DESIGN AND ANALYSIS OF DUAL-BAND MICROSTRIP ANTENNA USING DUAL SLOT-LOADING TECHNIQUE AT WI-FI FREQUENCIES

MUHAMMAD IRFAN BIN ROSMI

B.ENG (HONS.) ELECTRICAL ENGINEERING (ELECTRONICS)

UNIVERSITI MALAYSIA PAHANG
2022

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : MUHAMMAD IRFAN BIN ROSMI
Date of Birth : 02/04/1997
Title : DESIGN AND ANALYSIS OF DUAL-BAND MICROSTRIP ANTENNA USING DUAL SLOT LOADING TECHNIQUE AT WIFI FREQUENCIES
Academic Session : 2021/2022/Semester II

I declare that this thesis is classified as:

☐ CONFIDENTIAL (Contains confidential information under the Official Secret Act 1997) *
☐ RESTRICTED (Contains restricted information as specified by the organization where research was done) *
☑ OPEN ACCESS I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang
2. The Library of Universiti Malaysia Pahang has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

(Student's Signature)

970402-08-5877
New IC/Passport Number
Date: 25 JUNE 2022

(Supervisor's Signature)

Madam Nurulfadzilah Binti Hasan
Name of Supervisor
Date: 25 JUNE 2022

NOTE : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach a thesis declaration letter.

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and, in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Engineering in Electrical and Electronics Engineering.

____

(Supervisor's Signature)

Full Name : MADAM NURULFADZILAH BINTI HASAN
Position : Supervisor
Date : 25 JUNE 2022

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at University Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : MUHAMMAD IRFAN BIN ROSMI

ID Number : EA18026

Date : 25 JUNE 2022

DESIGN AND ANALYSIS OF DUAL-BAND MICROSTRIP ANTENNA USING DUAL SLOT-LOADING TECHNIQUE AT WIFI FREQUENCIES

MUHAMMAD IRFAN BIN ROSMI

Thesis submitted in fulfillment of the requirements
for the award of the
B.Eng (Hons.) Electrical Engineering (Electronics)

Faculty of Electrical & Electronics Engineering

UNIVERSITI MALAYSIA PAHANG

JUNE 2022

ACKNOWLEDGEMENTS

All praise be to Allah SWT, the only one who is the most merciful for providing the strength to complete this thesis. I would like to give this token of appreciation to Universiti Malaysia Pahang (UMP) for financial support for this project.

I would like to express my deep and sincere gratitude to my supervisor, Madam NurulFadzilah Binti Hasan, for allowing me to conduct this project and providing invaluable guidance. Her dynamism, vision, sincerity, and motivation have deeply inspired me. She has taught me the methodology to carry out the research and present the research works as clearly as possible. Working and studying under his guidance was a great privilege and honour. I am incredibly grateful for what she has offered me. I would also like to thank her for her empathy, patience, and great sense of humour during the discussion I had with her on research work and thesis preparation.

A special thanks go to beloved family and friends for the constant moral support and motivation. Their motivation keeps me going and brings the outs the potential in me to give my all for this project.

Lastly, I would like to express my heartfelt gratitude to anyone who contributed to the process of succeeding in this project. I hope that all the research done on putting this project into words will of a great use and will bring about a great inspiration.

ABSTRAK

Kesan pemuatan dua slot pada frekuensi resonan antenna tampalan jalur mikro telah disiasat dalam kertas ini. Antena jalur mikro dwijalur pada frekuensi wi-fi (2.4GHz dan 5GHz) telah direka bentuk menggunakan perisian CST Studio Suite untuk mendapatkan hasil analisis. Antena jalur mikro telah dibina menggunakan tampalan segi empat tepat, dan dua jalur frekuensi diperoleh dengan menambah sepasang slot selari pada tampalan segi empat tepat. Antena jalur mikro yang direka bentuk kemudiannya di bina dan diuji untuk mengukur prestasinya dan dibandingkan dengan hasil simulasi daripada perisian CST. Keputusan pengukuran dan simulasi S_{11} menunjukkan bahawa antena yang direka bentuk bergema pada 2.4GHz dan 5GHz. VSWR untuk antena ialah 1.0635 untuk 2.4GHz dan 1.5051 untuk 5GHz. Akhir sekali, perolehan antenna ialah 1.370dBi untuk 2.4GHz dan 0.6669dBi. Berdasarkan dapatan kajian, dapat disimpulkan bahawa antena ini boleh digunakan pada masa hadapan.

ABSTRACT

The effect of dual slot-loading on rectangular microstrip antenna resonant frequencies has been investigated in this thesis. The dual-band microstrip antenna at wi-fi frequencies (2.4GHz and 5GHz) was designed using CST Studio Suite to obtain the result of the analysis. The microstrip antenna was constructed using the rectangular patch, and two frequency bands were obtained by adding a pair of parallel slots on the rectangular patch. The designed microstrip antenna is then fabricated and tested to measure its performance and compared to the simulation results from CST software. S_{11} measurement and simulation results show that the designed antenna resonates at 2.4GHz and 5GHz. The VSWR for the antenna is 1.0635 for 2.4GHz and 1.5051 for 5GHz. Finally, the gain of the antenna is 1.370dBi for 2.4GHz and 0.6669dBi. Based on the findings, it can be concluded that this antenna can be used in the future.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

VSWR	Voltage Standing with Ratio
eff	Efficiency
VNA	Vector Network Analyzer

CHAPTER 1

INTRODUCTION

1.1 Project background

A microstrip antenna (also known as a printed antenna) is a type of antenna that is produced on a printed circuit board using photolithographic processes (PCB). It functions as an internal antenna(Lee & Luk, 2017). Microwave frequencies are where they are most commonly employed. An individual microstrip antenna comprises a patch of metal foil in various forms (a patch antenna) on the surface of a PCB (printed circuit board) and a metal foil ground plane on the opposite side. Most microstrip antennas are made up of numerous patches arranged in a two-dimensional array. Foil microstrip transmission lines link the antenna to the transmitter or receiver. A radio frequency current is delivered between the antenna and the ground plane (or, in receiving antennas, a received signal is created). Because of its lightweight, low cost of manufacture, tiny size, high gain, and high directivity gain, microstrip patch antennas are in high demand. Aside from linear polarisation, it also has circular polarisation. Satellites, spacecraft, airplanes, and wireless applications such as WLAN, WiMAX, and Wi-Fi can benefit from these antennas.

With its basic 2-dimensional physical form, microstrip antennas are relatively inexpensive to build and design. The antenna size is proportional to the wavelength at the resonant frequency, they are commonly used at UHF and higher frequencies. The highest directional gain of a single patch antenna is roughly 6–9 dBi. Printing an array of patches on a single (significant) substrate using lithographic processes is pretty simple. Patch arrays can produce significantly more gains at a lower cost than a single patch; matching and phase correction can be done via printed microstrip feed structures, which can be done in the same procedures as the radiating patches. Patch arrays are used aboard airplanes and in other military applications because they generate high-strength arrays in a low-profile antenna. However, this antenna has flaws, including a narrow bandwidth and poor gain. As a result, this antenna is designed to achieve a broad bandwidth.

1.2 Problem Statement

Microstrip antenna is been used by many companies in communication system because of the advantage from it. Advancement in wireless industry, demand for antenna that support high data transmission rise exponentially. Advanced wireless communication technology also requires robust, fast and uninterrupted internet connection. Other than that, a dual band antenna is also imperative to aim for the miniaturized antenna(*Why Do We Use Dual Band Antenna Instead of Two Single Band Antennas..??*, n.d.). To overcome the problems, Dual-Band Microstrip Antenna using dual slot loading technique at Wi-Fi frequencies is proposed. The antenna will operate at 2.4GHz and 5GHz. The ability of dual band antennas to offer a powerful, steady wireless connection in sometimes tough to reach regions is their greatest feature. They are frequently employed in cellular or dual band wireless access points because of this.

1.3 Objective

There are two main objectives in this research, which are:

- To investigate the effect of dual slot loading to rectangular microstrip antenna resonant frequencies.
- To design and fabricate dual band rectangular microstrip antenna and measure its performance.

1.4 Scope of project

Listed below are the scope and limitations of this research:

- Design the proposed antenna by using CST Studio Suite.
- Fabricate the proposed antenna. The antenna will be fabricated on an FR-4 PCB Board Single Sided that act as a substrate, and using copper as the conductor or patch.
- Testing and measurement of the fabricated antenna using Agilent Vector Network Analyzer.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Microstrip Patch Antenna

The patch antenna concept surfaced in the early 1950s, but due to its intrinsic restricted bandwidth, there was little activity for over two decades. It first caught the attention of antenna designers in the 1970s when they realized the benefits of this type of antenna, which included low profile, conformability to a curved surface, ease of production, and compatibility with integrated circuit technology. Over the last three decades, extensive research has been done to improve bandwidth and other performance parameters.

Because microstrip or patch antennas may be printed directly onto a circuit board, they are becoming increasingly desirable. Microstrip antennas are becoming increasingly used in mobile phones. Patch antennas are inexpensive, low profile, and simple to construct(*Microstrip Antennas: The Patch Antenna*, n.d.).

2.2 Literature Review on Dual Band Antenna Techniques

Dual-band antennas offer a wide range of applications, particularly in mobile devices. These antennas work on two frequency bands (similar to radio stations). Depending on the capability of the particular antenna, they can function on these distinct frequencies one at a time or simultaneously(*Explaing Dual Band Antennas*, n.d.).

Patch antennas come in various forms, including rectangular, circular, dipole, triangular, square, and elliptical, with rectangular and circular being the most popular(Kaur Sidhu & Singh Sivia, n.d.). Four types of patches have been researched to gain the information for this title. There are circular patches, rectangular patches, hexagon shapes, and gemini shapes.

Dual band antennas offer a wide range of applications, particularly mobile devices. These antennas function on two bands or frequencies (similar to radio stations) and, depending on the capability of the specific antenna, can work on these distinct frequencies one at a time or simultaneously. This section will focus more on dual band microstrip antenna where there are several ways to propose it, for example, by the design and the patch used.

2.2.1 Circular Patch

Based on Mukesh Kumar Khandelwal, Binod Kumar Kanaujia, Santanu Dwari, Sachin Kumar and A. K. Gautam, the antenna has a compactness of 36% and resonates at two frequencies of 2.55 GHz and 5.25 GHz in defected ground structure, making it a good choice for WiMax and WLAN applications. With antennas resonating at 2.45 GHz and 5.10 GHz with gains of 6 dBi and 7.2 dBi, the circular patch is covered by a dielectric superstate and compactness is enhanced to 38.3%(Khandelwal et al., 2015).

According to Junuthula Ashish and A. Prakasa Rao, the antenna design of U-slot for WLAN/WiMAX which resonates at 2.45GHz and 3.5GHz offers a good percentage impedance bandwidth which is 15.5 and 10.2(Ashish Junuthula & Rao Prakasa A., 2019). They also prove that this design gave a good radiation characteristic, followed with the radiation efficiency result of 97% and 92% on 2.45GHz and 3.5GHz. this showed that the U-slot that they design can be used in daily life.

Based on L. Magthelin Therase and Jayanthy Thangappan, a novel microstrip antenna using circular ring defected ground structure for X band applications will be used in X-band radar and satellite applications because of its small size, low manufacturing cost, good impedance matching, large bandwidth, improved gain, and directivity. The suggested antenna's efficiency was calculated to be 83 percent at 9.7 GHz and 69 percent at 11.4 GHz. The manufactured antenna's performance was verified, and the experimental and simulated findings were found to be in good agreement. Further enhancements can be made to this arrangement by utilising RF MEMS switches in larger applications(Magthelin Therase & Thangappan, 2021).

According to Sandip Ghosal and Raed M. Shubair, circular polarization was achieved at two bands with a single probe feeding for a Dual Band dual sense circularly polarised single feed microstrip patch antenna. The bottom band was created as a result of the square patch's corner truncation. The higher band CP was given by the inner circular patch with two slots. In two orthogonal planes, the dual bands of CP were illustrated. LHCP was the lower order resonance, while RHCP was the higher order resonance. The antenna can be used in wireless communication's polarisation diversity system(Ghosal & M. Shubair, n.d.).

2.2.2 Rectangular Patch

According to Funda Cirik Acikaya and Bahadir S. Yildirim, a microstrip patch antenna with harmonics suppression property with asymmetrical left and right cuts had achieved a 650MHz bandwidth at 5GHz WLAN. The matching circuitry on microstrip are improves the 2.45GHz low band response while having virtually no effect on the 5GHz band. The proposed antenna gain is 3.49dBi at 2.45GHz while 5.03dBi at 5.8GHz(Acıkaya & Yıldırım, 2021).

