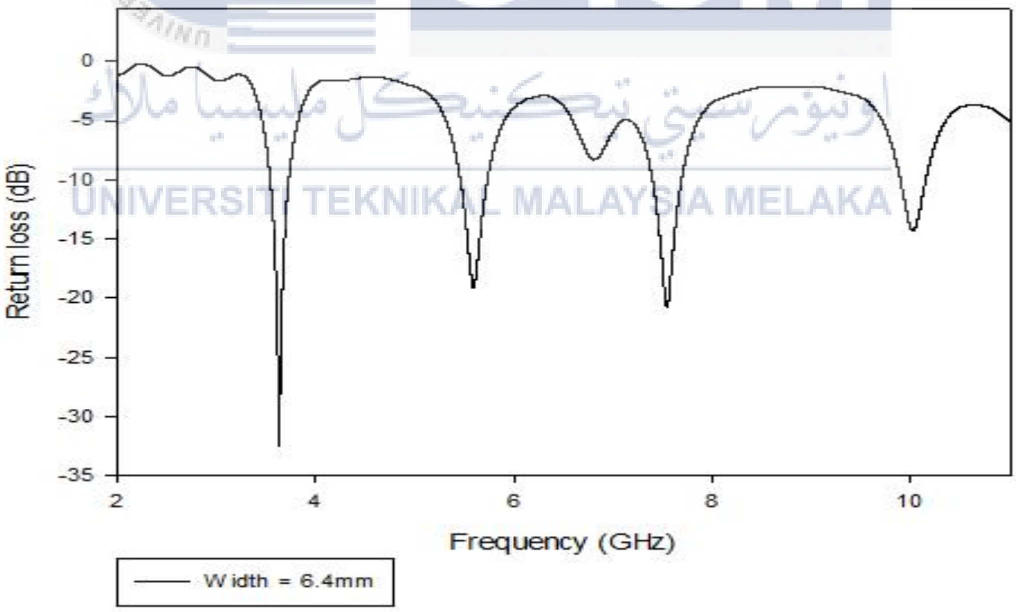


Figure 3.12: S_{11} after 1st slot

3.4.3.2 2nd slot

Then, 2nd slot was done onto the ground to make it into a dumbbell shape DGS. Parametric studies were done for the 2nd slot from 4.6mm to 2.2mm for the length as shown in Figure 3.14 where the length was chosen as 2.8mm. Then, for the width, 1.2mm to 1.6mm was tested and 1.6mm in width was chosen. The final dimensions of the 2nd slot were then shown in Figure 3.17.

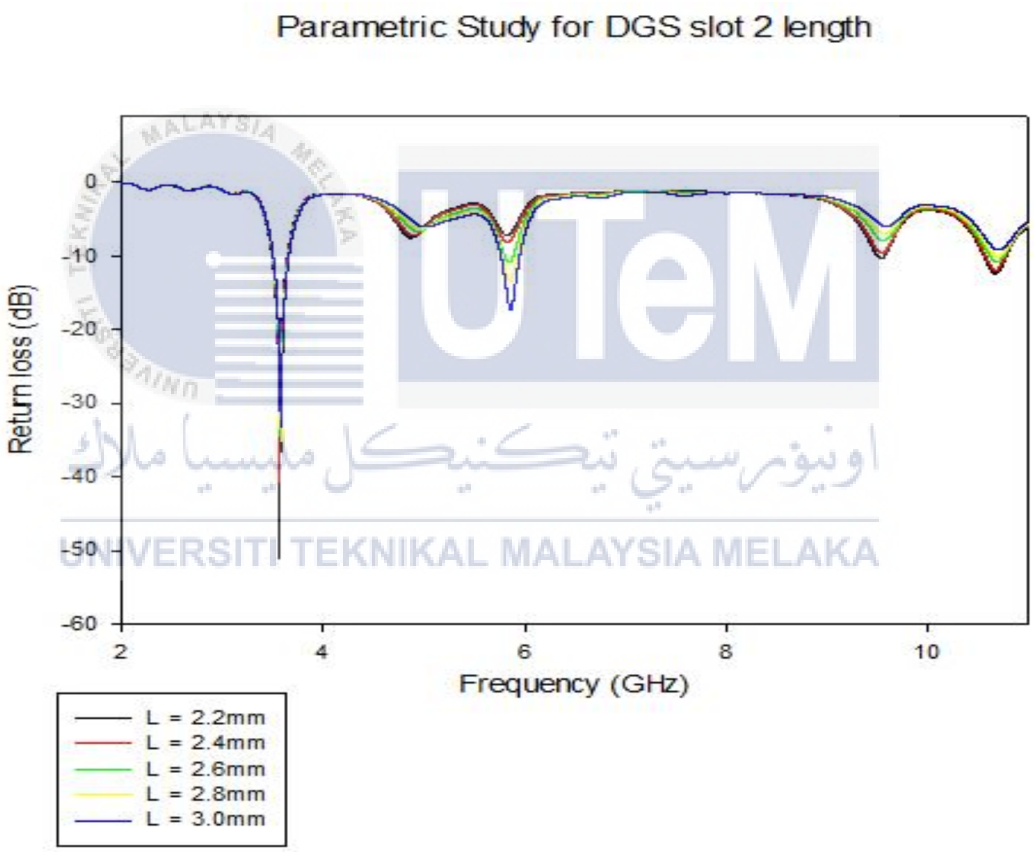


Figure 3.13: 2.2mm to 3.0mm (length)

Table 3.5: S_{11} of DGS slot 2 length parametric study

Frequency (GHz)	Return loss (dB)				
	L=2.2mm	L=2.4mm	L=2.6mm	L= 2.8mm	L= 3.0mm
3.65	-9.61	-9.98	-10.56	-10.96	-11.36
5.86	-6.93	-7.93	-10.74	-13.36	-17.21
9.53	-10.28	-9.49	-7.83	-6.77	-5.71
10.67	-12.42	-11.93	-10.79	-10.00	-9.06

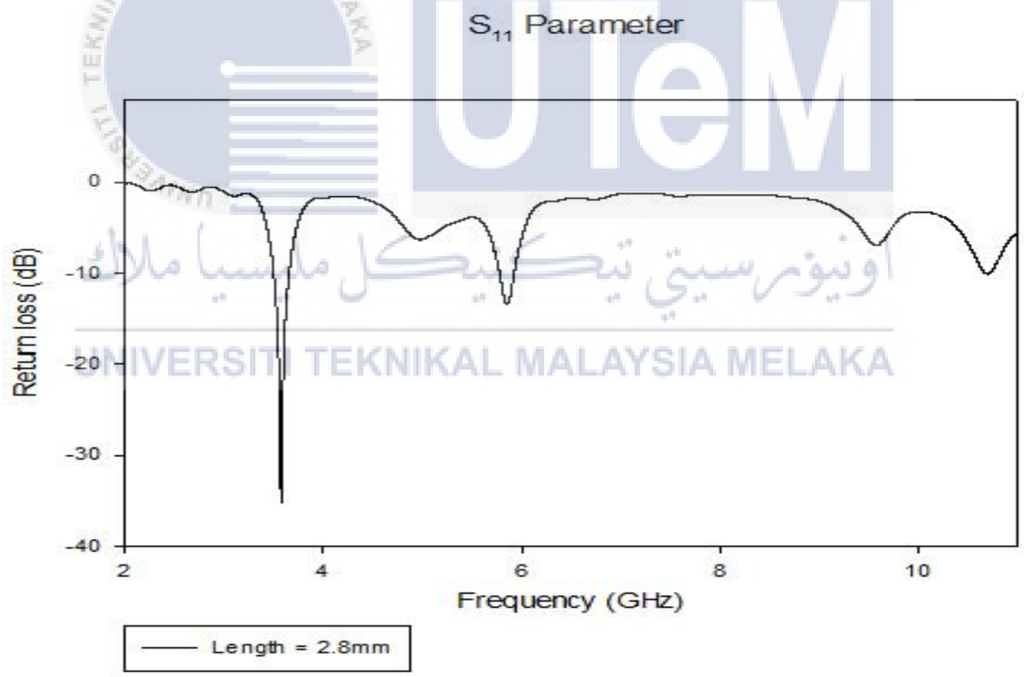


Figure 3.14: S_{11} slot for length = 2.8mm

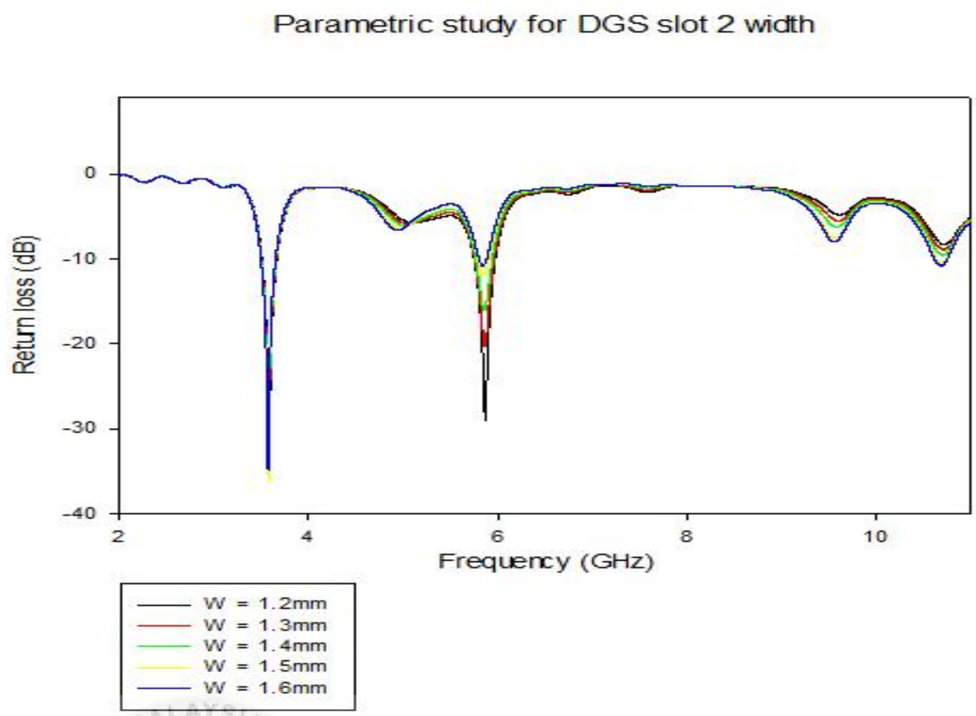


Figure 3.15: 1.2mm to 1.6mm (width)

