DESIGN OF VIVALDI ANTENNA FOR NON-DESTRUCTIVE MEASUREMENT APPLICATIONS

MOHD ZULFIKRI BIN ELVIS SYEFRIZAL

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

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : Mohd Zulfikri Bin Elvis Syefrizal

Date of Birth : 24 April 1996

Title : Design of Vivaldi Antenna for Non-destructive Measurement Application

Academic Session : Semester 2 (21/22)

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)

960424-56-5207
New IC/Passport Number
Date: 17/06/2022

(Supervisor's Signature)

DR. NURHAFIZAH BINTI ABU TALIP @ YUSOF
PENSYARAH KANAN
FAKULTI TEKNOLOGI KEJURUTERAAN ELEKTRIK DAN ELEKTRONIK
UNIVERSITI MALAYSIA PAHANG

Name of Supervisor
Date: 29/06/2022

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

THESIS DECLARATION LETTER (OPTIONAL)

Librarian,
Perpustakaan Universiti Malaysia Pahang,
Universiti Malaysia Pahang,
Lebuhraya Tun Razak,
26300, Gambang, Kuantan.

Dear Sir,

CLASSIFICATION OF THESIS AS RESTRICTED

Please be informed that the following thesis is classified as RESTRICTED for a period of three (3) years from the date of this letter. The reasons for this classification are as listed below.

Author's Name
Thesis Title

Reasons (i)

(ii)

(iii)

Thank you.

Yours faithfully,

____
(Supervisor's Signature)

Date:

Stamp:

Note: This letter should be written by the supervisor, addressed to the Librarian, *Perpustakaan Universiti Malaysia Pahang* with its copy attached to the thesis.

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 Electrical Engineering (Electronics).

____

(Supervisor's Signature)

Full Name : Ts. Dr. Nurhafizah Binti Abu Talip @ Yusof

Position : Senior Lecturer

Date : 29/06/2022

____

(Co-supervisor's Signature)

Full Name :

Position :

Date :

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 Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : Mohd Zulfikri Bin Elvis Syefrizal

ID Number : EA18140

Date : 17/06/2022

DESIGN OF VIVALDI ANTENNA FOR NON-DESTRUCTIVE MEASUREMENT APPLICATIONS

MOHD ZULFIKRI BIN ELVIS SYEFRIZAL

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

College of Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2022

ACKNOWLEDGEMENTS

Alhamdulillah, the final year project, entitled "Design of Vivaldi Antenna for Non-destructive Measurement Applications", has been completed within the time given. I thank Allah SWT for His blessings and for providing me with the physical and mental strength to complete this project, which has been a requirement to graduate with a Bachelor's in Electrical Engineering (Electronics). I want to take this opportunity to express my deepest gratitude to the people involved in the success of this project. First of all, I would like to express my gratitude and be very grateful to my project supervisor, Ts. Dr Nurhafizah Binti Abu Talip @ Yusof for giving me the ideas, support, and guidance in completing this project.

Besides that, I owe a debt of gratitude to all of the lecturers who have taught me at Universiti Malaysia Pahang for providing me with a dynamic and enjoyable atmosphere to learn and grow. Also, I would like to thank Universiti Malaysia Pahang for providing the facilities to carry out my experimental work in completing this project.

A special thanks to my family for giving me continuous support in the four years of study for my bachelor's degree at UMP. Without their support and encouragement, I would not be the person I am today. Not forget all my friends and colleagues who have been fighting together for the past four years. I acknowledge their support and help raise my spirits to strive diligently without recognizing the meaning of despair. Thank you very much. In Sha Allah, only Allah can repay your kindness.

ABSTRAK

Kertas kerja ini membentangkan antena Vivaldi jalur lebar ultra untuk pengukuran-tanpa-musnah dalam aplikasi 5G. Kaedah *Free-space* membolehkan pencirian dielektrik tanpa merosakkan material pada julat frekuensi yang luas. Penggunaan antena Vivaldi dalam sistem pengukuran-tanpa-musnah telah diperkenalkan untuk mengurangkan ruang persediaan dalam system pengukuran tersebut. Projek ini bertujuan untuk mereka bentuk antena Vivaldi dengan menyelidik dimensi reka bentuknya dan menganalisis *Return Loss* (S_{11}), *Voltage Standing Wave Ratio* (VSWR), bentuk radiasi dan *gain*. Antena telah direka pada substrat FR-4 dengan ketebalan 1.5mm (83.9*80.6*1.6mm). Selain itu, beberapa analisis telah dilakukan, antaranya analisis jenis reka bentuk Vivaldi, kesan radius bulatan kaviti pada prestasi antena, dan analisis jenis-jenis *Feeding*. Antena Vivaldi yang dicadangkan telah difabrikasi menggunakan teknik *etching* dan diuji menggunakan *Vector Network Analyzer*. Hasilnya, reka bentuk yang dicadangkan mempunyai frekuensi resonan 5GHz dan beroperasi dalam julat frekuensi 4.1 hingga 6 GHz dengan S_{11} di bawah -10dB dan VSWR antara 1 dan 2. Reka bentuk yang dicadangkan boleh menghantar dan menerima signal dengan jalur lebar yang luas dengan nilai *directivity* bersamaan 6.8dBi, dan nilai *gain* bersamaan 5.11dBi.