Microstrip patch antenna are used by many technologies nowadays. For example, like Intelligent Transportation Systems Application. According to Shivesh Tripathi, N. P. Pathak, M. Parida, Dual-Band Dual-Beam Microstrip Patch Antenna can be a good candidate for WLAN(Tripathi Shivesh et al., n.d.). This is because the measured and fabricate result reflection coefficients are close to each other. It shows that radiation patterns in E-plane and H-plane are good followed by the perfect gain for 5.3GHz and 5.9GHz where the gain is 4.8 and 5.7dBi.

According to Sanjay Chouhan, Vivek Singh Kushwah and Jitendra Yadav, two element multi-slotted MIMO antenna for dual band applications using FR-4 material can resonates at 3.6 GHz and 4.5 GHz. The multi-slot construction of the MIMO antenna self-resists mutual coupling and provides more than 15 dB isolation between radiators. The suggested antenna's bandwidth, ECC, and radiation patterns make it suited for wireless applications(Chouhan et al., 2020).

Based on Raad H. Thaher and Zainab S. Jamel, by inserting rectangular slot in the upper part and two slots in lower part, it can be applicate into WiMAX frequencies which is 3.5GHz and 5.8GHz(Thaher & Jamel, 2018). It is support by return loss (S11) value for both frequencies that is -32.04dB and -21.5dB. The values of VSWR are 1.05 at 3.5GHz and 1.18 at 5.8GHz and this proposed antenna also offers a good gain which is 3.9 and 4.91dB. Thaher and Zainab also mention that with those values, this antenna is suitable for WiMAX wireless application.

Based on Danny L. Torres, Luis P. Sumba, Juan P. Bormeo and Diego A. Cuji, dual band rectangular patch antenna with less return loss can be obtain for WiMAX and WBAN application(Torres L. Danny et al., n.d.). It can be seen that the design has a dual slot with the length of feed is so high. With that design, it observed a lower return loss which achieved the objective. Other than that, that design also give a higher gain in the range of 3.61GHz to 3.986GHz.

Based on P. Sandhiyadevi, V. Baranidharan, G. K. Mohanapriya, J. Roshini Roy, M. Nandhini, the proposed antenna which is rectangle microstrip patch antenna using FR4 Substrate material for wireless applications get high efficiency on the frequency range of 3.3GHz to 5.2GHz. The size of substrate makes a role to improve the performance by calculating the various parameter such as gain, impedance with increased return loss with -10dB. The antenna got 90% of bandwidth within desired frequency range(Sandhiyadevi et al., 2021).

Based on Sourav Roy and Ujjal Chakraborty, Dual Band Microstrip Patch Antenna with Meandered Ground Plane a provides wide impedance bandwidth (4.83-7 GHz) in the upper band that fulfils the bandwidth requirements of Wireless LAN 5 GHz and uplink C bands. At 5.8GHz, a good steady radiation pattern was established with a maximum simulated gain of 2dB(Roy & Chakraborty, n.d.).

A simple microstrip patch antenna power fed with microstrip feeding for Ka band (26.5–40 GHz) application is proposed by Dhananjay Singh, Surya Deo Choudhary and B. Mohapatra. The suggested antenna's resonating frequencies are 29.87 GHz and 35.02 GHz, which fall into the Ka band (26.5–40 GHz) of transformation for impulsive applications in Next Generation Networks (NGN). The results also reveal that the first band's bandwidth is 1.24 GHz and the second band's bandwidth is 2 GHz(Singh et al., 2021).

According to Pichitpong Soontornpipit, a dual band compact microstrip patch antenna has the ability to integrate wireless body-area networks (WBANs) to assess their performance, such as radiation properties. Because it must mount on human skin to avoid antenna shortening, silicon is employed as a superstrate. In both the on-body and off-body modes, the antenna performs admirably. The antenna successfully functions at the target bands of 403.5 MHz and 2.45GHz, according to the S11 and S12 results. The antenna radiation efficiency in the ISM band has fallen just a few percent when compared to patterns in the MICS band(Soontornpipit, 2016).

A dual band multiple input multiple output microstrip antenna with mathematical structure for LTE and WLAN application that been proposed by MirHamed Rezvani and Yashar Zehforoosh has two radiating patches which are supplied independently and provide the MIMO property. It also showed that the antenna are resonates at 2.4-3.1GHz and 5.1-5.8GHz frequency bands for simulated and measured results. When a PRS structure was placed on the substrate, the antenna gain was enhanced, and more stable values were achieved than when no PRS structure was utilised(Rezvani & Zehforoosh, 2018).

2.2.3 Hexagon Shape

Based on Nasrin Shoghi Badr and Gholamreza Moradi which present the design of the graphene-based slotted hexagonal patch antenna with linear polarization, the gain is quite good for the design where the result it gets was 4.71dB and 5.61dB(Badr & Moradi, 2020). In addition, the result of resonance frequency and efficiency are affected by the value of length of the horizontal slot.

According to Megha Agarwal, Jasdeep Kaur Dhanoa and Mukesh Kumar Khandelwal, operable from 2.1 GHz to 11.4 GHz with notched bands at 3.5 GHz and 5.5 GHz to disregard interference, this two-port hexagon shaped MIMO microstrip antenna for UWB applications is incorporated with double stop bands for WiMax and WLAN. With the usage of the regulated ground plane, high isolation of roughly 24.5 dB is achieved. Surface current distribution graphs are used to justify notched bands(Agarwal et al., 2021).

2.2.4 Gemini Shape

According to Gerard Djengomemgoto, Reha Altunok, Cem Karabacak, S. Taha Imeci and Tahsin Durak, Dual-band Gemini-Shaped Microstrip Patch Antenna can give a good impedance matching with input match (S11 <-10dB) for operating frequencies(Djengomemgoto et al., n.d.). Other than that, the microstrip patch antenna exhibits a theta polarized radiation pattern with high gain performance.

2.3 WIFI Frequency Bands

Many devices use Wi-Fi IEEE 802.11, including smartphones, laptops, tablets, remote sensors, actuators, TVs, and more. It is the principal wireless communications carrier in wireless LANs and small residential WLANs. Wi-Fi operates on several frequency bands within the radio spectrum, and many of them have been assigned numbers so that they can be identified.

Although many Wi-Fi channels and bands are often set automatically by household Wi-Fi routers, bigger wireless LANs and systems require frequency planning. To get the optimum performance from a wireless LAN, systematic planning is required when using several Wi-Fi accesses points over a big building or region. Even for residential systems with Wi-Fi extenders and repeaters, knowing which frequencies are accessible and how to use them effectively is beneficial. It is possible to boost the Wi-Fi installation network speed by using accessible settings in the Wi-Fi router and wireless extenders.

2.3.1 The 2.4GHz Frequency Band

The lower of the two bands served by these dual-band antennas is the 2.4GHz band, which spans 2400MHz to 2485MHz. There are up to fourteen overlapping 20MHz sub-bands known as channels that can be used for data transfer inside the frequency spectrum. In the United States, there are eleven channels numbered 1 to 11, with channels numbered up to 14 available in Europe, Africa, and Asia(*Wi-Fi Channels, Frequency Bands & Bandwidth » Electronics Notes*, n.d.).

It Is widely used for wireless networking, and can be used In conjunction with Wi-Fi to support Bluetooth and ZigBee, as well as connectivity for domestic appliances such as cordless phones. Because of the range and penetration, it can accomplish, it is often used for wireless communication. 2.4 GHz transmissions lose less energy as they spread, and less energy is absorbed as signals pass through materials like wood, insulation, and plaster, as compared to the 5 GHz frequency spectrum. As a result, in indoor contexts, 2.4 GHz networking can give multi-room coverage. Due to the huge number of wireless communications using this band's finite quantity of bandwidth, this frequency band has become a victim of its own success in many respects. The main effect is interference, which results in slower speeds and poor network performance. Dual-band networking solutions are an important method for dealing with 2.4 GHz interference.

2.3.2 The 5GHz Frequency Band

The 5 GHz ISM band, which spans 5.15 GHz to 5.35 GHz and 5.725 GHz to 5.825 GHz, has significantly larger bandwidth. There are four significant sub-bands in the 5GHz frequency band:

- An upper (indoor) spans 5.150 GHz to 5.250 GHz
- A lower (indoor) spans 5.250 GHz to 5.350 GHz
- B (indoor or outdoor) spans 5470 GHz to 5725 GHz
- C (outdoor) spans 5735 GHz to 5850 GHz

There are 26 channels within these vast sections of the spectrum that can be used for high-speed and throughput networking, 19 of which are non-overlapping and have channel widths of up to 160MHz. The wavelength of 5GHz radio frequency transmissions is significantly shorter (6 centimetres at 5GHz versus just over 12 centimetres at 2.4GHz). The 5GHz frequency spectrum is advantageous due to the availability of bandwidth. Users gain from connectivity with less interference from other business and consumer applications because the frequency is less congested(*Wi-Fi Channels, Frequency Bands & Bandwidth » Electronics Notes*, n.d.).

Because high-energy signals are easily reflected, refracted, or absorbed, they mostly travel by direct line of sight. This restricts 5 GHz WIFI's coverage to the indoor environment, despite the fact that it is capable of high-speed, high-throughput data transfer. When using 5 GHz WIFI outside, a higher restriction on radiated power for 5 GHz outdoor transmission helps to improve coverage for point-to-point links with good line of sight.

2.4 Summary

After researching the type of microstrip antenna, it can be seen that all of those types have their strength and advantage. Nevertheless, when comparing the circular patch and rectangular patch, both antenna layouts perform well regarding return loss, VSWR, gain, and radiation efficiency. However, the rectangular patch design performs better regarding return loss and gain, while the circular patch configuration performs better in terms of bandwidth, radiation pattern, and side lobe levels. Figure 1 shows the summary of literature review for several type of patch.

Because of that, the rectangular patch is chosen to be designed in this microstrip antenna. This process is done to get the best solution for the research so everything will go smoothly without having a problem.

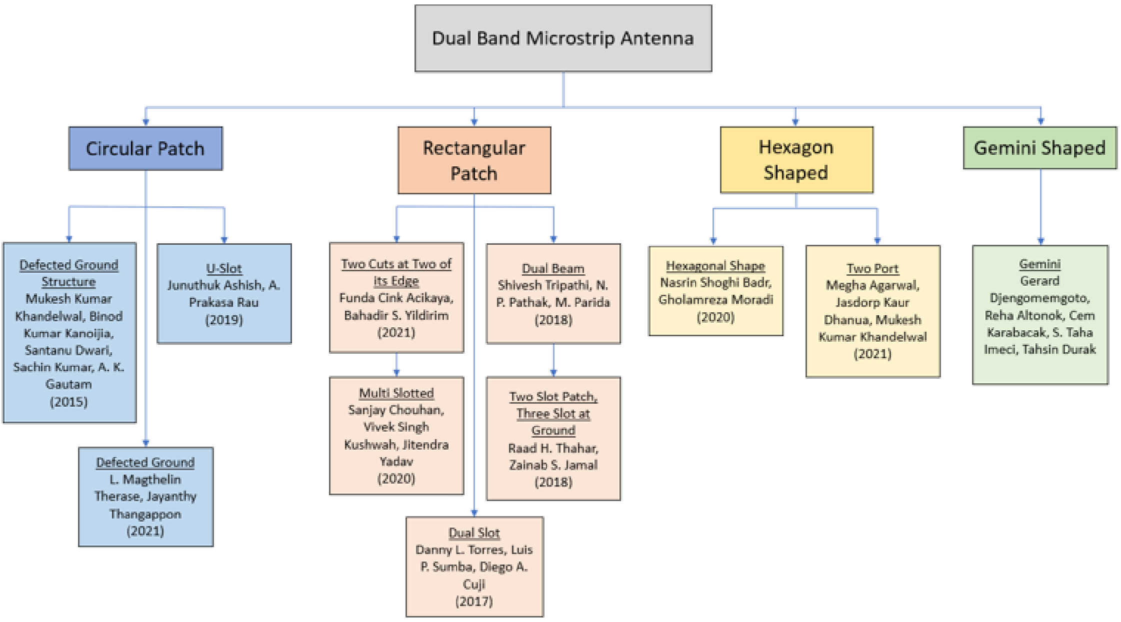


Figure 1: Literature Review Summary

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study, the antenna was modelled by using CST Studio Suite software. Parameter sweeping was conducted to obtain the optimum geometry of the antenna. The CST Studio Suite shows the effect and all the important data based on proposed dual band dual slot microstrip antenna.

3.2 Flow of methodology

Figure 2 shows the flowchart for this research. Overall, the processes can be divided into two phases which are simulation design result on CST software and antenna fabrication with S_{11} measurement result.