Table 3.6: S11 of DGS slot 2 width parametric study

Frequency (GHz)	Return loss (dB)				
	W=1.2mm	W=1.3mm	W=1.4mm	W=1.5mm	W=1.6mm
3.65	-11.98	-11.62	-11.26	-10.72	-10.52
5.87	-28.97	-20.11	-15.77	-11.60	-10.44
9.3	-2.71	-3.09	-3.46	-4.09	-4.33
10.72	-8.32	-8.92	-9.51	-10.30	-10.54

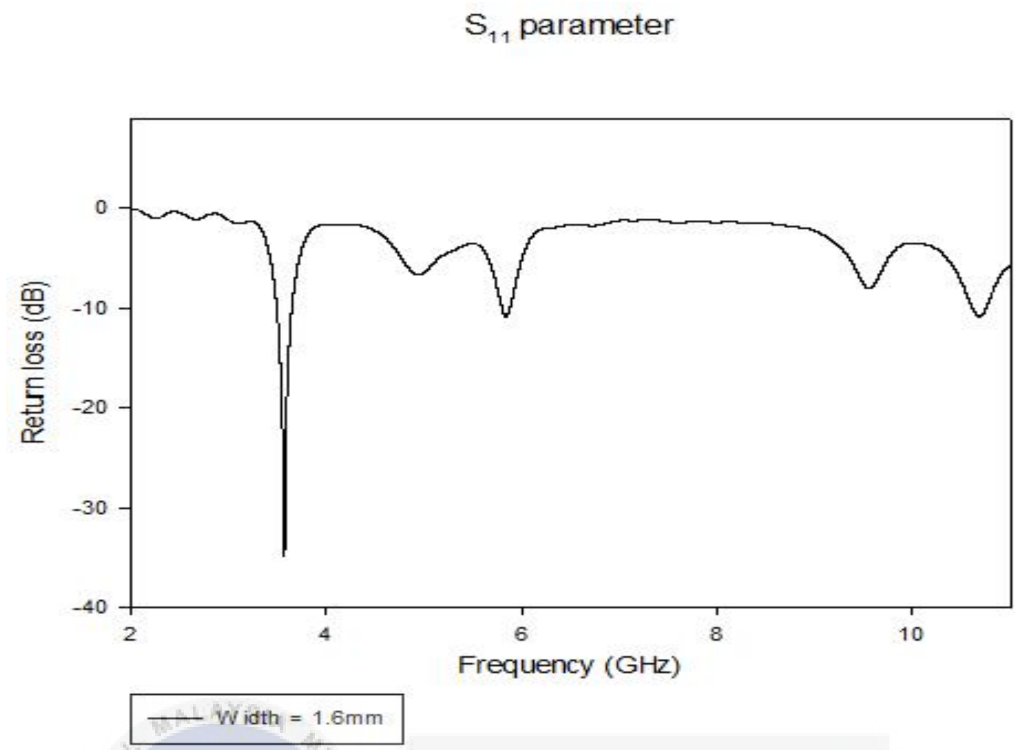


Figure 3.16: 1.6mm

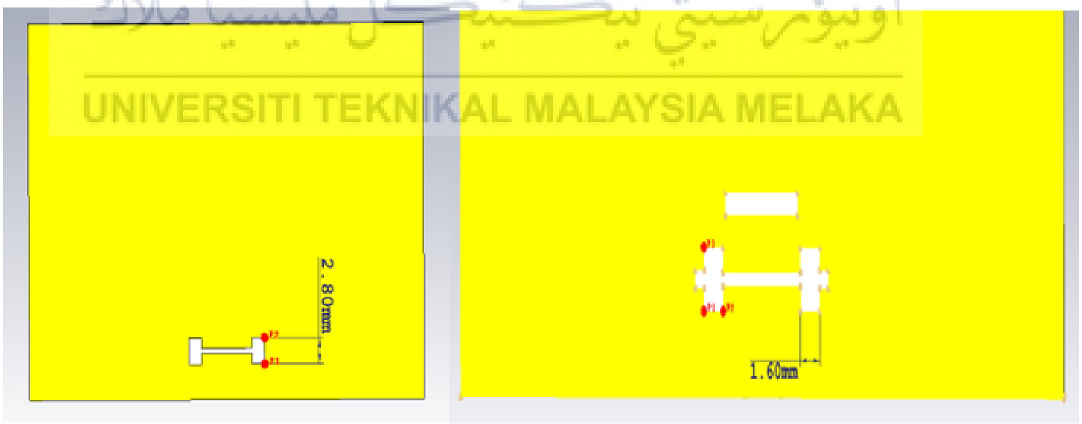


Figure 3.17: Final 2nd slot

3.4.3.3 3rd slot

As there were 2 harmonics left that were not suppressed as shown in Figure 3.18, another slot is needed to be added into the previous slot to suppress the harmonics even further. Parametric study was done from 1.4mm to 0.6mm for the length of the 3rd slot as shown in Figure 3.20 and 0.80mm of length and 0.70mm of width was chosen as the final dimensions of the 3rd slot.

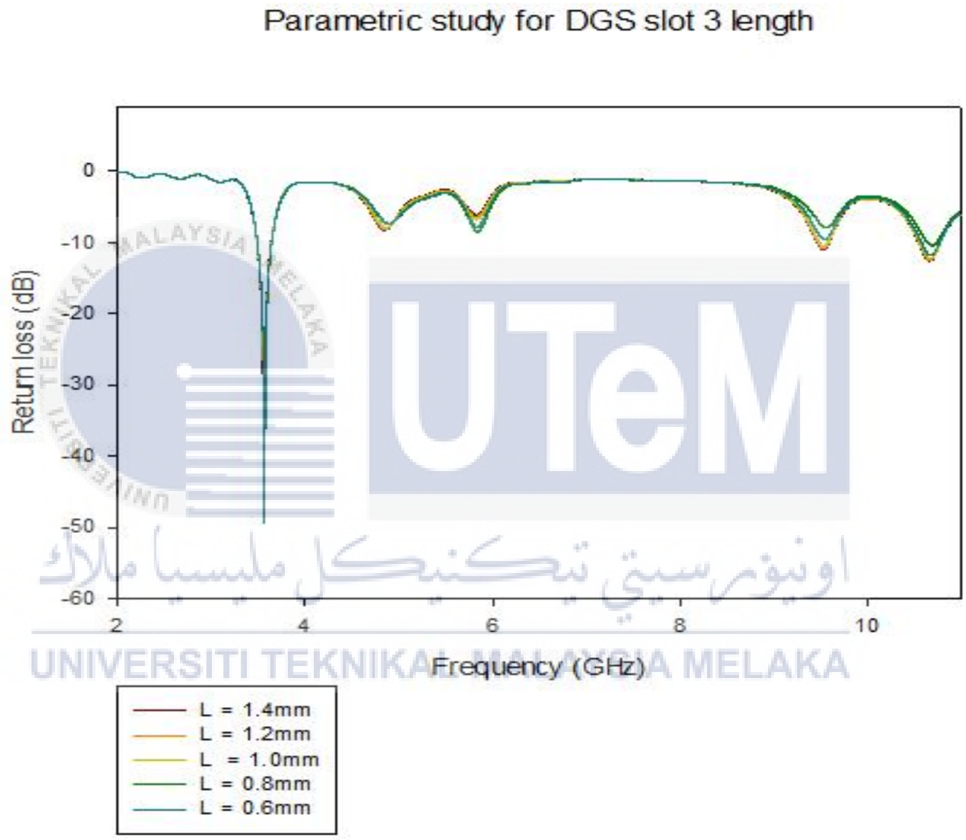


Figure 3.18: 1.4mm to 0.6mm (length)

Table 3.7: S_{11} of DGS slot 3 length parametric study

Frequency (GHz)	Return loss (dB)				
	L=1.4mm	L=1.2mm	L=1.0mm	L=0.8mm	L=0.6mm
3.65	-9.18	-9.34	-9.48	-9.69	-9.77
5.50	-2.63	-2.71	-2.78	-3.09	-2.99
9.50	-10.8	-10.6	-10.33	-7.5	-9.29
10.67	-12.53	-12.43	-12.26	-10.40	-11.79

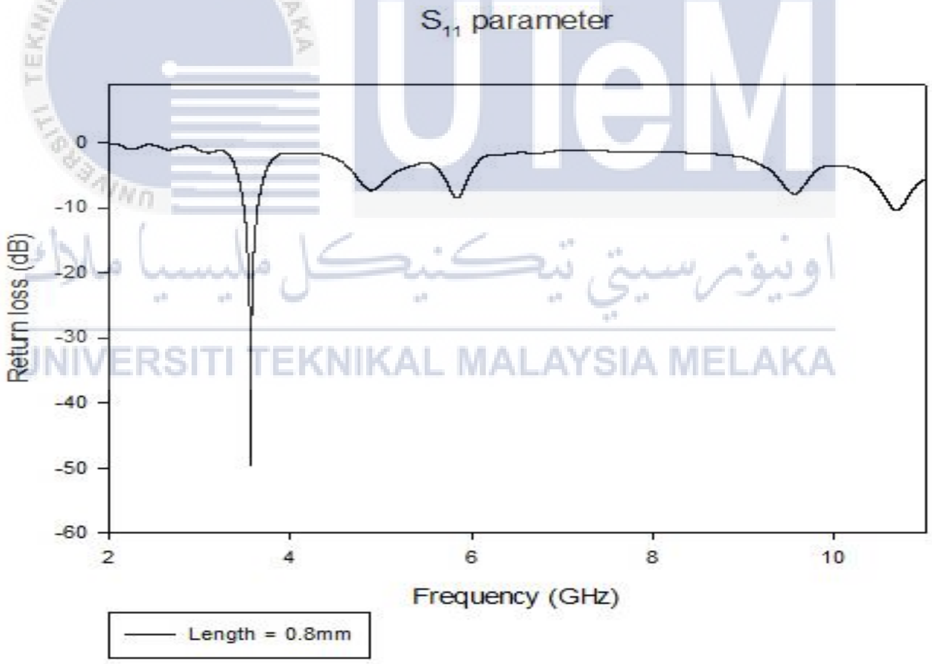


Figure 3.19: 0.8mm (length)

Table 3.8: S_{11} DGS slot 3 length = 1.08mm

Frequency (GHz)	Return loss (dB)
	L=0.8mm
3.65	-9.69
5.50	-3.09
9.50	-7.5
10.67	-10.40

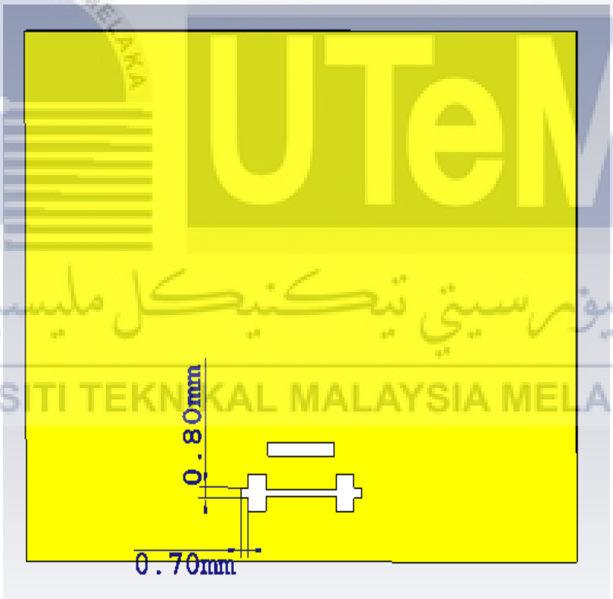


Figure 3.20: Final 3rd slot

3.4.3.4 4th slot

After doing a 3 slots DGS on the antenna, the S_{11} has only one unwanted harmonic that has not been fully suppressed below -10dB. Therefore, a 4th slot was done above the existing DGS to suppress the unwanted harmonic and to further suppress the other harmonics so that during fabrication, the harmonics would not reduce below -10dB due to precision error. The dimension of the 4th slot is 6.0mm in width and 1.0mm in length as shown in Figure 3.23 and the simulated S_{11} is shown in Figure 3.24.