ABSTRACT

This paper presents an ultra-wideband Vivaldi antenna for non-destructive measurement in 5G applications. The free-space method enables the non-destructive dielectric characterization of materials over a wide frequency range of different material characterization techniques. The use of the Vivaldi antenna in the non-destructive measurement system has been introduced to reduce the measurement setup space. This project aims to design the Vivaldi antenna by investigating its design dimensions and analyzing the antenna performance by its return loss (S_{11}), Voltage Standing Wave Ratio (VSWR), radiation pattern, and gain. The antenna is designed on the FR-4 substrate with a thickness of 1.5mm (83.9*80.6*1.6mm). Several analyses have been done, which include the Vivaldi design type analysis, the effect of cavity radius, and the feeding type analysis. The proposed Vivaldi antenna has been fabricated using etching techniques and tested using the vector network analyzer. As a result, the proposed design has a resonant frequency of 5GHz and operates in the frequency range of 4.1 to 6 GHz with a return loss below -10dB and VSWR between 1 and 2. The proposed design can send and receive signals with a wide bandwidth, high directivity of 6.8dBi, and a gain of 5.11dBi.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

ε_r	Relative Permittivity
W_a	Aperture Width
L_a	Aperture Length
f_L	Lower Frequency
c	Speed of Light
s	Constant
r	Taper rate
dB	Decibel
dBi	Decibel per isotropic
mm	millimeter
GHz	Gigahertz

LIST OF ABBREVIATIONS

FSM	Free Space Method
MUT	Material Under Test
VNA	Vector Network Analysis
UWB	Ultra-wide Band
VSWR	Voltage Standing Wave Ratio
CST	Computer Simulation Technology
VA	Vivaldi Antenna
VAHCS	Vivaldi Antenna with Hemicylindrical Slots
VAHCSD	Vivaldi Antenna with Hemicylindrical Slots and Directors
RCS	Radar Cross Section
VAC	Vivaldi Antenna with Cavity
VACR	Rounded-end Vivaldi Antenna with Cavity

CHAPTER 1

INTRODUCTION

1.1 Project Background

A non-destructive measurement system is a system that measures the characteristics of materials without changing the structure of the material [1]. The characteristics of a material can be obtained by measuring its electrical properties. Electrical properties are consists of conductivity, dielectric strength, arc resistance, permittivity, and dissipation factor [2]. For example, the purity of a bar of gold can be determined by measuring its conductivity value and comparing it with the conductivity value of natural gold. Besides that, the system can be used in the agriculture applications [3][4][5], A non-destructive measurement system does not require sample preparation and can be applied directly to the material. Therefore, this system can provide fast and accurate evaluations in many applications [4].

There are four standard methods for measuring the permittivity of the material. The methods include the transmission/reflection method [6], the open coaxial probe method [7], the resonant method [8], and the free-space method [9]. Sample preparation is required for the transmission/reflection method, open coaxial probe, and resonant methods [10]. The sample preparations include cutting, compressing, and extruding the material to be measured. These methods are called "destructive tests." In contrast, the free-space method only requires that the material under test be parallel in between the sensors.

Since no sample preparation is required, the free space measurement method or can be called as the non-destructive measurement method is the most straightforward approach to determining the permittivity of a material. The non-destructive measurement system is a measurement setup that consists of a Vector Network Analyzer (VNA), two sets of antennas (transmitter and receiver), and the material to be tested [10]. The antennas are used to fire the microwave beam through the material sample, and the VNA measures the reflection coefficients [3]. The benefits of non-destructive measurement system include high-frequency measurement, which is suitable for measuring solids and liquid samples. Figure 1.1 below shows the measurement setup of non-destructive measurement system.