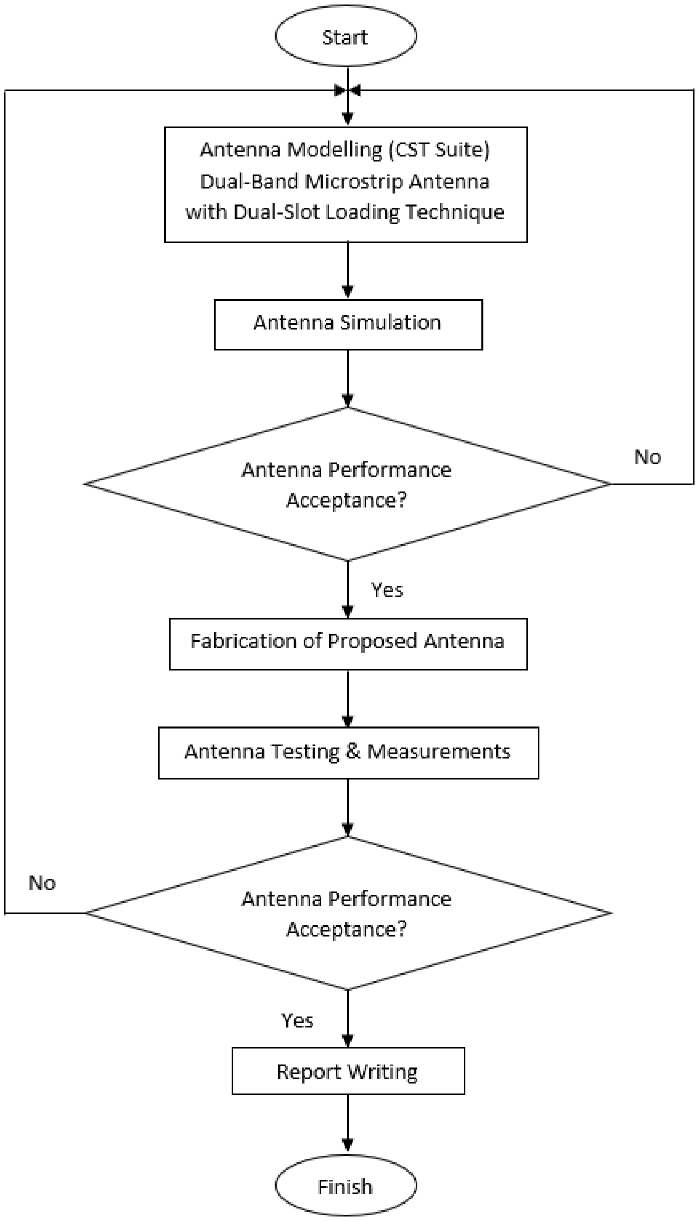


Figure 2: Flowchart for simulation and fabricate antenna process

3.3 Antenna Design & Modelling

Before the antenna can be fabricated, it must first be designed and modelled using CST Studio Suite software.

The CST Studio Suite is a high-performance 3D electromagnetic (EM) analysis software suite for developing, evaluating, and optimising EM components and systems. CST Studio Suite contains electromagnetic field solutions for applications across the electromagnetic spectrum in a single user interface.

3.3.1 Antenna Dimensions Calculation

Transmission line model was used to construct the basic rectangular MPA. Figure 3 shows the structure of a rectangular MPA. The width was calculated using eq. (1) and (2).

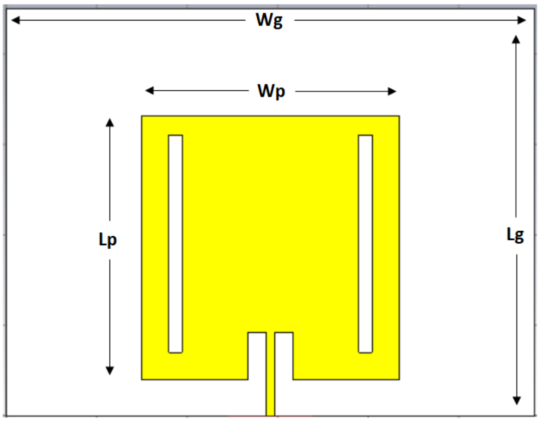


Figure 3: Important Parameter List

The width of the antenna is obtained by using eq. (1) :

$$Width = \frac{c}{2f_o\sqrt{\frac{\epsilon_R+1}{2}}} \quad (1)$$

The length of the antenna is calculated by using eq. (2) :

$$Length = \frac{c}{2f_o\sqrt{\in eff}} - 0.824h(\frac{(\in_{eff}+0.3)(\frac{W}{h}+0.264)}{(\in_{eff-0.258})(\frac{W}{h}+0.8)}) \quad (2)$$

Where:

c = speed of light

$\in_R$ = dielectric constant

$\in_{eff}$ = effective dielectric

W = width

h = height

For other parameter values like ground width, Wg, and ground length, Lg, it just needs to put the value on the parameter list to declare the value to get the proposed value. Moreover, the integral equation in this design is the dual slot. So, to get the dual-slot design on the patch, the equation used in eq. (3) below.

$$X = \frac{Wg}{3} + L1 \quad (3)$$

where X is slot, Wg is ground width and L1 is slot width

When these equations are inserted into the transform, it will give the one slot in the rectangular patch. So, the next step that needs to do is to declare all the essential parameter lists in the CST Suite software.

3.3.2 Antenna Modelling using CST

The proposed antenna will be designed using the CST Suite software, a popular software used by other people in this field. So, install the software on the laptop or PC and start with a new template. The figure 4 below showed the template of CST Suite Design.

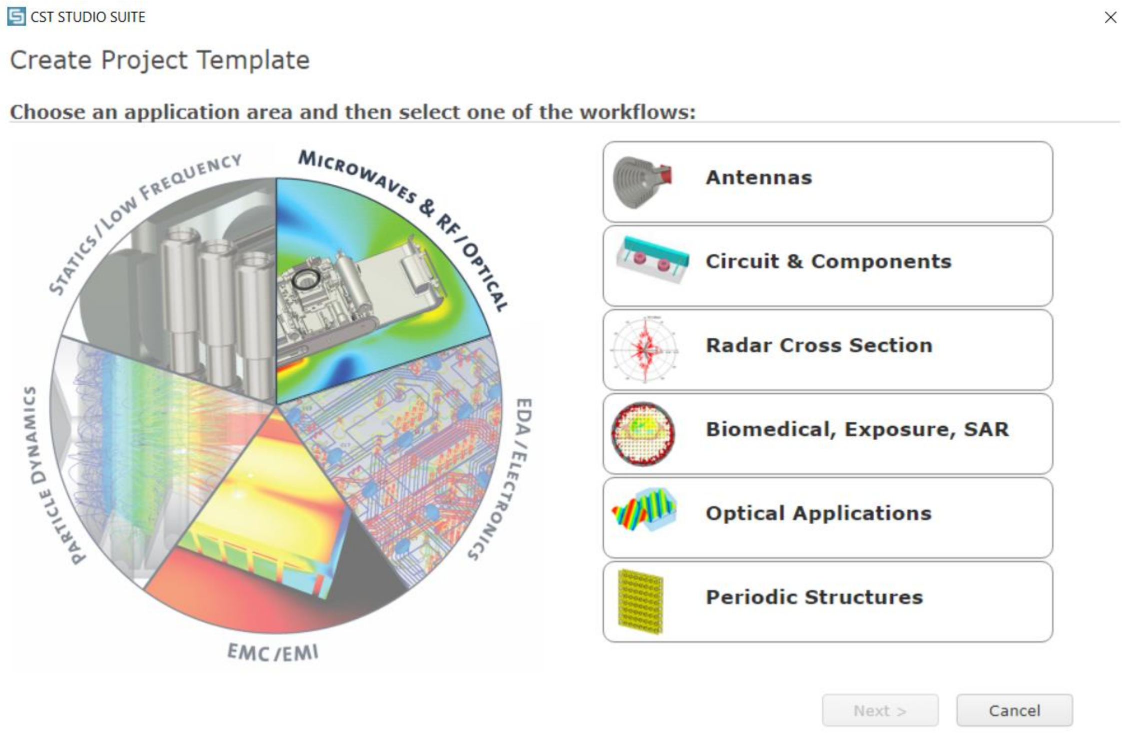


Figure 4: CST Suite Design template

To design the antenna, a parameter list needs to be declared so it will be easy to design using the CST software. So, simply add the name and value at the bottom of the CST part. Table 1 shows the parameter list to design the whole rectangular patch microstrip antenna with the dual-slot technique. Table 1 below shows the value of all parameters with dimensions.

Table 1: Design parameter value

NAME	EXPRESSION	DESCRIPTION
Wg	58.4	Ground Width
Lg	45	Ground Length
Ht	0.035	Ground Height
Hs	1.4	Substrate Height
Wf	1	Feed Width
Lf	4	Feed Length
Wp	28.45	Patch Width
Lp	29.2	Patch Length
Wc	2	Cut Feed Width
Lc	5.2	Cut Feed Length
L1	1.5	Slot Width
H1	3	Slot Y Coordinate
W1	24	Slot Length

This design has three main components: ground, patch, and substrate. The first one that needs to be designed is the ground. Click the brick button, and it is required to define the brick. The material of the ground is by using copper. Figure 5 below shows the brick for the ground design.

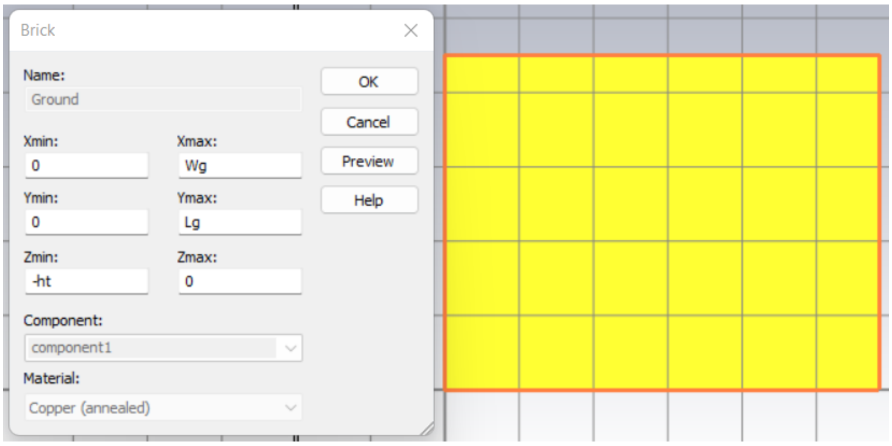


Figure 5: Bricks and ground design

After that, make a design for the substrate, which is very important. Many substrates can be chosen on CST. However, for this microstrip, FR-4 was chosen on the substrate. The substrate plays an essential role in the result, meaning different substrates will give antenna results. Figure 6 below the brick for the substrate design.

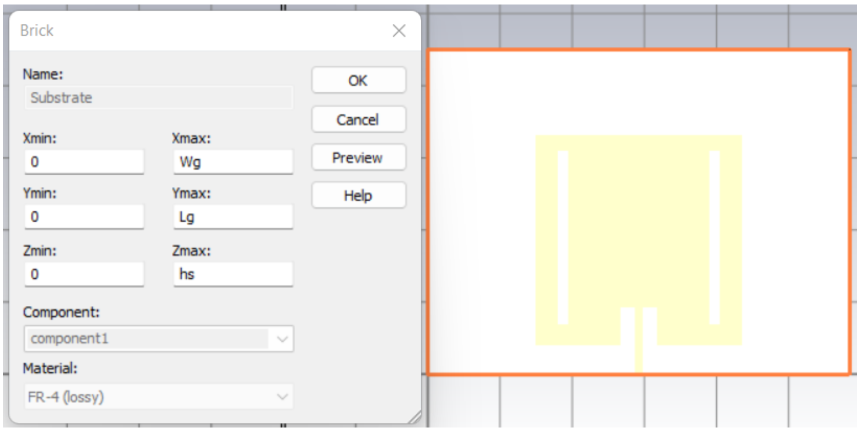
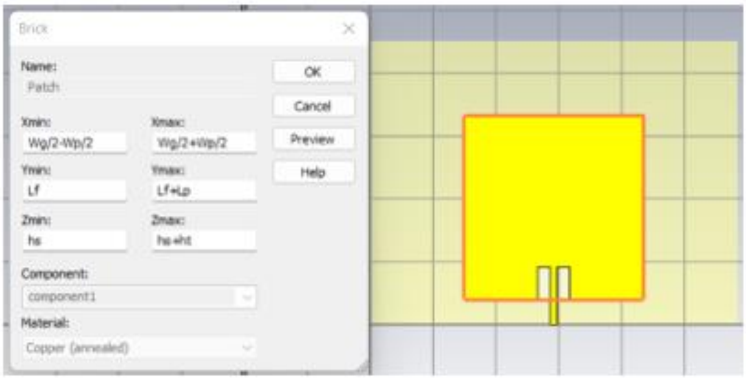
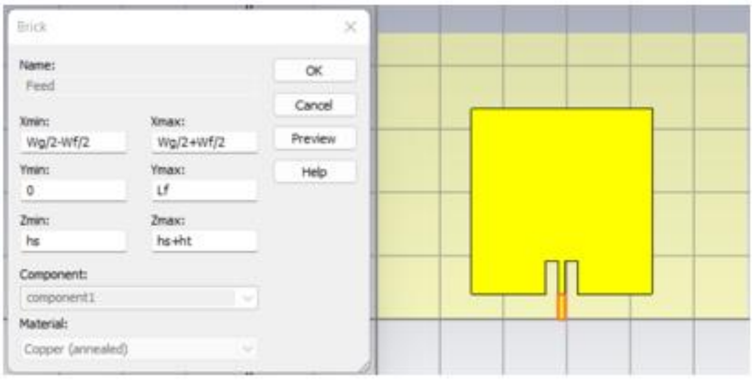