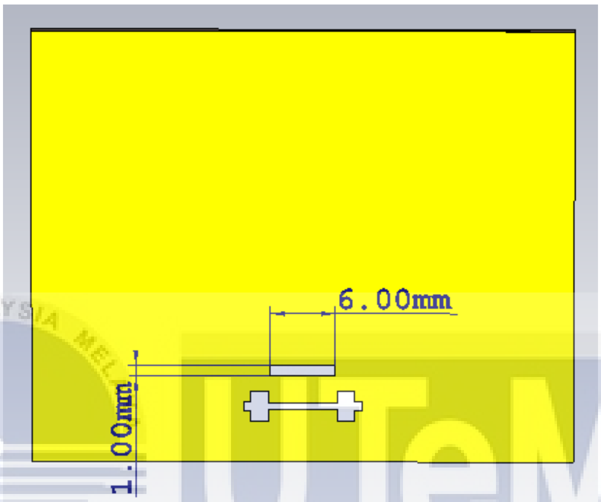


Figure 3.21: Final 4th slot

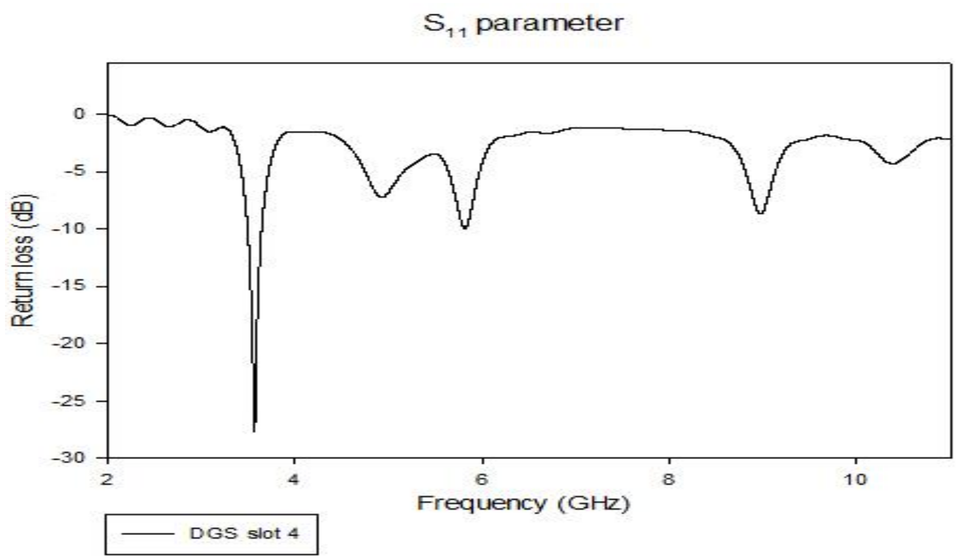


Figure 3.22: S_{11} after 4th slot

Table 3.9: S11 of DGS slot 4

Frequency (GHz)	Return loss (dB)
	DGS slot 4
3.65	-10.16
5.81	-9.94
8.96	-8.63
10.50	-3.87

3.4.3.5 5th slot

All the harmonics was suppressed as shown in Figure 3.24. However, to reduce the possibility that the harmonics will be less than -10dB during fabrication due to precision error another slot was introduced to further suppress those unwanted harmonics. The dimensions of the 5th slot are 1.0mm in width and 2.0mm in length as shown in Figure 3.25.

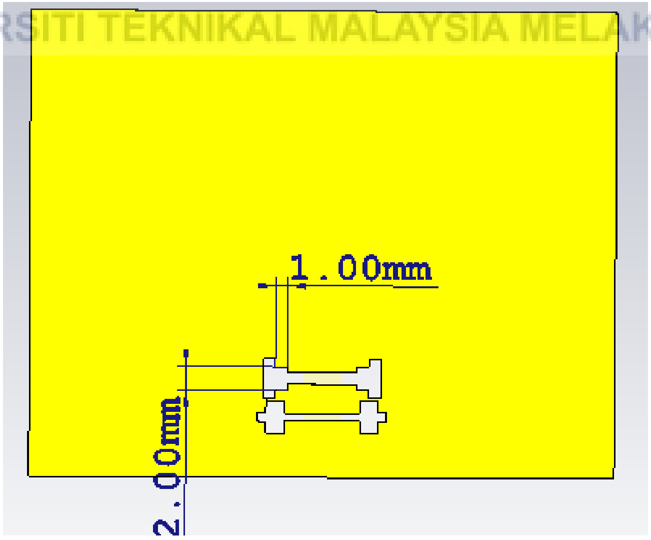


Figure 3.23: Final 5th slot

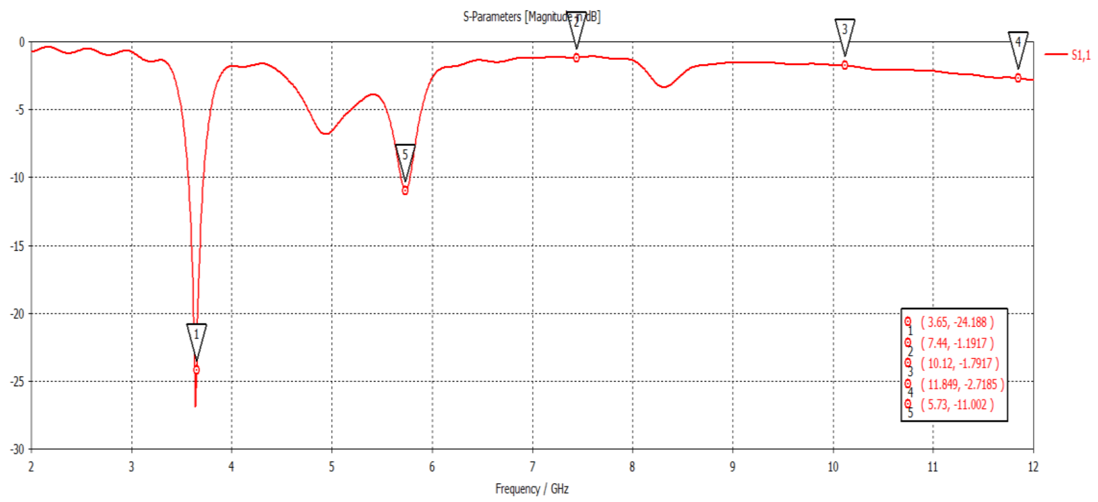


Figure 3.24: S_{11} after 5th slot

3.4.3.6 6th slot

After introducing the 5th slot as shown in Figure 3.25, the S_{11} at 7.44GHz reduces below -10dB. However, the harmonics above 7.44GHz were suppressed until below -5dB which is ideal for fabrication at a later stage. The dimensions of the 6th slot 1.0mm in width and 3.4mm in length. This slot successfully reduces the S_{11} at 7.44GHz to below -10dB. However, the resonant frequency of the current antenna is above 3.65GHz as shown in Figure 3.29. Therefore, the patch length of the antenna is reduced to 17.7mm as shown in Figure 3.28.

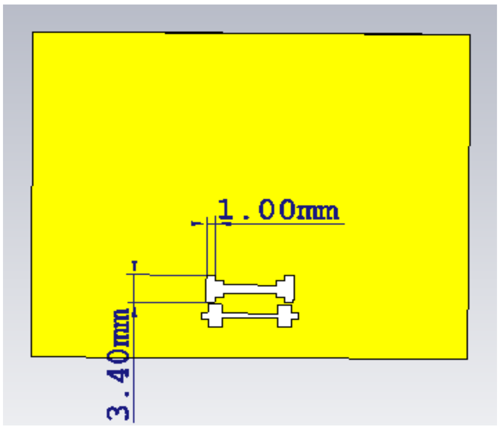


Figure 3.25: Final 6th slot

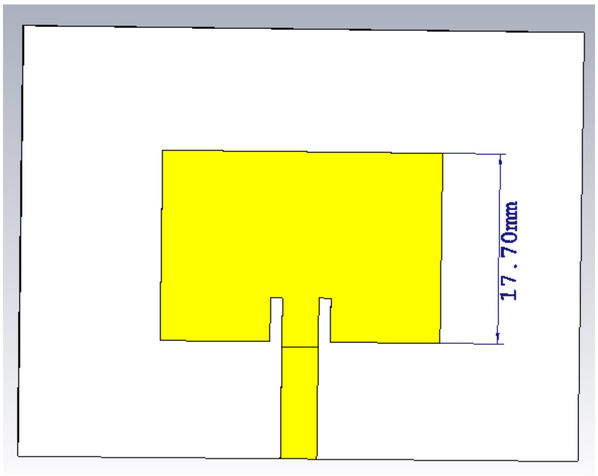


Figure 3.26: Adjusted patch length

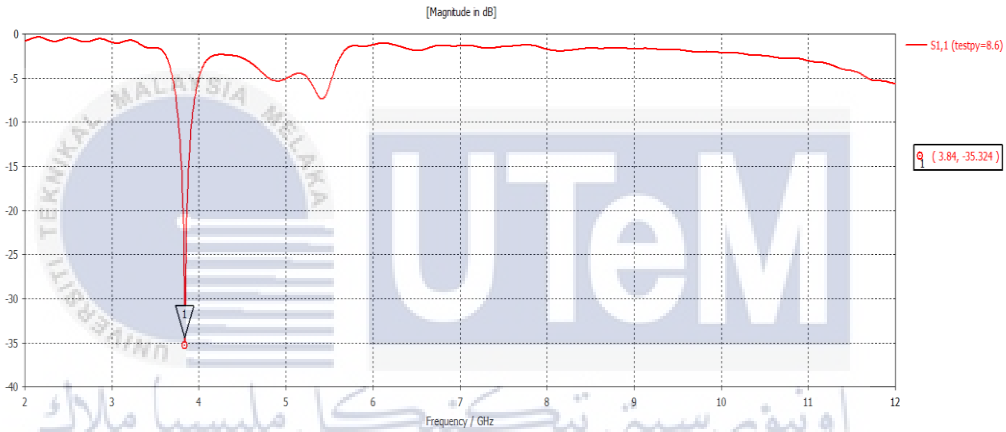


Figure 3.27: S_{11} of 6th slot

3.4.4 Reduce Patch Length

As the current S_{11} has a resonant frequency at 3.84GHz, the patch length needs to be increased to shift the resonant frequency to the left. This because the length of the patch is related to wavelength (λ) and λ has a direct relation to frequency. It can be concluded that the patch length is inversely proportional to the resonant frequency. Therefore, a parametric study was done from 0mm to 1.0mm to increase the length of the patch and thus, effectively shift the resonant frequency to the left. Then, the final length of the patch was chosen as 1.05mm as the resonant frequency is at 3.65GHz as shown in Figure 3.32.