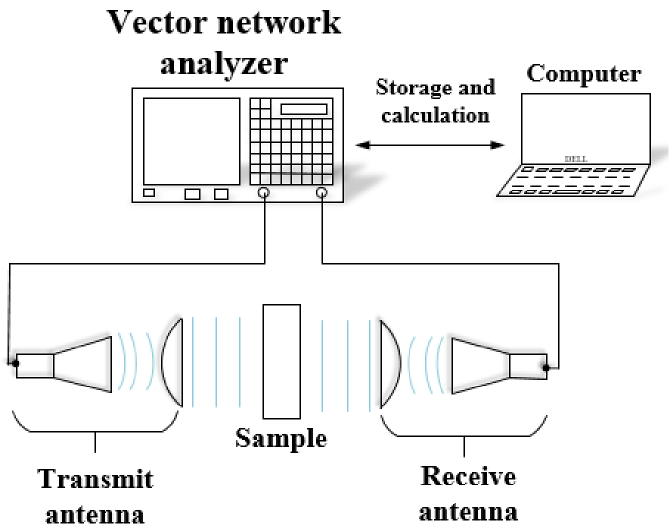


Figure 1.1 Non-destructive Measurement Setup [10].

A high-performance antenna design is needed to create the non-destructive measurement setup. The antenna needs to have high directivity and good radiation characteristics [11]. Based on previous research on non-destructive measurement system [4], the horn antenna is the most common type of antenna used in the measurement setup because it has high directivity and good radiation characteristics. Figure 1.2 below shows the structure of the horn antenna with its radiation gain.

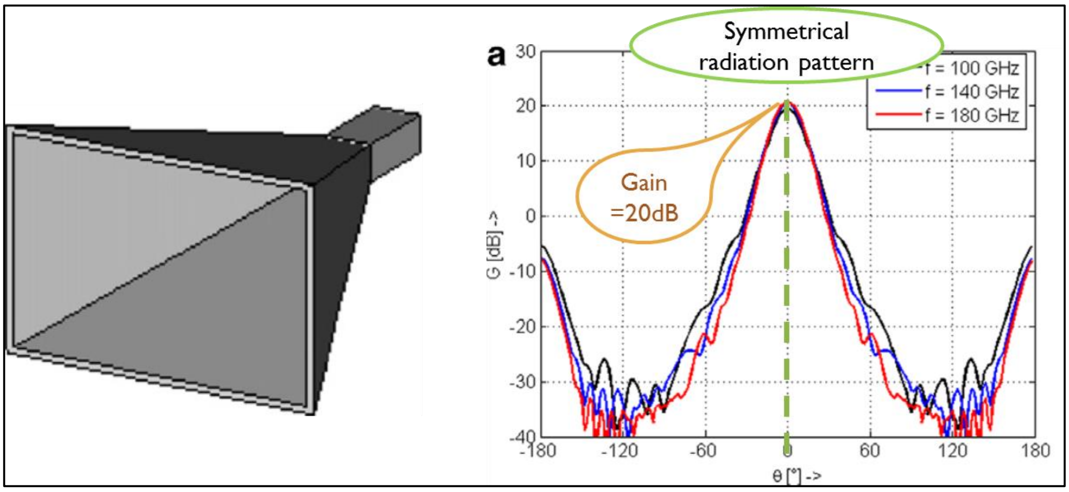


Figure 1.2 Horn Antenna Structure and Radiation Gain [11].

Another type of antenna that can provide almost the same performance as the horn antenna, which is the Vivaldi antenna. The Vivaldi antenna is a planar antenna that can operate in Ultra-Wide Bandwidth (UWB) frequencies ranging from 3.1 to 10.6 GHz [12][13][14]. In addition, the Vivaldi antenna is more compact compared with the horn antenna. The Vivaldi antenna can fit into small spaces with its planar and compact design. Figure 1.3 below shows the structure of the Vivaldi antenna with its radiation pattern.

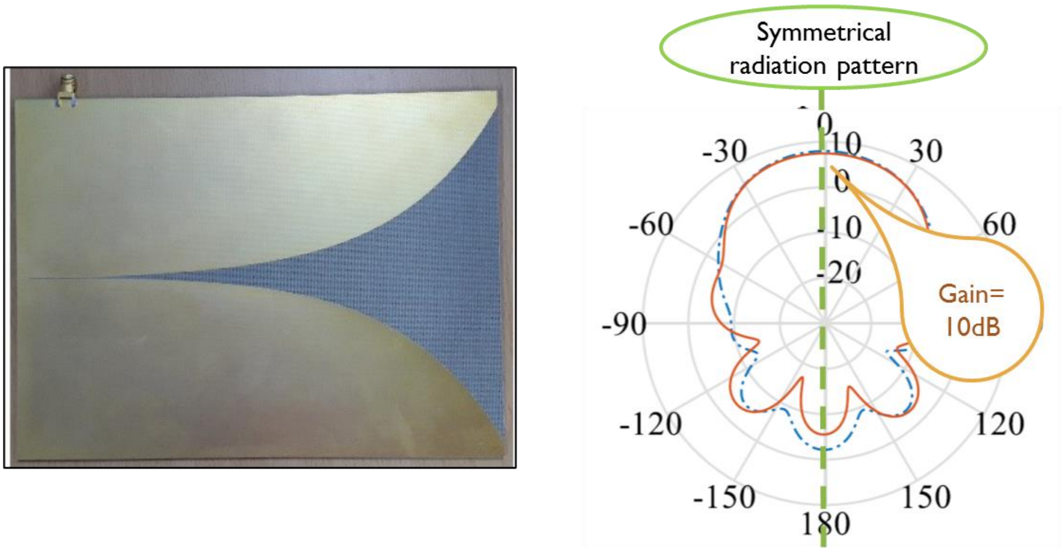


Figure 1.3 Vivaldi Antenna Structure and Radiation Pattern [15].