Figure 6: Bricks with substrate design

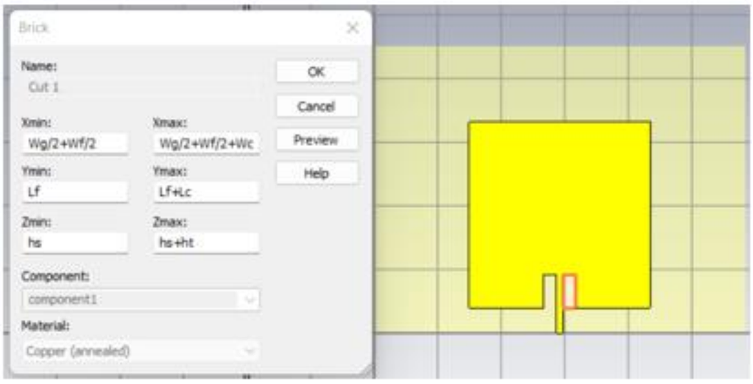
The next one is the patch itself. Several bricks were made like the patch, feedline, and the slot itself. The first is the design of the rectangular patch. After that, design the feedline connected with the female SMA Connector. Other than that, do the bricks for the cut between feedlines on the patch body. For cutting between feedlines, it will use transform mode was used, which will copy the first cut bricks, as shown in Figure 7 below.



(a)



(b)



(c)

Figure 7: Designing process of dual slot antenna in CST (a) rectangular patch, (b) feedline, (c) cut between feedlines

Then, another cut between feedline was added by Transform Selected Object as shown in Figure 8 below.

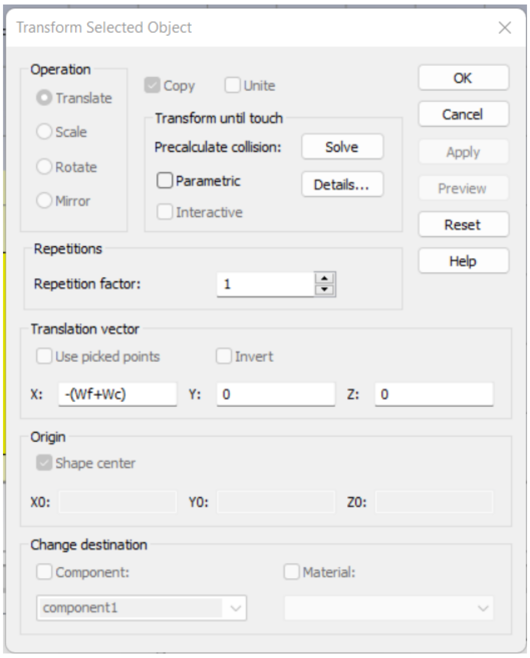


Figure 8: Transform for cut 2

And then is the design of the slot. It was the same process like the cut between feedline design where it will use transform to make another slot. So, make a design on one slot first and then make a equation for another slot that will be copy or reflected with slot 1 as shown in Figure 9 and Figure 10.

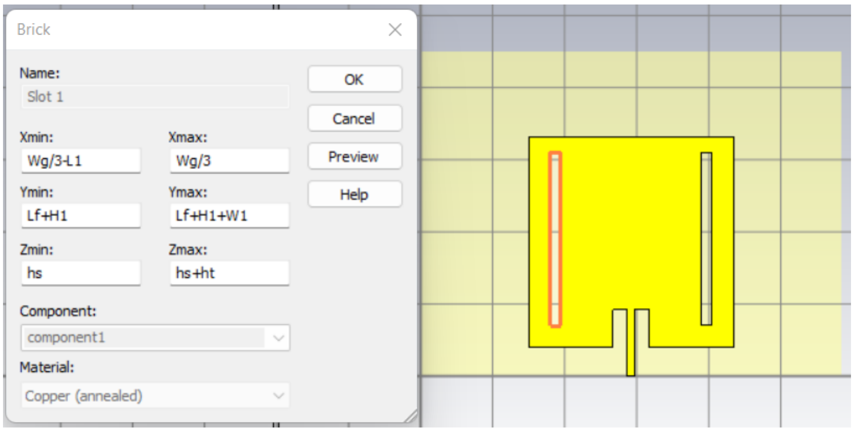


Figure 9: Bricks with Slot 1 design

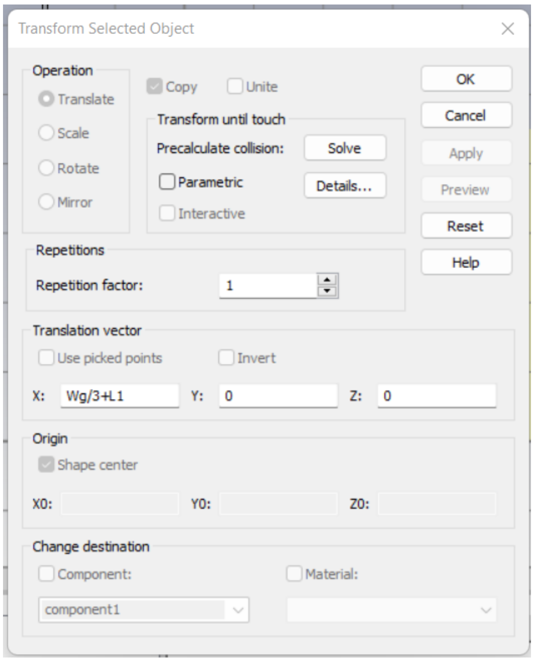


Figure 10: Transform for slot 2

After designing all these three essential bricks, the antenna design is complete, which is a Rectangular Patch Microstrip Antenna using Dual Slot Technique. Figure 11 below shows the Rectangular Microstrip Patch Antenna design's complete design.

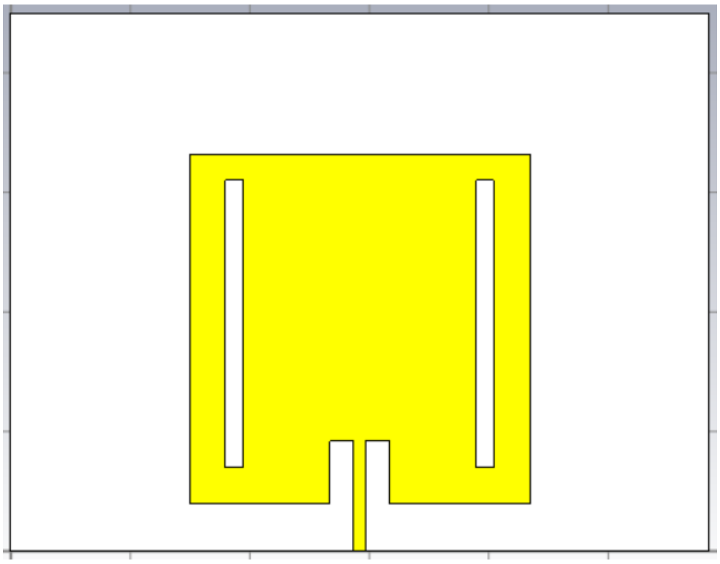


Figure 11: Complete design

3.3.3 Antenna Performance Simulation using CST

To know whether the antenna performance is good or not, several results or parameter values can be referred to from the simulation result. For example, VSWR, Efficiency, Gain, S_{11} Parameter, and others. Each of these parameters has its function of knowing the performance of the proposed antenna.

3.4 Antenna Fabrication Process

There are several ways to fabricate the antenna, for example, photography and etching. Nevertheless, for this project, the traditional fabrication method is used. The main materials used to fabricate the antenna are FR4 PCB Board Single Sided Copper Plate and Adhesive Conductive Copper Slug Foil Tape. The FR4 PCB Board Single Sided Copper Plate act as a substrate, while the Adhesive Conductive Copper Slug Foil Tape is the antenna patch. Figure 12 below shows the primary material for fabricating the antenna.

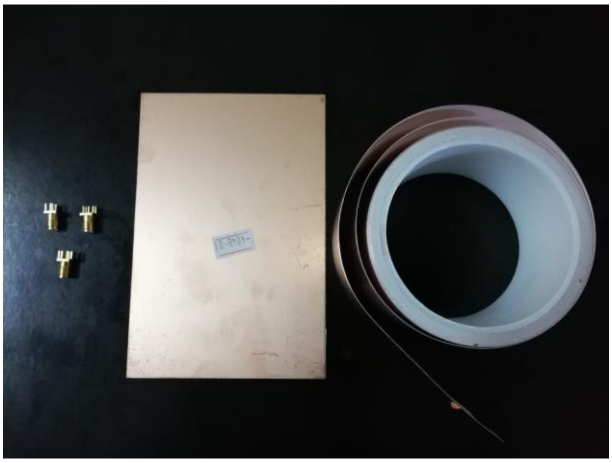


Figure 12: Major material to fabricate

The process starts by cutting the PCB Board by following the dimension of the simulation design. This process is shown in Figure 13. It is very important to ensure that the substrate height is 1.4mm, width is 58.4mm and length is 45mm, which is identical to the simulation design, if the dimension is not accurate as the simulation, the result for measurement might be different too. Next, a mark was made on the PCB Board using a pencil with the intended dimension. Then, the board cut carefully using a junior hacksaw.

After cutting the PCV Board with Junior Hacksaw. The next step is to use sandpaper to remove material from surfaces so it will look smoother.

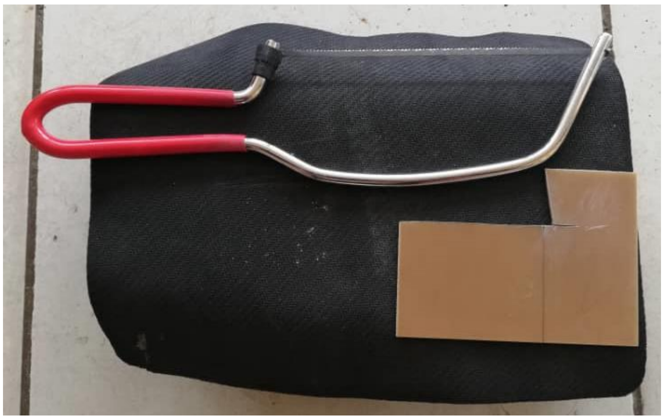


Figure 13: Cutting process

The next step was to prepare one small piece of stiff paper. This tiny hard paper will follow the exact design from the CST simulation design, as shown in Figure 14. After that, it was put on the copper tape and the shaped was traced on the paper side, as shown in Figure 15.

Figure 14: Paper stick

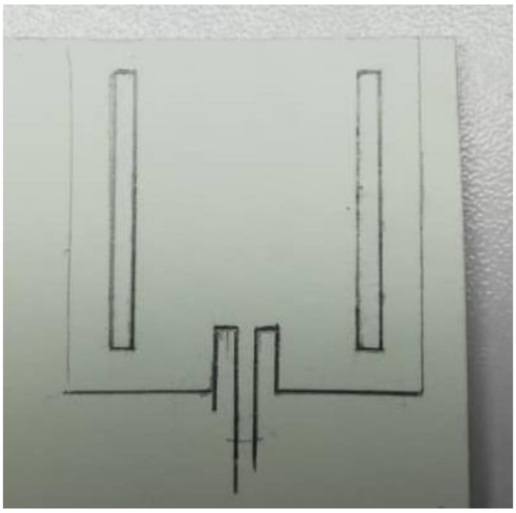


Figure 15: Sketch on Copper Tape Paper side

Next, the copper tape was cut, according to the shaped drawn on the tape. This step was done carefully, to avoid any mistake on cutting process like cutting on the wrong part. The whole cutting process might end with failure and need to make another traced on copper tape.

The next step is to tape it into the FR4 PCB Board, as shown in Figure 16 below. It is crucial here to tape it in the exact position like the design's dimension because when the position for the tape is wrong, the result for the fabricated antenna will be substantially different from the simulation result. This step can be considered very hard from all the processes because the tape must be taped perfectly without any wrinkles or scratches. The last step is by doing the soldering process. The part that will be soldered is at the feedline of the patch antenna and the ground part of the FR4 PCB Board.