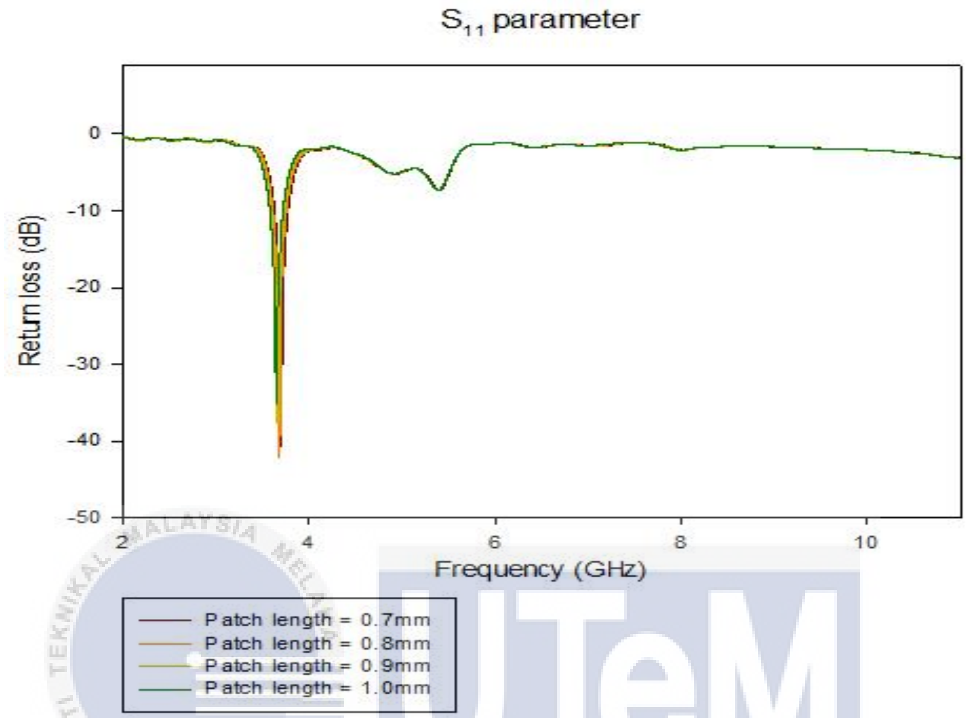


Figure 3.28: Patch length 0.7 mm to 1.0mm

Table 3.10: S_{11} of patch length parametric study

Frequency (GHz)	Return loss (dB)			
	PL=0.7mm	PL=0.8mm	PL=0.9mm	PL=1.0mm
3.65	-11.56	-14.56	-19.64	-31.14
5.50	-5.48	-5.42	-5.35	-5.30
9.30	-1.76	-1.73	-1.74	-1.74
10.5	-2.47	-2.50	-2.49	-2.52

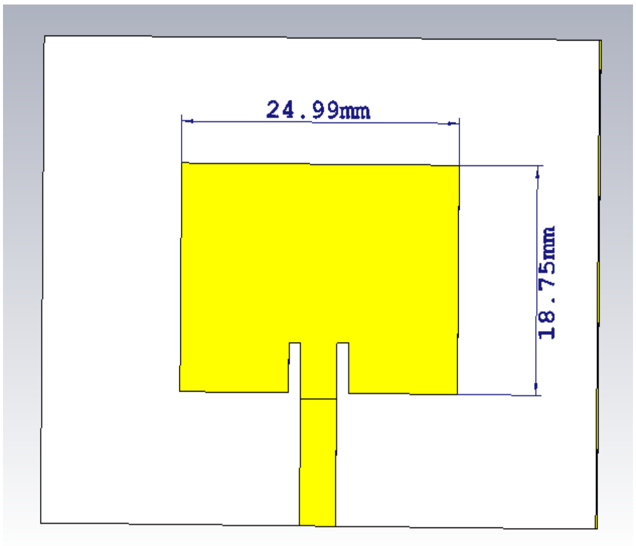


Figure 3.29: Patch

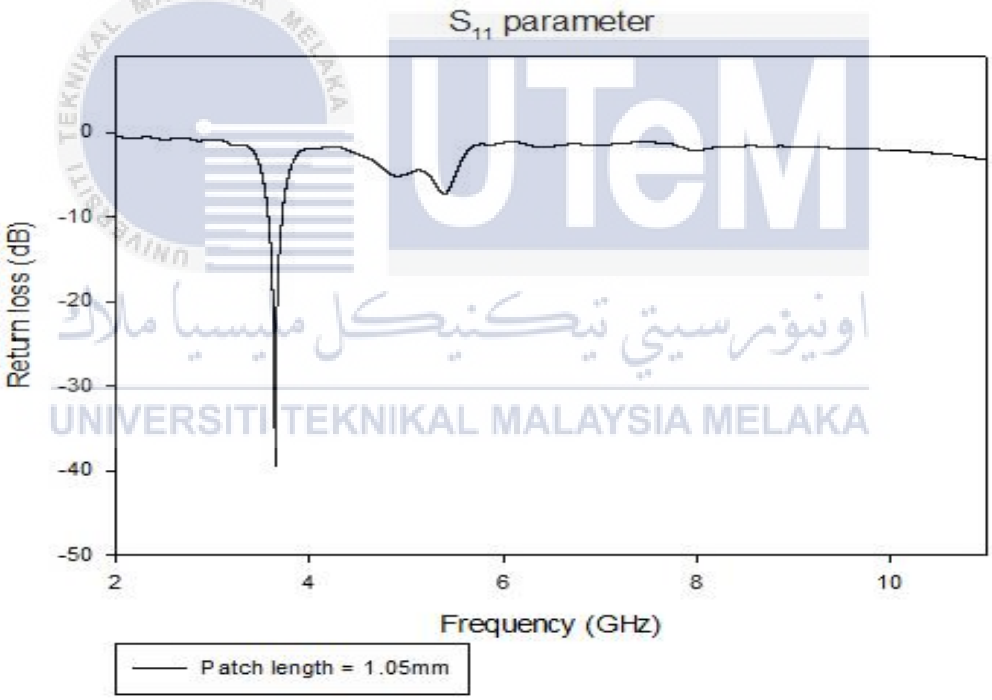


Figure 3.30: S_{11} of two dumbbell DGS and patch length reduce by 1.05mm

Table 3.11: S_{11} of patch length = 1.05mm

Frequency (GHz)	Return loss (dB)
	PL=1.05mm
3.65	-39.45
5.50	-5.28
9.30	-1.77
10.50	-2.52

3.4.5 Circular Polarization

Circular polarization is essential in mobile communication antenna as it ensures that the antenna can transmits signal in all the plane instead of just in a single direction. To determine whether the antenna is a CP antenna, the axial ratio is measured. If the value of the axial ratio at 3.65GHz is less than 3, the antenna is a CP antenna. To make the patch antenna radiate CP, several orthogonal slots were done onto the patch antenna. For the first step, two corners of dimension 1.90mm x 3.35mm from the patch were truncated as shown in Figure 3.33. This lowers the original axial ratio from 40 to 33.54 as shown in Figure 3.35. Then, a cross slot was done on the middle of the patch using two rectangular slots of dimension 7mm x 0.9mm and 0.9mm x 7mm each respectively as shown in Figure 3.34. This lowers the axial ratio from 33.54 to 2.2202 as shown in Figure 3.35, fulfilling the value of axial ratio below 3, making it a CP antenna. Then the S_{11} of this final design is then showed in Figure 3.36 with the S_{11} of the resonant frequency, 3.65GHz being -39.54dB.