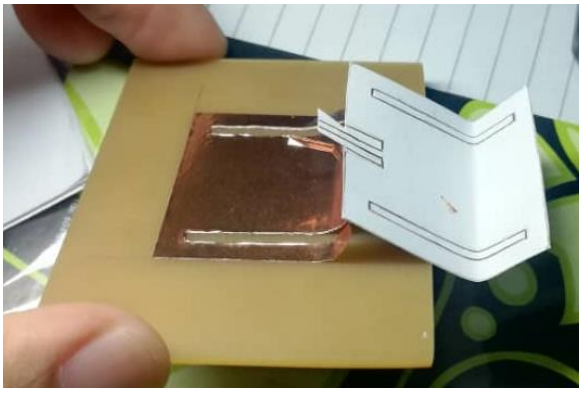
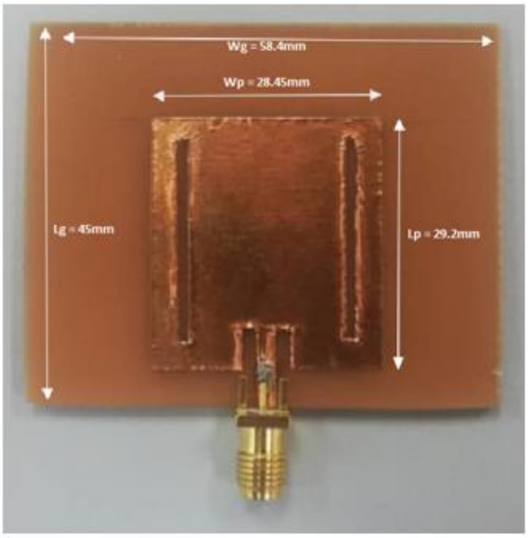


Figure 16: Stick process

The final fabricated antenna is shown in Figure 17 below. The SMA connector was attached to the antenna at the end of feeding line. The overall dimension of antenna is Wg = 58.4mm, Lg = 45mm, Wp = 28.45mm and Lp = 29.2mm.



(a)

(b)

Figure 17: Fabricated Antenna

3.5 Fabricated Antenna Measurement

The measurement from the fabricated antenna is critical to compare it with the simulation result in CST Suite. In this project, the parameters that will be measured for the fabricated antenna are only the $S11$ Parameter. The important material to be measured is Agilent Vector Network Analyzer(VNA), as shown in Figure 18 below.

Figure 18: Agilent Vector Network Analyzer (VNA)

A vector network analyzer is a device that examines the frequency response of a single component or a network of several components, both passive and active. The VNA's built-in computer determines important network metrics such as return loss and insertion loss. It may also visualise the data in a variety of ways, such as real/imaginary, magnitude/phase, Smith chart, and so on. VNA is frequently used to describe multi-port networks comprising of components such as connectors, filters, amplifiers, and transmission line/coaxial channels in high-speed system evaluations.

Before measuring the S_{11} Parameter for the fabricated antenna, the Vector Network Analyzer needs to be calibrated first. The process of measuring devices with known or partially known properties and utilizing these results to construct measurement reference planes is known as VNA calibration. Even in tests with the reference plane set at the instrument front panel connections or the ends of cables, VNAs rely on calibration for accuracy. Calibration also helps to fix the measuring system's flaws. The non-ideal nature of cables and probes, as well as the internal properties of the VNA itself, are among these flaws.

Open the Vector Network Analyzer and plug the coaxial cable into the socket. If using both ports, plug two coaxial cables into it. SMA Torque Wrench Calibrate was used to tighten the coaxial cable. Torque wrenches must operate within precise tolerances to apply the proper force to tighten bolts or nuts which mean it cannot be use by other tools to tighten the coaxial cable. Afterward, the range of frequency are set at the VNA setting where the frequency are 2GHz and 5.5GHz. coaxial cable are connected into female Short, Open, Load, Thru SMA calibration standards and the calibration process are started. The SMA calibration will be disconnected from coaxial cable once all the process of calibration are done, then, those coaxial cables will be connected with SMA connector from the fabricated antenna. The S_{11} parameter are measured and the data are saved into a pen drive that are already formatted as shown in Figure 19 below.

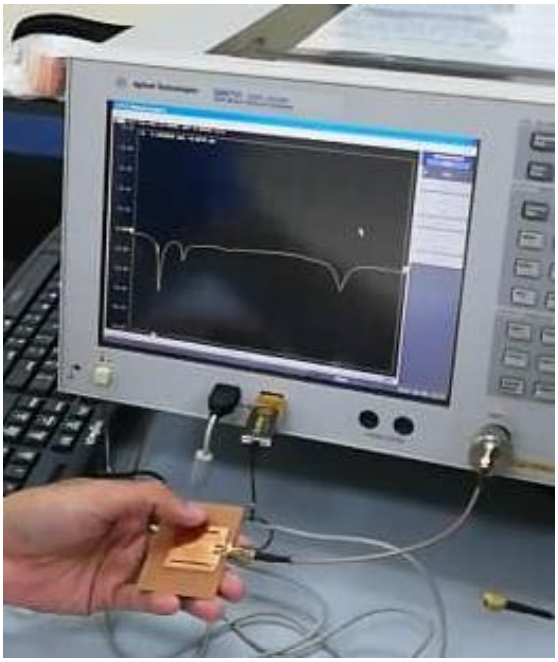


Figure 19: $\boldsymbol{S_{11}}$ measurement

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This section will discuss all the measurement results from the simulation and fabricated antenna. For the simulation result, all the parameters like S_{11}, VSWR, Efficiency, and Gain are measured in CST, while for the fabricated antenna, only S_{11} will be measured by using VNA.

4.1.1 Rectangular Microstrip Patch Antenna Operating at 2.4GHz

Figure 20 shows the S_{11} results for rectangular microstrip patch antenna with patch dimension of patch width, Wp is 28.45mm and patch length is 29.2mm. The result shows that this antenna resonate at 2.4GHz. This is a good start, so everything will go well for making a design for dual-band frequency. Figures 21 show the result for radiation frequency and total efficiency. For total efficiency, the value is 31.15%, while for total frequency is 29.50%. Lastly, the gain result shown in Figure 22 for the one band is 2.4GHz are 1.320dBi. This result shows that the antenna performs very well, so it can go to the next step, which is to design the dual-slot for dual-band frequencies.

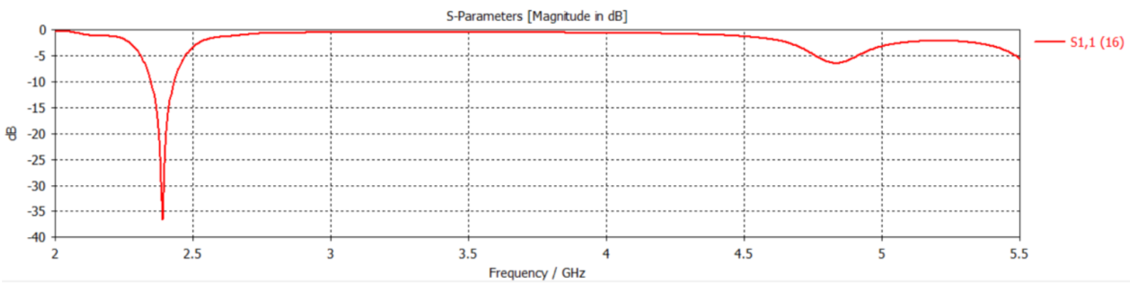


Figure 20: S_{11} Parameter for 2.4GHz

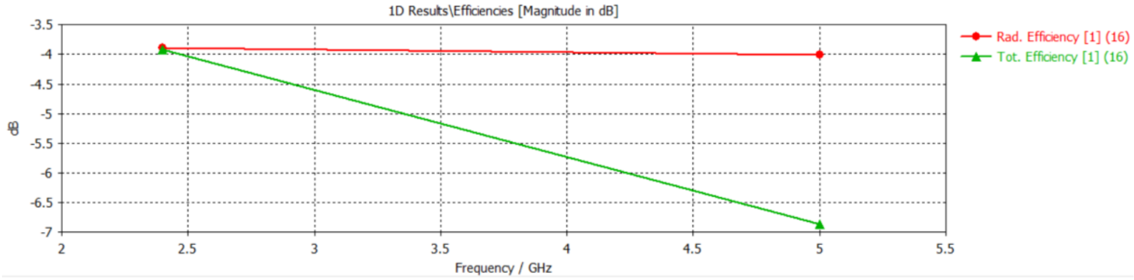


Figure 21: Efficiency for 2.4GHz

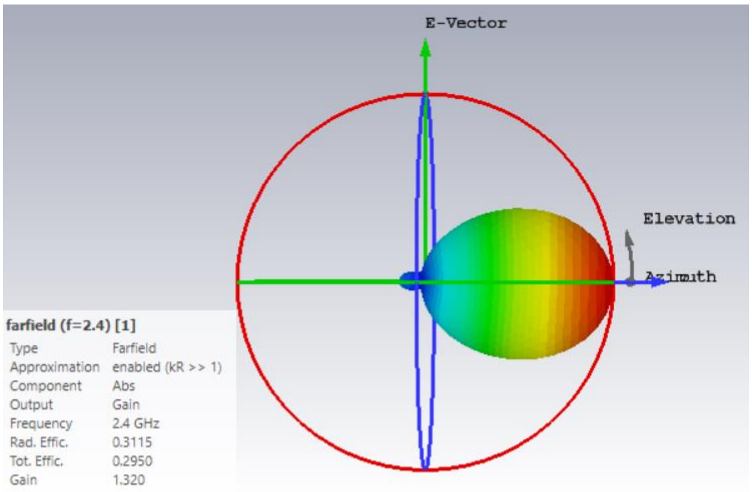


Figure 22: Gain for 2.4GHz

4.2 Effect of Slot Length and Slot Width to Antenna Performance

In this part, some analysis has been carried out to find which provides a good and better result. Two crucial analyses have been investigated here: what will be affected if the slot length and width are different and at what dimension it gives a good performance. Parameter sweeping has been done to find the best length and width of the slots. Figure 23 below shows the dual-slot dimension that will be analyzed.

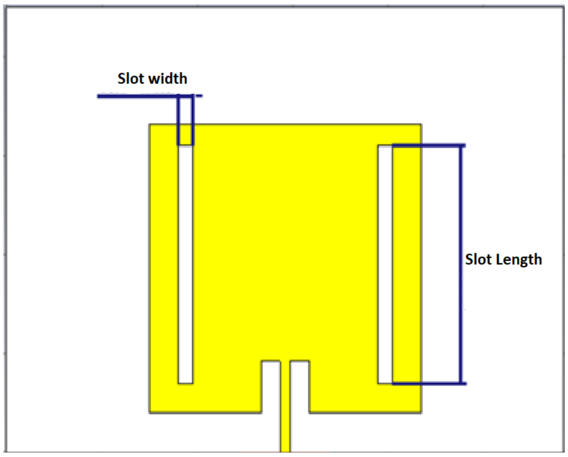


Figure 23: Dual-slot loading technique design

4.2.1 Slot Length Effect

Five samples in the thorough parameter process will be 5mm, 9.75mm, 14.5mm, 19.25mm, and 24mm. Figure 24 shows the S_{11} for every sample. All the samples are resonating at 2.4GHz, but for 5GHz, only the dimension of 24mm resonates at -15dB.

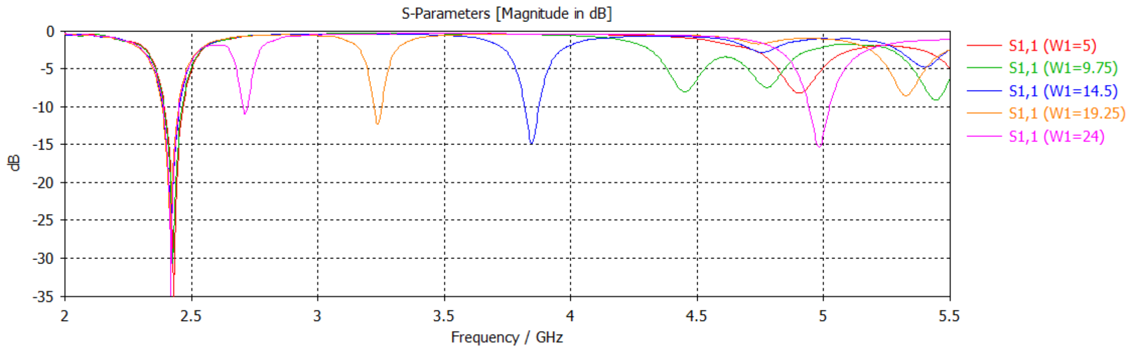


Figure 24: S_{11} Parameter on 5 Samples

Next is VSWR, where all the samples also give a good result for 2.4GHz. The accepted VSWR in the antenna is below 2dB, so all the samples give an excellent result to be chosen. For 5GHz, only the dimension of 24mm gives a good result with 1.5517dB, while others give a value that cannot be accepted. Figure 25 shows the result for VSWR.

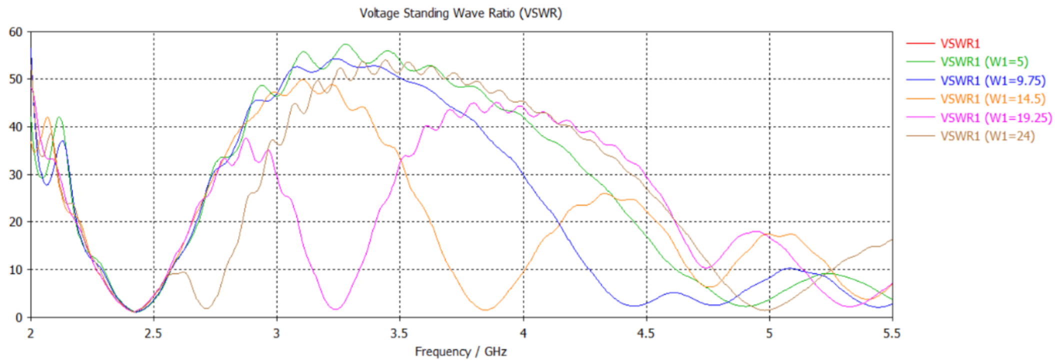


Figure 25: VSWR on 5 Samples

Figure 26 below shows the value of radiation efficiency and total efficiency for all the samples on 2.4GHz and 5GHz. The results of Radiation Efficiency and Total Efficiency are different for every samples. The excellent efficiency for microstrip antenna is 40%-50%, so it was pretty good for all samples where the result is not below 10%(*What Is Antenna Efficiency? - Everything RF*, n.d.). For radiation and total efficiency at 5GHz, 24mm dimension results can be acceptable, which are 23.69% and 22.66%. 24mm gives the best value and performance for total efficiency if compared with others.

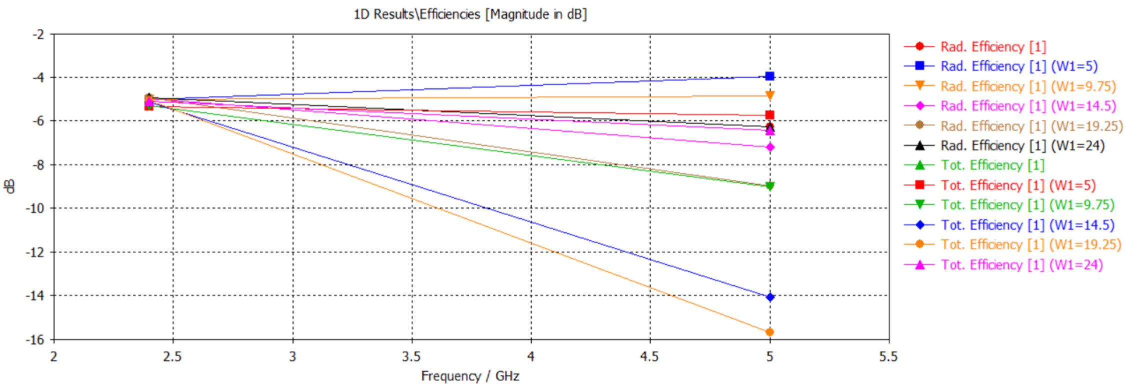


Figure 26: Efficiency on 5 Samples

From table 2 and 3, 24mm slot length shows the best parameter value where it gives a good performance for the antenna. Table 3 also shows the worst efficiency and S_{11} out of the five samples for 5GHz which is 5mm, 9.75mm, 14.5mm and 19.25mm. From the analysis, it can be seen that the length of 24mm gives a good performance almost at all the criteria, which are S_{11} parameter, VSWR, Radiation Efficiency, Total Efficiency, and Gain.

Table 2: For 2.4GHz on length

Length of Slot	S_{11}	VSWR (dB)	Radiation Efficiency (%)	Total Efficiency (%)	Gain (dBi)
5	-35.918	1.7291	31.492	29.194	1.368
9.75	-30.619	1.1191	31.48	29.56	1.335
14.5	-26.185	1.1096	31.92	30.68	1.355
19.25	-26.585	1.1252	32.15	31.25	1.367
24	-34.905	1.7366	32.35	30.89	1.370

Table 3: For 5GHz on length

Length of Slot	S_{11}	VSWR (dB)	Radiation Efficiency (%)	Total Efficiency (%)	Gain (dBi)
5	-8.1875	3.6833	32.60	12.50	1.454
9.75	-2.0602	8.3054	32.60	12.50	1.454
14.5	-0.99932	17.41	19.10	3.926	0.7404
19.25	-1.0399	16.593	12.67	2.707	0.5142
24	-15.221	1.5517	23.69	22.66	0.6759

4.2.2 Slot Width Effect

The effect of slot width on antenna performance has been tested for five different values which are 1.5mm, 2.125mm, 2.75mm, 3.375mm and 4mm. Figure 27 below shows the S_{11} for every width. For 2.4GHz, all dimensions give acceptable resonance frequency except for the dimension of 4mm, where the result is only -10.7dB. While for 5GHz, the samples that pass the level of S_{11} parameter (below -10dB) are 1.5mm, 2.125mm, 2.75mm, and 3.375mm. The best among these three is 1.5mm, where the S_{11} parameter result is -15.221dB. The width of 4mm is not acceptable in this part because it only resonates at -4.3335dB.

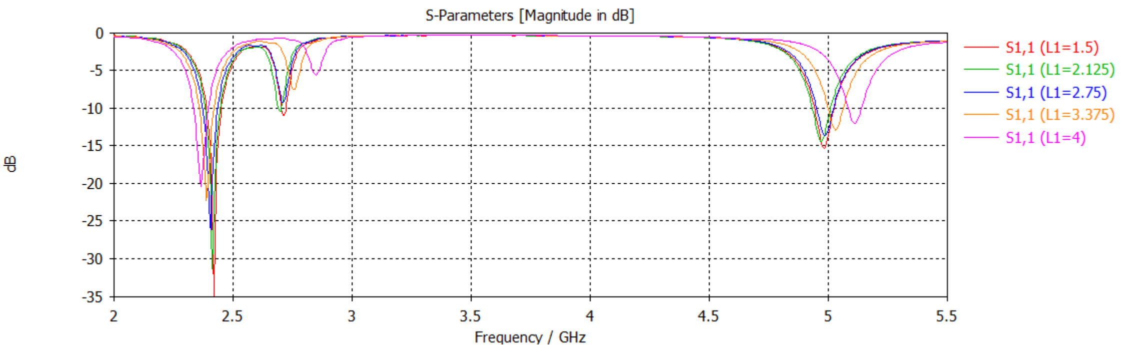


Figure 27: S_{11} Parameter of 5 samples

The next parameter is VSWR which is shown in Figure 28. Results show that for 2.4GHz, VSWR for 4mm 1.5142 is identical to S_{11} parameter, where all samples give a good result except 4mm. The 4mm gave 3.0703, which is exceeds the maximum acceptable value of VSWR. Thus, based on the results, antenna with 4mm slot width is rejected because of its performance. For 5GHz, all samples give an acceptable result except for 4mm, where the value is too high, which is 4.7794dB.

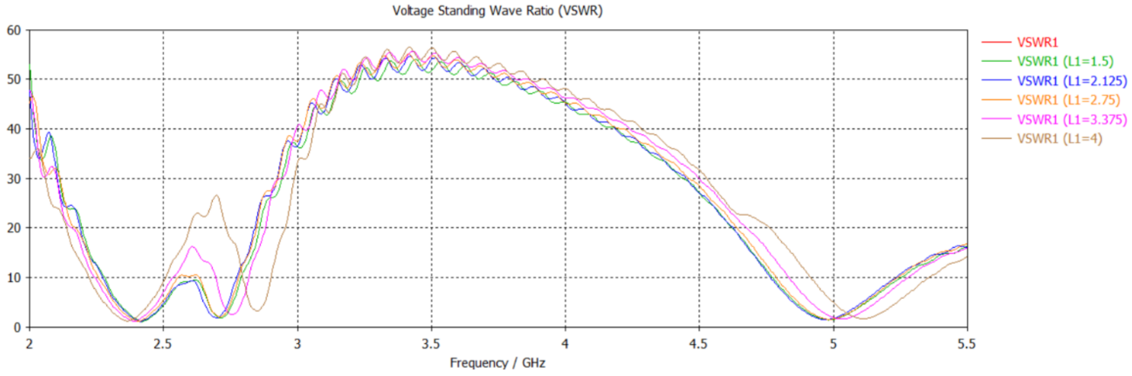


Figure 28: VSWR of 5 samples

Figure 29 shows the results for all samples' radiation efficiency and total efficiency. At 2.4GHz, a dimension of 1.5mm gives a good result as it gives 32.25% and 30.89%. For 5GHz, the highest percentage samples are 1.5mm, 2.125mm, and 2.75mm. The reason 3.375mm and 4mm are not chosen is that the total efficiency is below 20% if compared with other dimensions or samples.

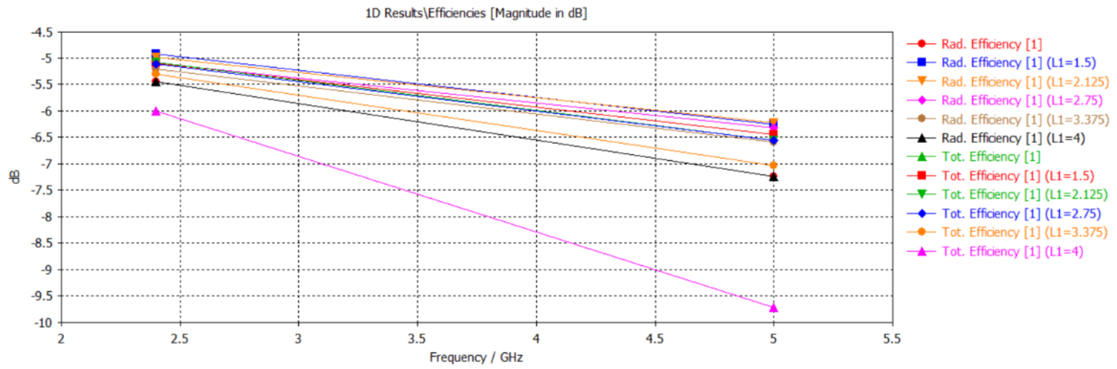


Figure 29: Efficiency of 5 samples

From the table 4, it can be seen from the result of S_{11} where the 4mm give a worst performance to be accepted. 4mm also give a worst result at VSWR too where the value is already exceeded 2dB. While for the table 5, only 1.5mm give a good performance for all the parameter list. The worst width at 5GHz is 4mm where the S_{11} result are only -4.3335, followed by other VSWR and efficiency which give non acceptable performance for the antenna. The table analysis shows that the dimension of 1.5mm is the best of all the samples because it gives a consistent and good performance for all parameter values.

Table 4: For 2.4GHz on width

Width of Slot	S_{11}	**VSWR (dB)**	**Radiation Efficiency (%)**	**Total Efficiency (%)**	**Gain (dBi)**
1.5	-34.905	1.5142	32.25	30.89	1.370
2.125	-31.231	1.1298	31.77	31.10	1.351
2.75	-23.893	1.1352	30.93	30.78	1.317
3.375	-19.863	1.2631	30.11	29.52	1.284
4	-10.7	3.0703	28.59	25.12	1.223

Table 5: For 5GHz on width

Width of Slot	S_{11}	**VSWR (dB)**	**Radiation Efficiency (%)**	**Total Efficiency (%)**	**Gain (dBi)**
1.5	-15.221	1.4144	23.69	22.66	0.6759
2.125	-11.467	2.0242	23.89	22.12	0.6787
2.75	-10.879	1.5423	23.33	22.10	0.6718
3.375	-11.86	1.921	21.94	19.83	0.6482
4	-4.3335	4.7794	18.86	10.67	0.5743

4.3 Simulation Result for Optimized Antenna

From the analysis of the effect of length and width of the slot, it can be seen that the best dimension for the antenna is 1.5mm for width and 24mm for the length. This is shown in the Figure 30 below as the fin design for the Dual-band Microstrip Patch Antenna.