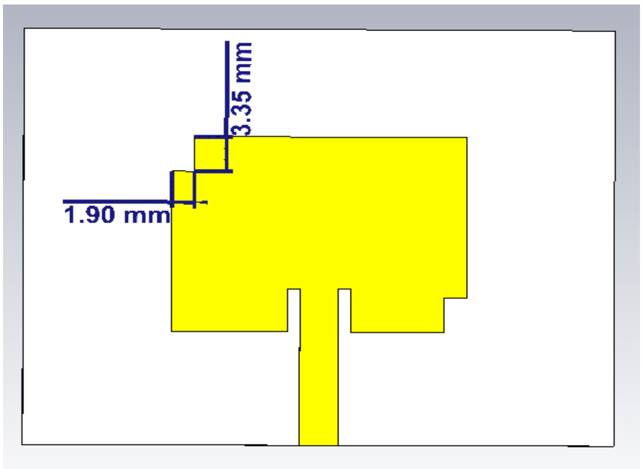


Figure 3.31: Truncated corners

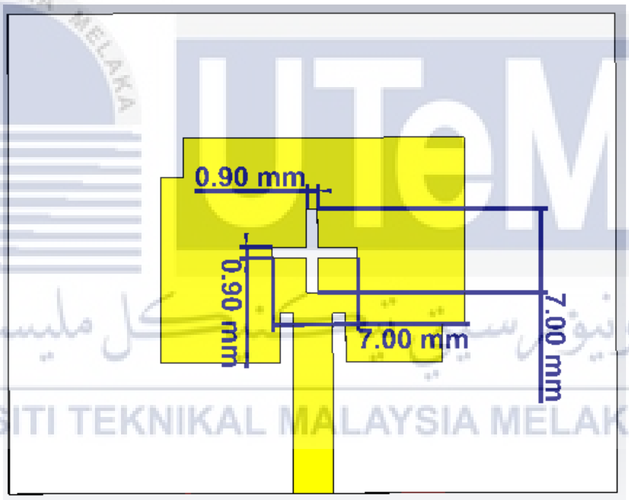


Figure 3.32: Cross slot

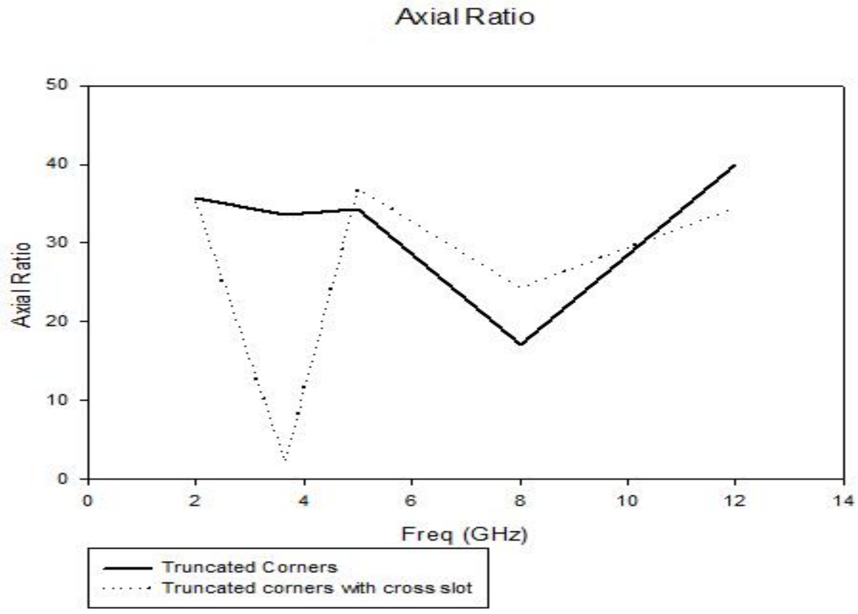


Figure 3.33: Axial ratio

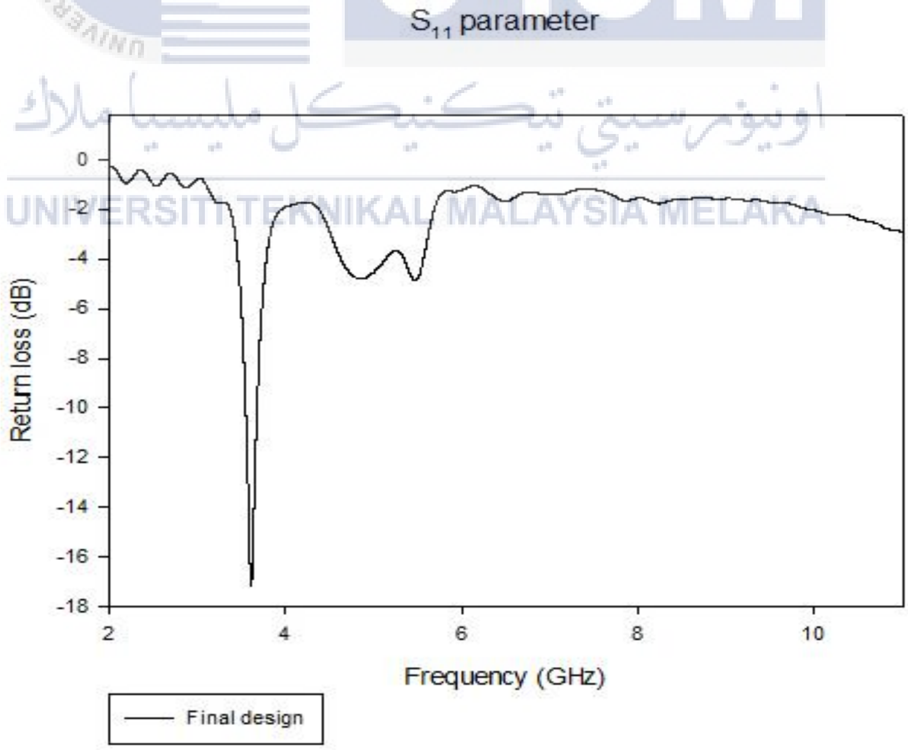


Figure 3.34: S_{11} of final design

3.4.6 Fabrication of antenna

After the antenna was designed using CST, the a .dxf file of that design was then exported using CST software. Then the .dxf file is then edited using Corel Draw software and printed out onto a glossy paper. Photo lithographic technique was then used to imprint the design layout onto the FR-4 substrate. Then, the imprinted FR-4 substrate undergoes etching process to remove the unwanted part of the substrate.

After the antenna was fabricated, SMA port was soldered onto the transmission line of the patch antenna. Then, it is connected to the VNA to measure the S_{11} parameter and horn antenna at one meter distance was used to measure the gain of the fabricated antenna.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, it will discuss the results that was done according to the methodology done in Chapter 3. The results obtained, which are the gain, axial ratio, polarization and S_{11} parameters are discussed in this chapter.

4.2 Results of the simulated antenna

The antenna shown in Figure 4.1 is the preliminary design that has suppressed the higher order of harmonics. Two dumbbells shaped DGS were used to act as a filter and suppress the higher order harmonics. The result of the corresponding S_{11} parameter is then shown in Figure 4.2 where the resonant frequency is at 3.65GHz with return loss of -14.02dB. The dimensions used for the DGS on the ground plane is then summarized in Table 4.1, dimensions used for CP is summarized dimensions of the substrate, patch and ground summarized in Table 4.3.

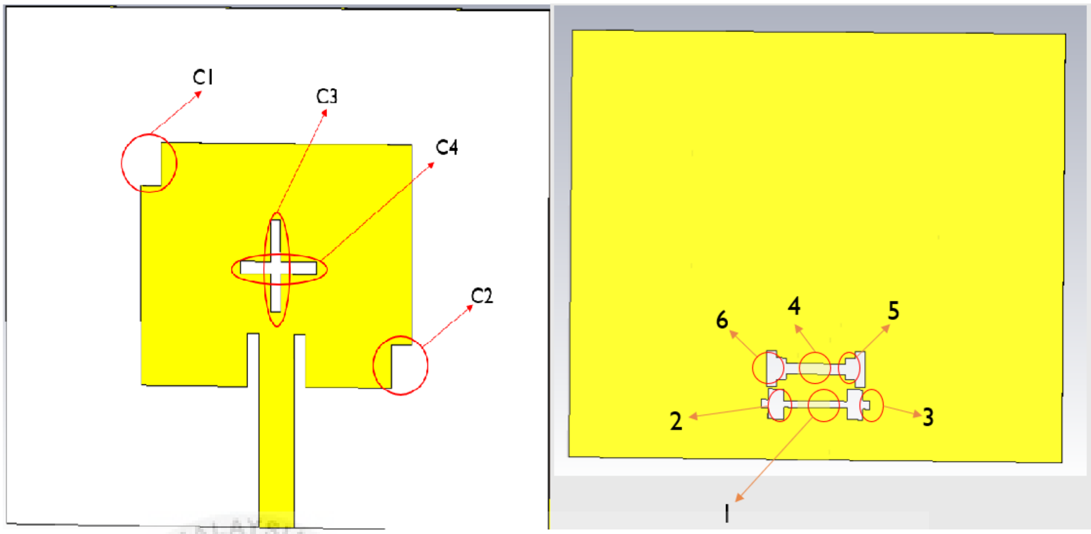


Figure 4.1: Patch antenna (a) Front (b) Back

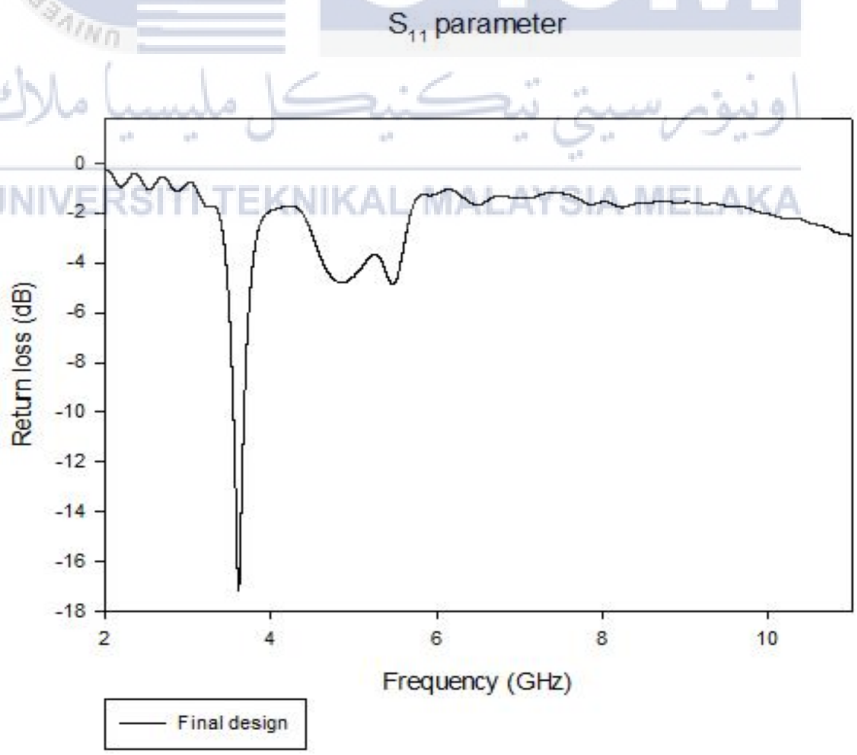


Figure 4.2: Simulated S_{11} of designed antenna

Table 4.1: Dimensions of DGS

DGS slots	Length (mm)	Height (mm)
1	0.6	6.4
2	2.8	1.6
3	0.8	0.7
4	1.0	6.0
5	2.0	1.0
6	1.0	3.4

Table 4.2: Dimensions for CP slots

CP slots	Length (mm)	Height (mm)
C1	1.9	3.35
C2	1.9	3.35
C3	0.9	7.00
C4	0.9	7.00

Table 4.3: Dimensions of patch, substrate and ground

Antenna parts	Length (mm)	Width (mm)
Patch	24.99	18.75
Substrate	50.00	40.00
Ground	50.00	40.00

To make this antenna a CP antenna, four CP slots has been done onto the front patch of the antenna as shown in Figure 4.1(a). These four slots were done to lower down the axial ratio at 3.65GHz to below 3. As shown in Figure 4.3 below, the truncated corners and cross slots has reduced the value of the axial ratio to 2.22 which fulfills the requirement for a CP antenna.

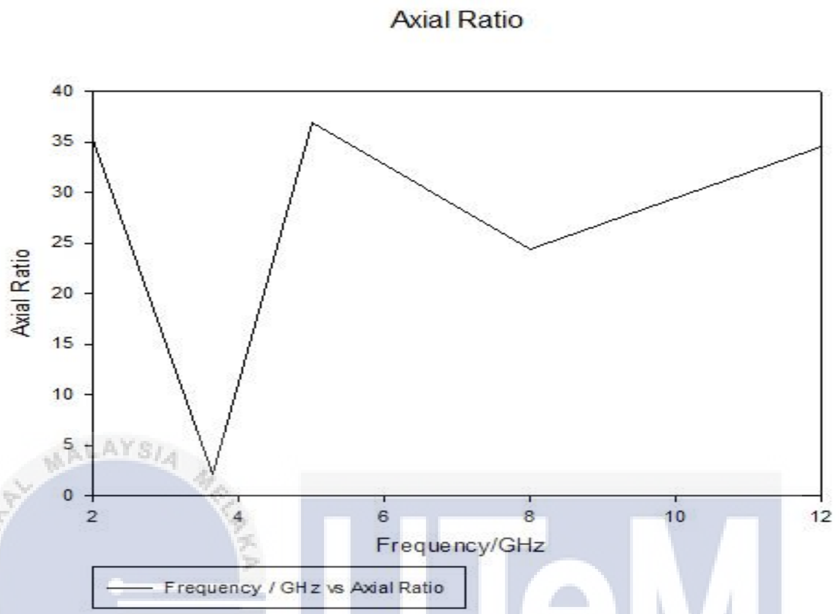


Figure 4.3: Axial Ratio

The gain of the antenna, which describes the whole efficiency of the antenna is simulated using the farfield monitor in CST. The gain obtained through simulation is 2.348dB with radiation efficiency of -4.185dB (38%), a total efficiency of -4.361dB (36.6%) and directivity of 6.709dBi as shown in Figure 4.3. These parameters were then summarized in Table 4.4 below. Figure 4.4 to 4.6 then shows the radiation pattern at phi = 0°, 90° and theta = 90°. The radiation pattern indicates that the designed antenna is a CP antenna.

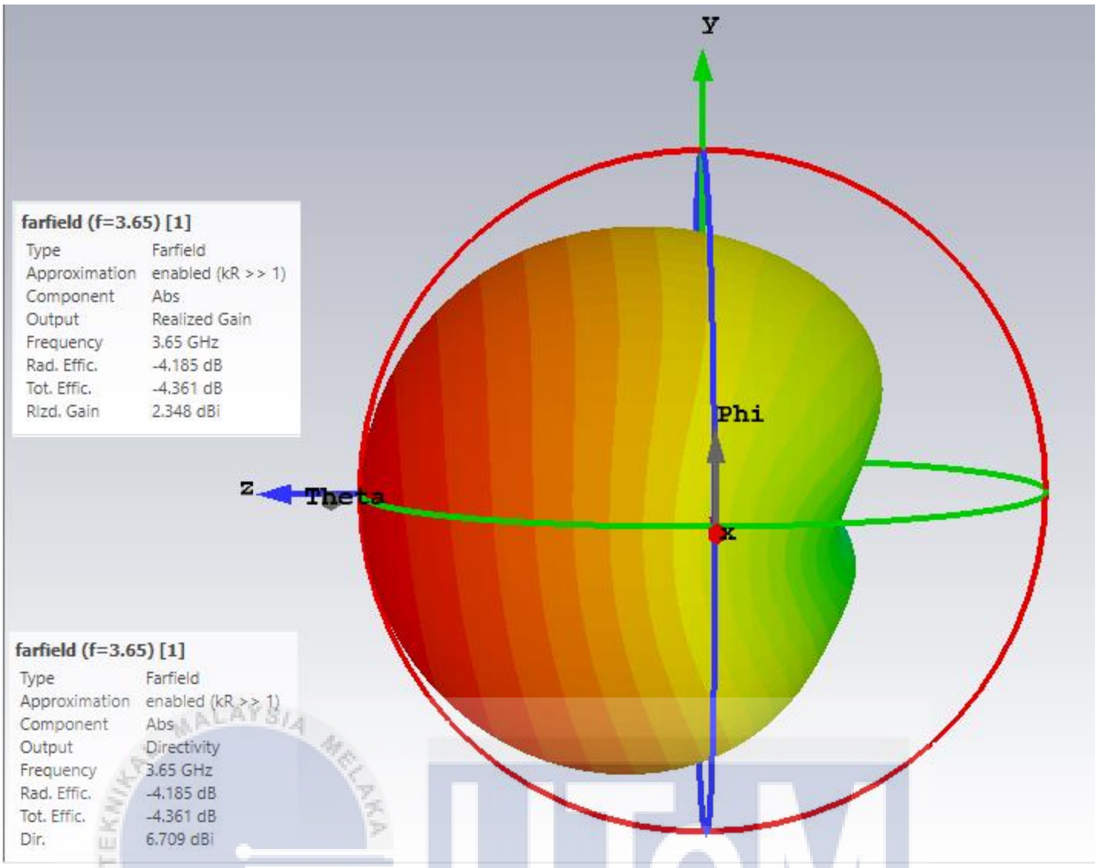


Figure 4.4: Farfield monitor of antenna

Table 4.4: Summary of simulated parameters

Freq/GHz	S_{11}/dB	Gain/dB	Directivity/dBi	Radiation efficiency/%	Total efficiency/%
3.65	-14.02	2.348	6.709	38	36.6