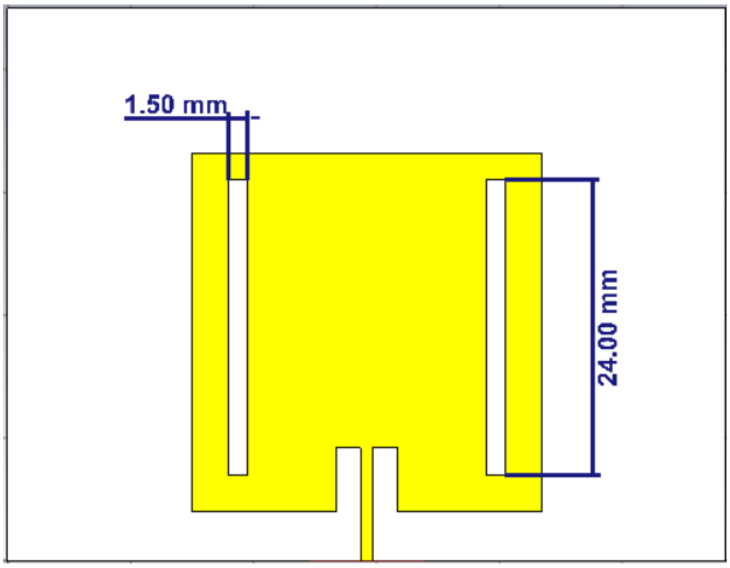


Figure 30: The chosen dimension for length & width of slot

For S_{11} parameter, it can be seen that the frequency resonates at 2.4GHz and 5GHz as shown in Figure 31. At 2.4GHz, the result is -34.715dB, which was an excellent performance for the antenna. The bandwidth frequency intercepts at -10dB are 2.3893GHz and 2.4515GHz, which means this is the frequency that can be operated for 2.4GHz. At 5GHz, the result obtained is -15.293dB. This result can be accepted because the minimum S_{11} parameter is -10dB: the bandwidth frequency 4.9419GHz and 5.0241GHz. So, the result showed that the antenna resonated at WIFI frequency (2.4GHz and 5GHz).

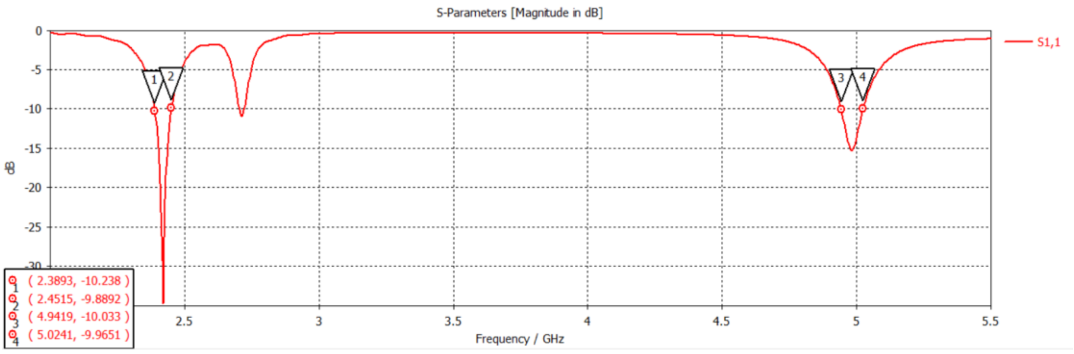


Figure 31: S_{11} parameter

Figure 32 shows the VSWR result for the final design. For VSWR, both frequencies perform well, where the 2.4GHz result is 1.0635 while 5GHz is 1.5051.

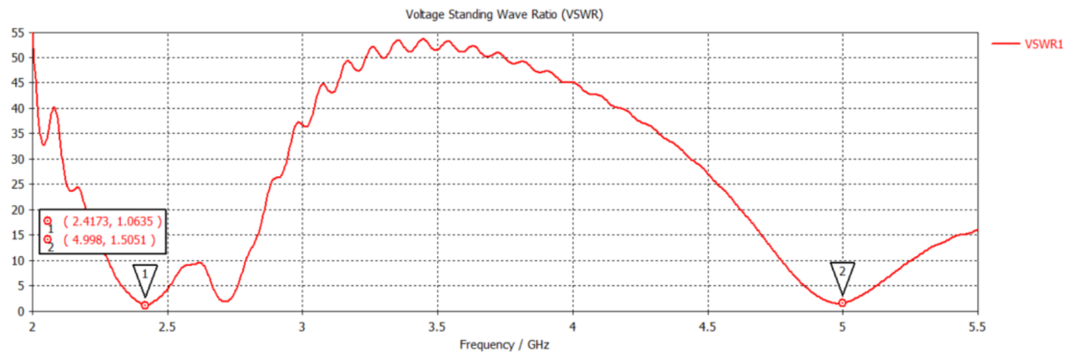


Figure 32: VSWR

Next, the radiation efficiency and total efficiency for 2.4GHz is shown in Figure 33 where it give excellent results with 32.24% and 30.88%. For 5GHz, radiation Efficiency is 23.66%, while total efficiency is 22.63%. If compare between this 2.4GHz and 5GHz, it can be seen that 2.4GHz will operate more efficiently because the percentage for 2.4GHz is higher than 5GHz. This means that for the 2.4GHz frequency, the ratio of power emitted by the antenna to the power provided to the antenna is reasonable compared to 5GHz. Both radiation efficiency and total efficiency performance are accepted. Figure 37 below shows the result of efficiencies.

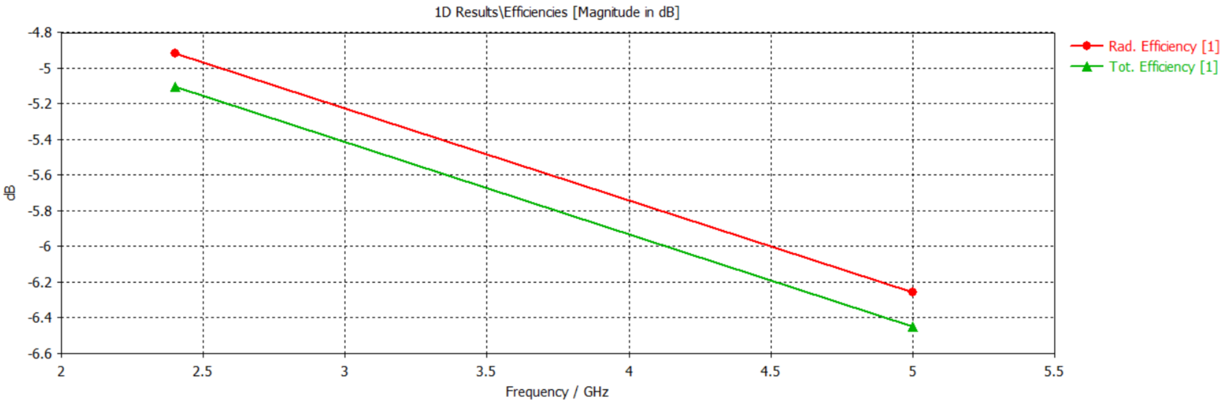


Figure 33: Efficiency

For gain, the result for 2.4GHz is 1.370dBi while for 5GHz is 0.6669dBi which is shown in Figure 34 and Figure 35. With this result, the antenna will not perform well because the value is low. The antenna gain is essential to reduce the radiation's ability in any direction. Several causes can make this design microstrip antenna get low gain on it. One of them is because of FR4 itself, which was a lossy material, so it cannot be expected to gain higher from it(*How Can I Improve the Gain of a Patch Antenna and What Is the Maximum Attainable Gain Using a FR4 Substrate?*, n.d.). On FR4, a single patch antenna may yield 3-5dBi gain.

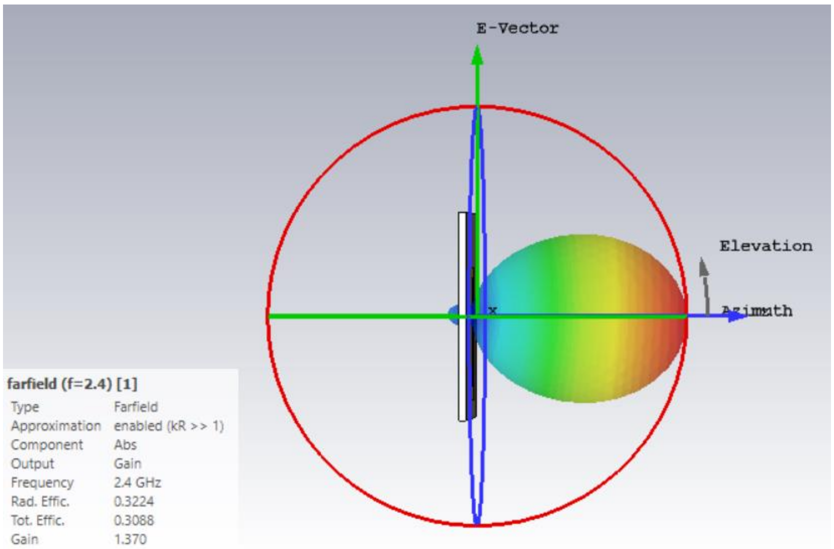


Figure 34: 2.4GHz farfield

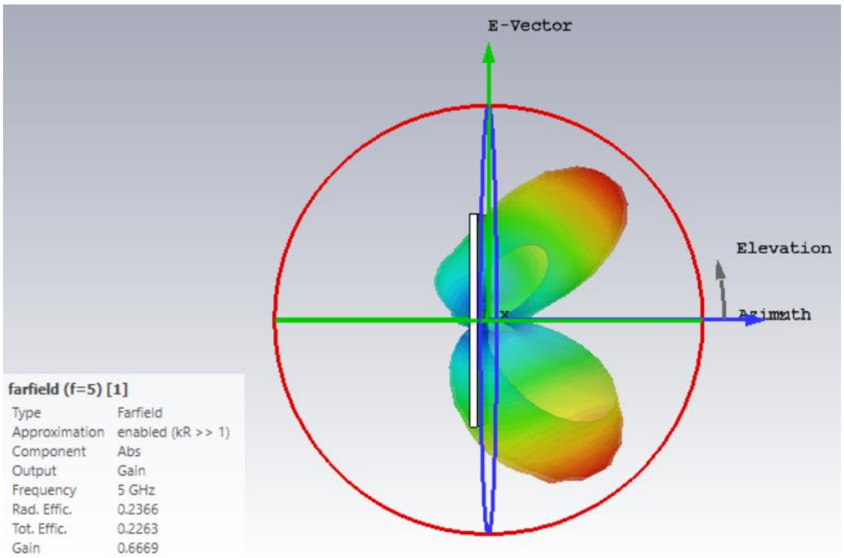


Figure 35: 5GHz farfield

Table 6 and 7 shows the result of important parameter for 2.4GHz and 5GHz. The frequency are resonate at the 2.4GHz and 5GHz as shown in S_{11} result which are acceptable for antenna. For other parameter like VSWR, Radiation Efficiency, Total Efficiency, the performance are also can be acceptable as it meet the requirements for the antenna to be work. For gain, the result is low for the antenna to work for 5GHz except for 2.4GHz.

Table 6: 2.4GHz result

S_{11}	VSWR (dB)	Radiation Efficiency (%)	Total Efficiency (%)	Gain (dBi)
-34.715	1.0635	32.24	30.88	1.370

Table 7: 5GHz result

S_{11}	VSWR (dB)	Radiation Efficiency (%)	Total Efficiency (%)	Gain (dBi)
-15.293	1.5051	23.66	22.63	0.6669

4.4 S_{11} Parameter Comparisons Between Simulation and Measured Result

The fabricated antenna is measured by using Agilent Vector Network Analyzer. Figure 36 below shows the resulting picture snap from the VNA.

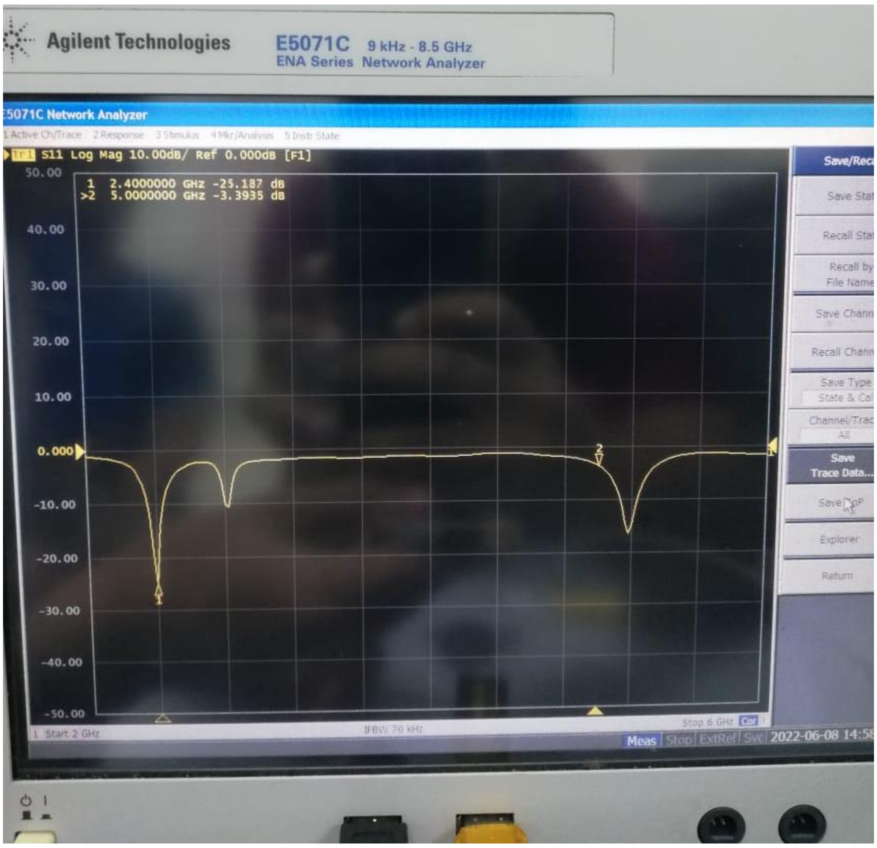


Figure 36. Result

Figure 37 and Figure 38 show the result of fabricated and simulation measurements. The S_{11} parameter result for the fabricated antenna resonates at 2.4GHz and 5GHz. For 2.4GHz, the value is -20.8dB while for 5GHz is -16.2dB. Both results can be accepted because the value is below -10dB which is good for antenna performance. For a fabricated antenna, the measurement is only for the S_{11} parameter.

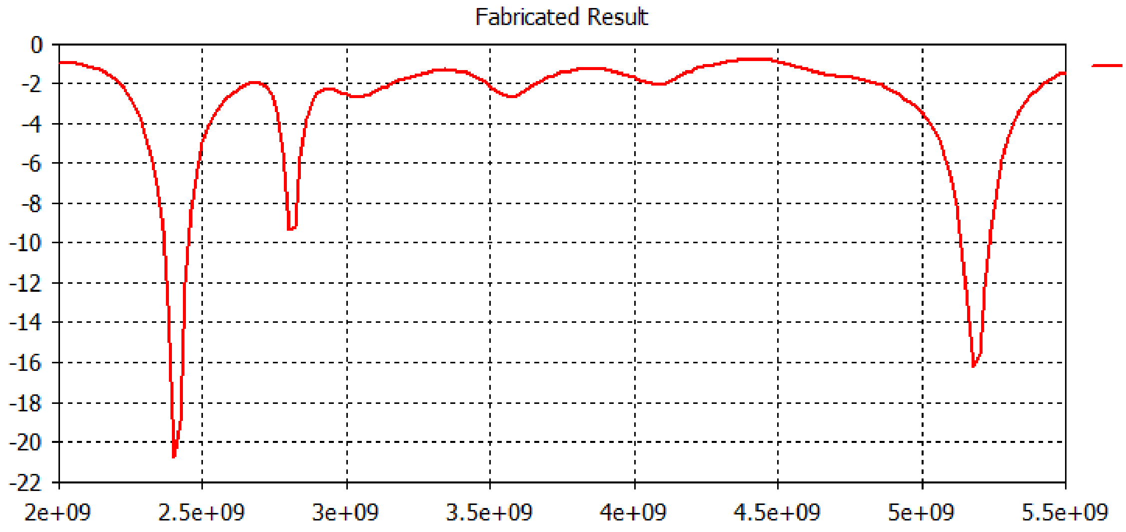


Figure 37: Fabricated Result

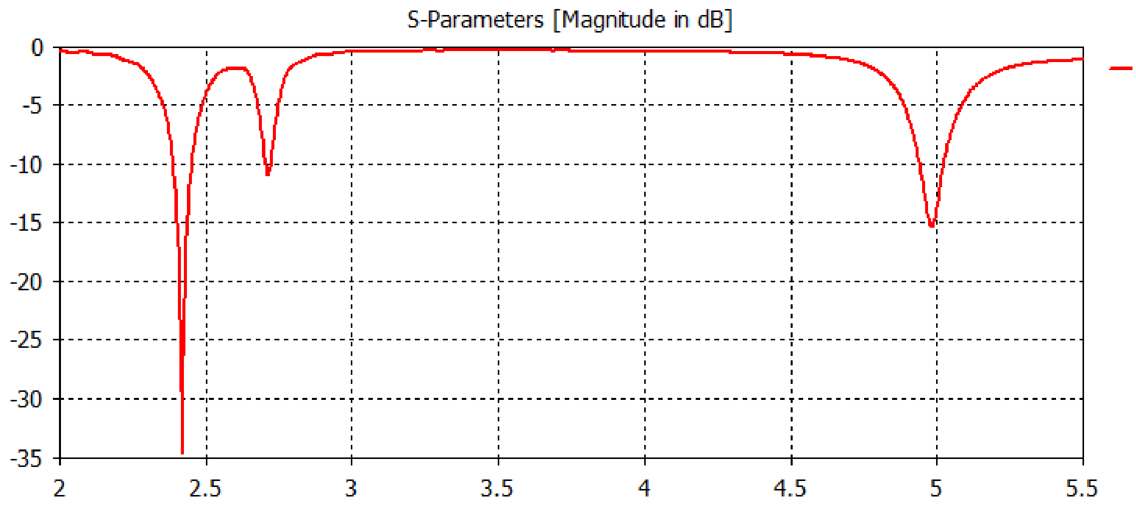


Figure 38: Simulation Result

At 2.4GHz, the frequency resonates only -20.8dB for the fabricated antenna, while the simulation antenna is -34.715dB. At 5GHz, the fabricated antenna gives -16.2dB, while 5GHz is -15.39dB. The effect of tolerance will differ in both designs because fabrication variation is an absolute value that affects two designs with different dimensions in different ways. After the FR4 has been cut, the surface needs to be smooth where sandpaper is needed. The dimension may not be identical or accurate to the simulation design, which will make a result different from the simulation. Other than that, the dual-slot has also been cut with no accurate dimension. It was difficult to cut at that part because it was minimal to cut with knives, so it may be one of the reasons the fabricated result is not identical to the simulated result.

CHAPTER 5

CONCLUSION

5.1 Conclusion

On this design and analysis of dual slot technique microstrip antenna in simulation, it can be seen that the values of S_{11} parameter showed the antenna resonates at 2.4GHz and 5GHz. From the simulation results, it also shows that the antenna design performance is acceptable except for value of gain where it was too low on antenna. The other measurement parameter like VSWR, Radiation Efficiency and Total Efficiency made a good performance too on simulation.

For fabricated antenna, S_{11} parameter showed that it resonates at 2.4GHz and 5GHz. The analysis that been done also showed that the width and length value of dual slot can affected the performance of antenna. It gives the best dimension for both of it which is 1.5mm for width while 24mm for length.

REFERENCES

Acıkaya, F. C., & Yıldırım, B. S. (2021). A dual-band microstrip patch antenna for 2.45/5-GHz WLAN applications. *AEU - International Journal of Electronics and Communications*, *141*. https://doi.org/10.1016/j.aeue.2021.153957

Agarwal, M., Dhanoa, J. K., & Khandelwal, M. K. (2021). Two-port hexagon shaped MIMO microstrip antenna for UWB applications integrated with double stop bands for WiMax and WLAN. *AEU - International Journal of Electronics and Communications*, *138*. https://doi.org/10.1016/j.aeue.2021.153885

Ashish Junuthula, & Rao Prakasa A. (2019). *Microstrip Antenna for 2.4GHz WLAN and 3.5GHz WiMAX Applications*.

Badr, N. S., & Moradi, G. (2020). Graphene-Based microstrip-fed hexagonal shape dual band antenna. *Optik, 202*. https://doi.org/10.1016/j.ijleo.2019.163608

Chouhan, S., Kushwah, V. S., & Yadav, J. (2020). Two element multi-slotted MIMO antenna for dual band applications using FR-4 material. *Materials Today: Proceedings*, *47*, 6874–6878. https://doi.org/10.1016/j.matpr.2021.05.149

Djengomemgoto, G., Altunok, R., Karabacak, C., Imeci, T., & Durak, T. (n.d.). *Dual-Band Gemini-Shaped Microstrip Patch Antenna for C-Band and X-Band Applications*.

Explaing Dual Band Antennas. (n.d.). Retrieved June 21, 2022, from http://air802.com/blog/dual-band-antennas-explained/

Ghosal, S., & M. Shubair, R. (n.d.). *A Dual Band Dual Sense Circularly Polarised Single Feed Microstrip Patch Antenna*.

How can I improve the gain of a patch antenna and what is the maximum attainable gain using a FR4 substrate? (n.d.). Retrieved June 17, 2022, from https://www.researchgate.net/post/How_can_I_improve_the_gain_of_a_patch_antenna_and_what_is_the_maximum_attainable_gain_using_a_FR4_substrate

Kaur Sidhu, S., & Singh Sivia, J. (n.d.). Comparison of Different Types of Microstrip Patch Antennas. In *International Journal of Computer Applications*.

Khandelwal, M. K., Kanaujia, B. K., Dwari, S., Kumar, S., & Gautam, A. K. (2015). Analysis and design of dual band compact stacked microstrip patch antenna with defected ground structure for WLAN/WiMAX applications. *AEU - International Journal of Electronics and Communications*, *69*(1), 39–47. https://doi.org/10.1016/j.aeue.2014.07.018

Lee, K. F., & Luk, K. M. (2017). *Microstrip Patch Antennas*. World Scientific. https://books.google.com/books?id=57ZQDwAAQBAJ

Magthelin Therase, L., & Thangappan, J. (2021). A novel microstrip antenna using circular ring defected ground structure for X band applications. *Measurement: Journal of the International Measurement Confederation*, *183*. https://doi.org/10.1016/j.measurement.2021.109768

Microstrip Antennas: The Patch Antenna. (n.d.). Retrieved June 21, 2022, from https://www.antenna-theory.com/antennas/patches/antenna.php

Rezvani, M. H., & Zehforoosh, Y. (2018). A dual-band multiple-input multiple-output microstrip antenna with metamaterial structure for LTE and WLAN applications. *AEU - International Journal of Electronics and Communications*, *93*, 277–282. https://doi.org/10.1016/j.aeue.2018.06.034

Roy, S., & Chakraborty, U. (n.d.). *Dual Band Microstrip Patch Antenna with Meandered Ground Plane*.

Sandhiyadevi, P., Baranidharan, V., Mohanapriya, G. K., Roy, J. R., & Nandhini, M. (2021). Design of Dual-band low profile rectangular microstrip patch antenna using FR4 substrate material for wireless applications. *Materials Today: Proceedings*, *45*, 3506–3511. https://doi.org/10.1016/j.matpr.2020.12.957

Singh, D., Choudhary, S. D., & Mohapatra, B. (2021). Design of microstrip patch antenna for Ka-band (26.5-40 GHz) applications. *Materials Today: Proceedings*, *45*, 2828–2832. https://doi.org/10.1016/j.matpr.2020.11.805

Soontornpipit, P. (2016). A Dual-band Compact Microstrip Patch Antenna for 403.5 MHz and 2.45 GHz On-body Communications. *Procedia Computer Science*, *86*, 232–235. https://doi.org/10.1016/j.procs.2016.05.105

Thaher, R. H., & Jamel, Z. S. (2018). New design of dual-band microstrip antenna for Wi-Max and WLAN applications. *1st International Scientific Conference of Engineering Sciences - 3rd Scientific Conference of Engineering Science, ISCES 2018 - Proceedings*, *2018-January*, 131–134. https://doi.org/10.1109/ISCES.2018.8340541

Torres L. Danny, Sumba P. Luis, Bermeo P. Juan, & Cuji A. Diego. (n.d.). *Dual Band Rectangular Patch Antenna with Less Return Loss for WiMAX and WBAN Applications*.

Tripathi Shivesh, Pathak N. P., & Parida M. (n.d.). *Dual-Band Dual-Beam Microstrip Patch Antenna for Intelligent Transportation Systems Application*.

What is Antenna Efficiency? - everything RF. (n.d.). Retrieved June 21, 2022, from https://www.everythingrf.com/community/what-is-antenna-efficiency

Why do we use dual band antenna instead of two single band antennas..?? (n.d.). Retrieved June 25, 2022, from https://www.researchgate.net/post/Why-do-we-use-dual-band-antenna-instead-of-two-single-band-antennas

Wi-Fi Channels, Frequency Bands & Bandwidth » Electronics Notes. (n.d.). Retrieved June 25, 2022, from https://www.electronics-notes.com/articles/connectivity/wifi-ieee-802-11/channels-frequencies-bands-bandwidth.php