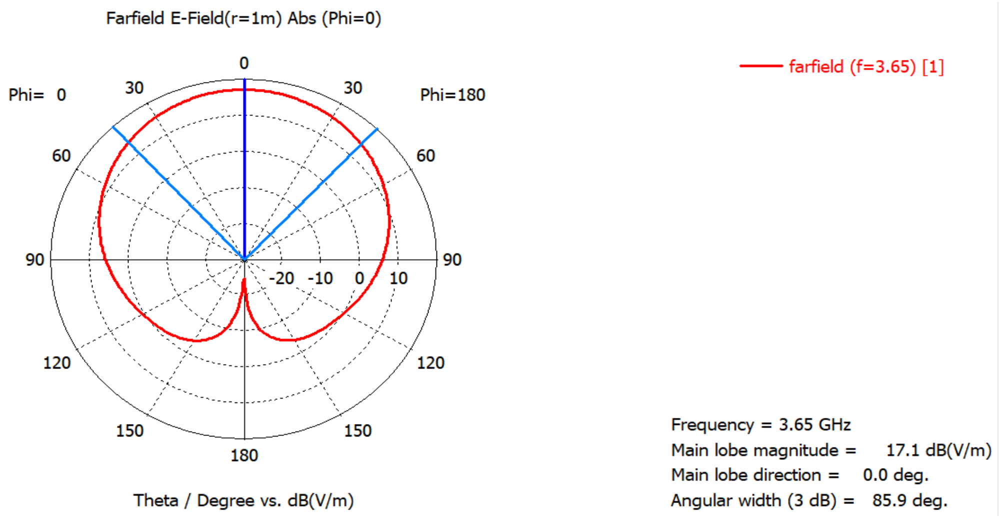


Figure 4.5: Phi = 0°

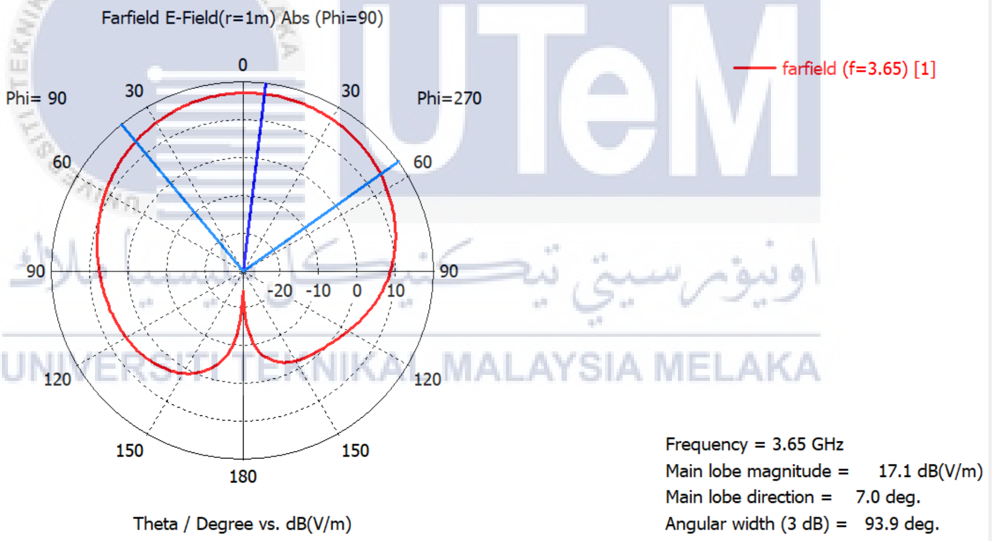


Figure 4.6: Phi = 90°

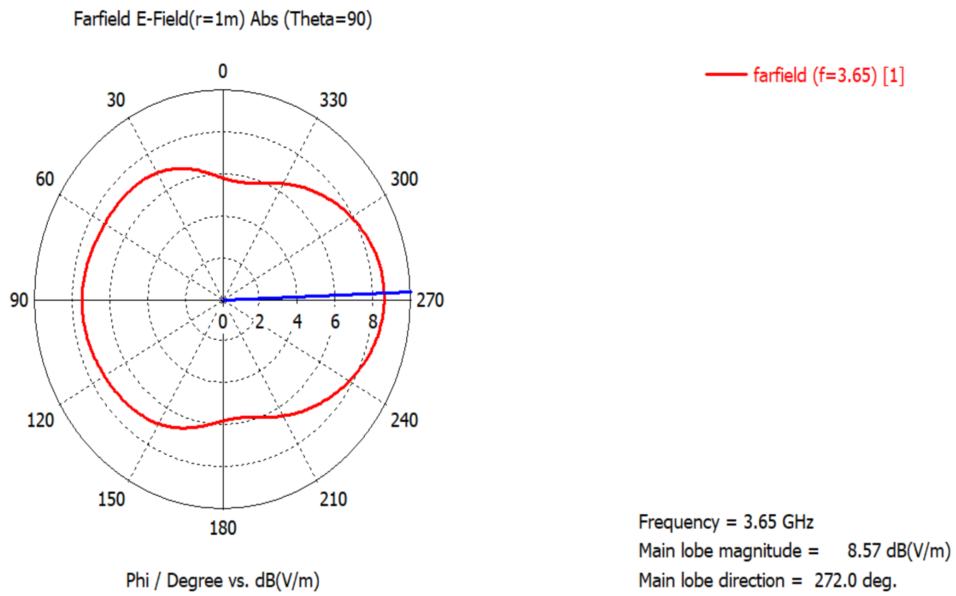
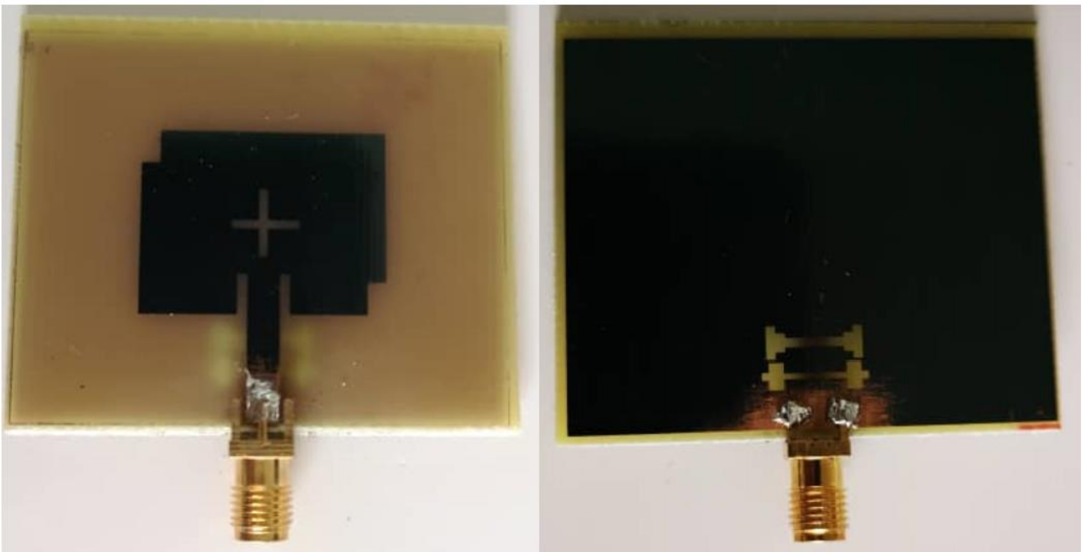


Figure 4.7: Theta = 90°

4.3 Measurement results of the antenna

When the simulation results of the antenna were confirmed to be of satisfactory, the design was exported from the CST to be fabricated using FR-4 substrate as shown in Figure 4.7. The antenna was then connected to VNA to measure the S_{11} parameter of the microstrip patch antenna as shown in Figure 4.8 where at 3.65GHz, it has return loss of -11.759dB. Then, the microstrip patch antenna was set up as shown in Figure 4.9 to measure the gain. By taking into account of parameters such as power transmitted, power received, distance between the antenna, cable loss and gain transmitted, the gain of the antenna was calculated as 1.932dB. The measured parameters of the fabricated antenna were then summarized into Table 4.5 as shown below. Then the comparison between simulated S_{11} and measured S_{11} is then shown in Figure 4.11 where the difference between the two S_{11} at 3.65GHz is -2.26dB. The comparison between the parameters of the simulation and the measurement is then shown in Table 4.6 below.



a) Front b) Back

Figure 4.8: Fabricated microstrip patch antenna

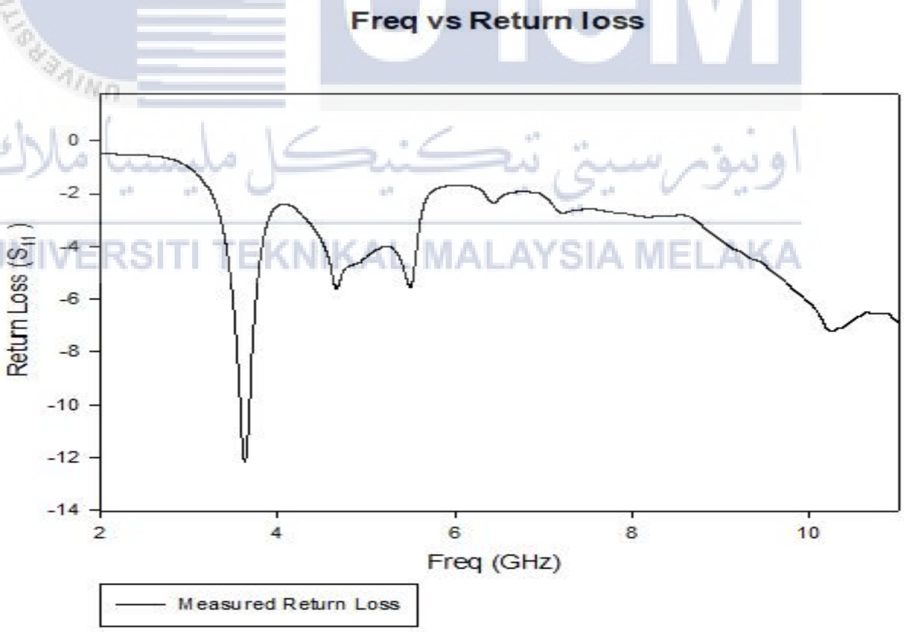


Figure 4.9: Measured S_{11} parameter

Figure 4.10: Gain measurement

Table 4.5: Summary of measured parameters

Freq/GHz	**S_{11}/dB**	**Gain/dB**
3.65	-11.759	1.932

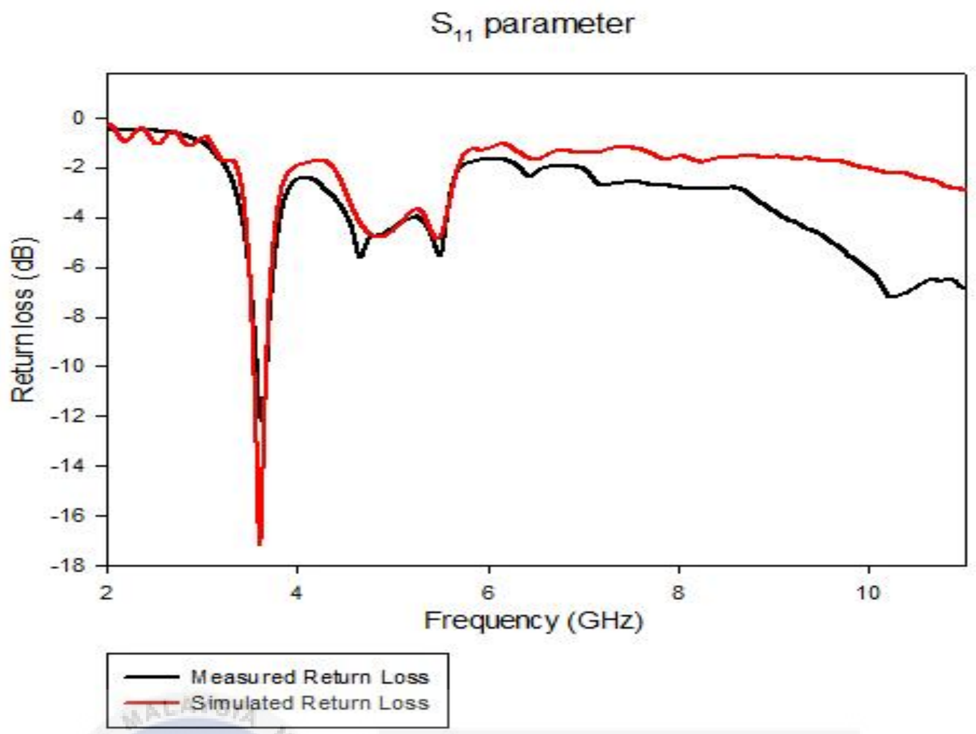


Figure 4.11: Comparison of S_{11} between simulation and measured

Table 4.6: Comparison between parameters of measurements and simulations

Types of results	Freq/GHz	S_{11}/dB	Gain/dB
Simulation	3.65	-14.02	2.348
Measurement	3.65	-11.759	1.932

4.4 Discussion

Based on the comparison between the S_{11} parameter from the simulation and measurement results in Figure 4.11, the results closely resemble each other except at the resonant frequency where the S_{11} parameter degrades in measurement results. The design of the antenna also produces low efficiency (36.6%) for measured result. This is due to the usage of FR4 substrate instead of other substrate such as RT-duroid materials which is harder to obtain readily as compared to FR4 substrate. For the radiation pattern of the simulated antenna, overall, it indicated that the antenna is a CP antenna as the radiation pattern shows an omnidirectional pattern. Next, the simulated antenna shows a better performance as compared to the fabricated antenna in terms of return loss and gain. Moreover, with its light weight and compact size, if the gain and efficiency were to be improved, it can be a possible design for 5G applications.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

The 5G technology has become the solution that many people seek these days. This is due to the limitations that brought about by the 4G technology where there was higher latency as compared to 5G, low data transfer rate and problem of traffic network. To achieve a 5G mobile communication, one of the important components is antenna. Therefore, when designing the antenna for 5G mobile communication, many aspects needs to be considered such the mobile frequency band allocated for 5G mobile communication, the polarization, and the return loss. To achieve the important objectives of the design, DGS technique was used as a filter to filter the unwanted higher order harmonics and truncated corners with cross slot was also used to make the antenna a CP antenna. Although due to MCO that was announced on 18th of March 2020, there were some measurements that could not be taken from the fabricated antenna such as the radiation pattern due to the anechoic chamber under maintenance during that period. However, the gain and S_{11} were managed to be measured before the MCO starts.

5.2 Suggestions for Future Work

Based on the conclusions and results drawn, several suggestions can be done to improve the performance of the antenna that was proposed such as:

- Increasing the gain of the antenna for different applications. In this work, the design was mainly focused on the S_{11} of the antenna and making it CP antenna. So, the design can be adjusted to increase the gain.
- In this work, the antenna was designed using a microstrip transmission line. There are other types of feed techniques such as coaxial probe, proximity coupled feed and aperture coupled feed where different feed line techniques can provide better bandwidth and reduce unwanted harmonics.
- This work focuses on resonant frequency at 3.65GHz for 5G mobile communications. In the future, the antenna can be designed to work in the millimeter wave spectrum (24.25GHz – 52.6GHz) where it can be used for short range wireless network in the industrial applications.

REFERENCES

[1] M. Daga, (2018), "*5G Is Coming: An Overview of the Advantages and Challenges*". Retrieved from https://dzone.com/articles/5g-is-coming-an-overview-of-the-advantages-amp-cha

[2] Malaysian Communications and Multimedia Commission (MCMC). (2019). "*National 5G Task Force Findings and Recommendations to the Government*", Page 4 and 21.

[3] GSMA Intelligence, (2019). "*Global 5G Landscape Q1 2019*". Retrieved from https://www.gsmaintelligence.com/research/2019/04/global-5G-landscape-Q1-2019/753/.

[4] Sharma, N., Jain, B., Singla, P., & Prasad, R. R. (2014). RECTANGULAR PATCH MICRO STRIP ANTENNA: A SURVEY. *International Advanced Research Journal in Science, Engineering and Technology*, *1*. Retrieved from www.iarjset.com

[5] M.K. Khandelwal, B.K. Kanaujia, and S. Kumar, "*Defected Ground Structure: Fundamentals, Analysis, and Applications in Modern Wireless Trends*", International Journal of Antennas and Propagation, vol. 2017, Article ID 2018527, 22 pages, 2017.

[6] J.B. Jabhav, P.J. Deore, (2016). "*Filtering Antenna with Radiation and Filtering Functions for Wireless Applications*", Journal of Electrical Systems and Information Technology, Volume 4, Issue 1, May 2017, Page 125 – 134.

[7] Visser, H. (n.d.). *Chapter 1: Introduction - Antenna Theory and Applications*. Retrieved from https://learning.oreilly.com/library/view/antenna-theory-and/9781119990253/9781119990253c01.xhtml

[8] Balanis, C. A. (2012). Antenna technology: Past, present and future. *2012 IEEE International Workshop on Antenna Technology, IWAT 2012*, 5–7. https://doi.org/10.1109/IWAT.2012.6178384

[9] Peixeiro, C. (2011). Microstrip patch antennas: An historical perspective of the development. *SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference Proceedings*, *2013*(Cac2s), 684–688. https://doi.org/10.1109/IMOC.2011.6169224

[10] Ramirez, L. A. R., & Santos, J. C. A. (2017). Design, Simulation, and Optimization of an Irregularly Shaped Microstrip Patch Antenna for Air-to-Ground Communications. *International Journal of Antennas and Propagation, 2017*. https://doi.org/10.1155/2017/5156263

[11] M.I. Memon and Prof. A. Paliwal, (2013). Microstrip Patch Antenna Design Calculator, International Journal of Engineering Research & Technology (IJERT), Volume 2, Issue 9, September 2013.

[12] Sharma, S., Vikas Thakare, V., & Student, M.-T. (2016). Resonant Frequency Analysis of Circular Microstrip Patch Antenna Design with U-Slot Using Artificial Neural Networks. In *International Journal of Science, Engineering and Technology Research (IJSETR)* (Vol. 5).

[13] Bisht, S., Saini, S., Prakash, V., & Nautiyal, B. (2008). International Journal of Emerging Technology and Advanced Engineering Study The Various Feeding Techniques of Microstrip Antenna Using Design and Simulation Using CST Microwave Studio. In *Certified Journal* (Vol. 9001). Retrieved from www.ijetae.com

[14] Arameters, A. N. P. (2015). *Microstrip Patch Antenna Parameters, Feeding Techniques and Shape of the Patch - A Survey*. *6*(4), 981–984

[15] Balanis, C. A. (2005). *Antenna Theory* (Third Edit). John Wiley & Sons.

[16] Zainol, N., Zakaria, Z., Abu, M., Jawad, M. S., & Yunus, M. M. (2015). *A Review Of Antenna Designs With Harmonic Suppression For Wireless Power Transfer*. *10*(11). Retrieved from www.arpnjournals.com

[17] Khandelwal, M. K., Kanaujia, B. K., & Kumar, S. (2017). Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends. *International Journal of Antennas and Propagation*, Vol. 2017. https://doi.org/10.1155/2017/2018527

[18] Sabran, M. I., Rahim S. K. A., Rahman, T. A., Eteng, A. A., Yamada, Y. (2014). U-Shaped Harmonic Rejection Filtenna for Compact Rectenna Application. Proceedings of Asia-Pacific Microwave Conference 2014.

[19] Rahim, R. A., Malek, F., Hassan, S. I. S., & Junita, M. N. (2012). A 2.45 GHz circular patch antenna with harmonic suppression for wireless power transmission. *CHUSER 2012 - 2012 IEEE Colloquium on Humanities, Science and Engineering Research*, 283–287. https://doi.org/10.1109/CHUSER.2012.6504325

[20] Elftouh, H., Amar, N. T., McHbal, A., Zakriti, A., & Elbakkali, M. (2019). Suppression of Harmonic of Microstrip Patch Antenna Using Defected Ground and Defected Microstrip Structure. *Procedia Manufacturing*, *32*, 653–660. https://doi.org/10.1016/j.promfg.2019.02.267

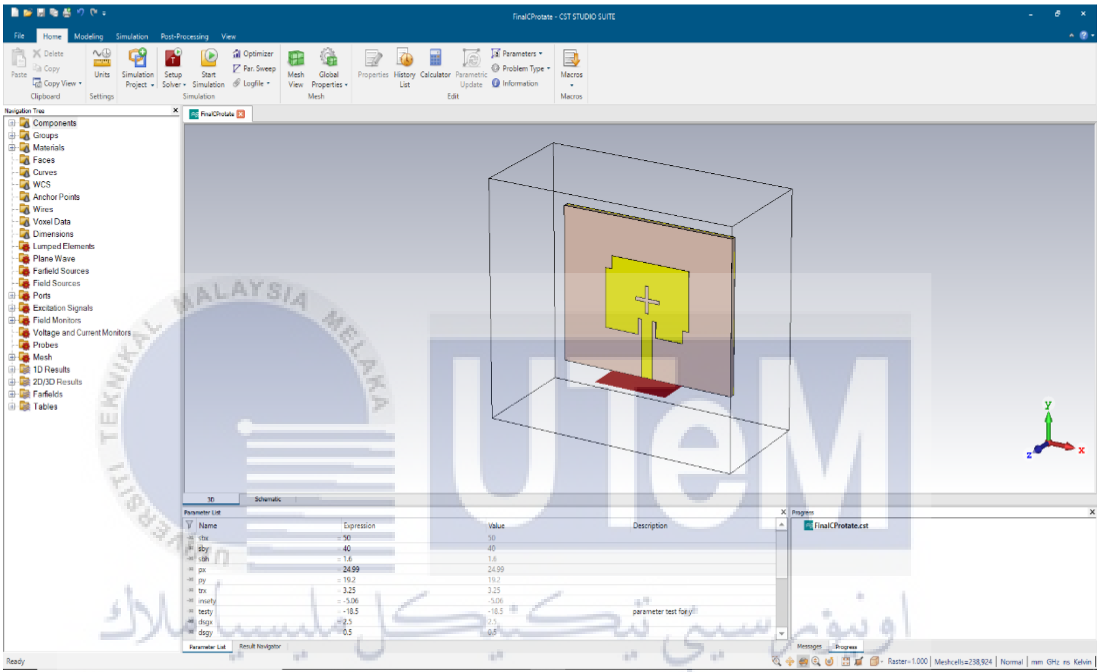
[21] Chopra, R., & Kumar, G. (2017). Compact dumbbell shaped microstrip antenna with suppressed harmonics. *Progress in Electromagnetics Research Symposium*, *2017-November*,2838–2843. https://doi.org/10.1109/PIERS-FALL.2017.8293618

[22] Verma, S., Mahajan, L., Kumar, R., Saini, H. S., & Kumar, N. (2016). A small microstrip patch antenna for future 5G applications. *2016 5th International Conference on Reliability, Infocom Technologies and Optimization, ICRITO 2016: Trends and Future Directions*, 460–463. https://doi.org/10.1109/ICRITO.2016.7784999

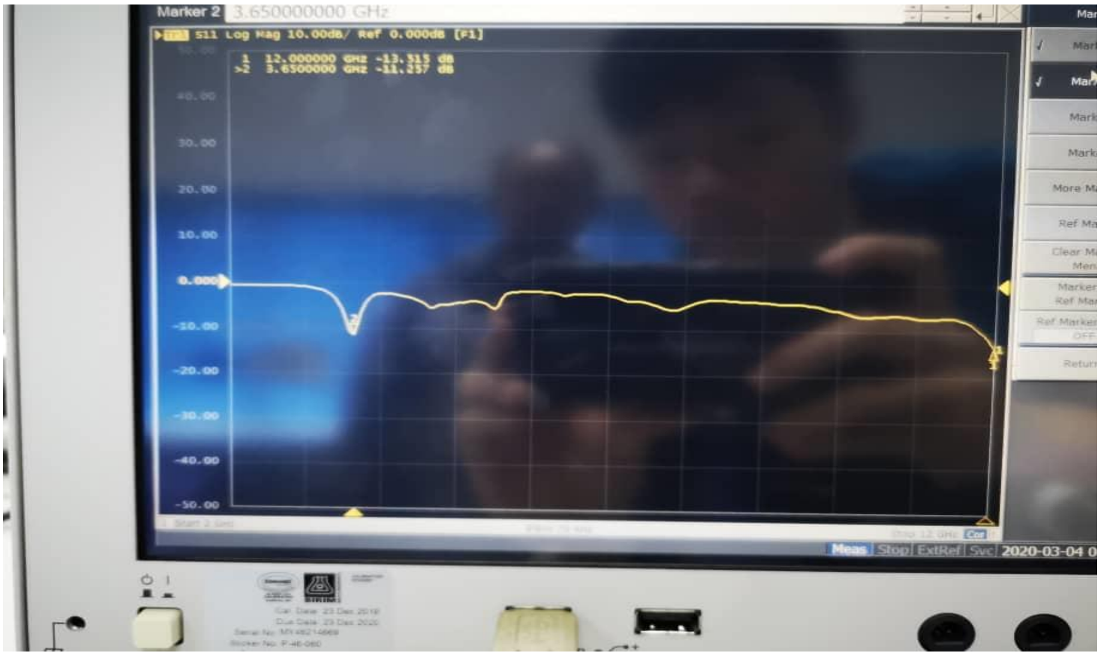
[23] Zainol, N., Zakaria, Z., Abu, M., & Yunus, M. M. (2016). Harmonic suppression rectangular patch antenna with circularly polarized. *Telkomnika (Telecommunication Computing Electronics and Control)*, *14*(2), 471–477. https://doi.org/10.12928/telkomnika.v14i2.2394

[24] J. Singh, "International Journal of Computer Science and Mobile Computing Inset Feed Microstrip Patch Antenna," 2016.

APPENDICES



Appendix A: Design of antenna using CST software



Appendix B: S_{11} parameter of fabricated antenna