1.2 Problem Statement

A non-destructive measurement system allows rapid evaluation with no sample preparation and contactless measurement [4]. Based on previous research on the non-destructive measurement system [10][4][16], the horn antenna is the most common antenna type used in the measurement system.

Due to the big and bulky structure of the horn antenna, the non-destructive measurement system requires a large setup space. In addition, the size of the antenna needs to be smaller than the material to be measured to reduce the diffraction from the edge of the material [10]. To overcome these issues, a simple and compact antenna is required.

According to research [15], Vivaldi antenna can provide a high gain and good radiation characteristics. With its planar and compact design, the Vivaldi antenna is a promising antenna to be applied in the free-space measurement system or can be said as non-destructive measurement system. Therefore, the optimal Vivaldi antenna design is being proposed to achieve good performance and can be used in non-destructive measurement applications.

1.3 Objective

The purpose of this project is to design a Vivaldi antenna for non-destructive measurement applications by:

- To design the Vivaldi antenna by investigating its optimal dimension and dielectric material used for the substrate.
- To analyse the Vivaldi antenna's performance by its Return Loss, Voltage Standing Wave Ratio (VSWR), gain, and radiation directivity.
- To fabricate the Vivaldi antenna and evaluate the performance in the non-destructive measurement system

1.4 Project Scope

The limitation of this project is:

- To design a Vivaldi antenna that operates in a G-band frequency (4 to 6 GHz) with a resonant frequency of 5GHz.

- The Vivaldi antenna's return loss should be below -10dB and its VSWR should be between 1 and 2 to achieve the excellent performance of the antenna.

- The Vivaldi antenna is designed and simulated using the Computer Simulation Technology (CST) Studio Suite.

- To fabricate two units of the Vivaldi antenna as a transmitter and receiver in the non-destructive measurement system.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, various Vivaldi antenna designs from previous research are being reviewed to assist in the process of completing the project of designing the Vivaldi antenna. The reference sources are gained from past theses, research journals and articles, and related videos from the internet. From the reviews, observations have been made to identify the methods for designing a Vivaldi antenna. Aside from that, the simulation results from the various antenna designs are being studied to analyse the performance of the antennas. This information is critical for designing a Vivaldi antenna that can be applied in a non-destructive measurement application.

2.2 The Theory of Vivaldi Antenna Design

The structure of the Vivaldi antenna designs is divided into three parts: the radiating structure, substrate, and feeding structure. The radiating structure of the Vivaldi antenna design is in the exponential curve form as shown in Figure 2.1. Hasan et al. (2018) [15] say that the lower cut-off frequency is based on the maximum x-coordinate (x_2) and the higher cut-off frequency is based on the minimum x-coordinate (x_1).

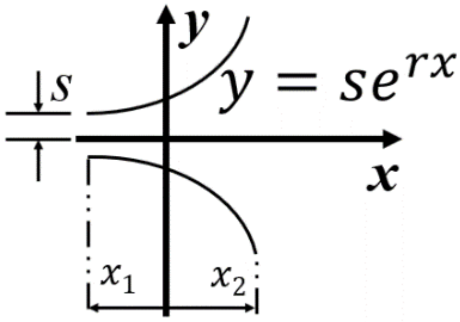


Figure 2.1 Exponential Curve of the Radiating Structure [15].

Based on Figure 2.1, the expression of the exponential curve is given as in equation 2.1:

$$y = \pm s e^{rx} \tag{2.1}$$

Where *s* is a constant and *r* is the taper rate of the curve. Based on Guruswamy et al. (2019) [12], The taper rate, *r* can be expressed as in the equation 2.2.

$$r = \frac{1}{L_a} ln\left(\frac{W_a}{2s}\right) \tag{2.2}$$

Where L_a is the aperture length and W_a is the aperture width.

2.3 Vivaldi Antenna Designs from Research Article

Several Vivaldi antenna designs from the research articles that have been published were reviewed. The purpose is to study more about antenna designs and it helps with ideas in designing the antenna.

2.3.1 A Printed Compact UWB Vivaldi Antenna with Hemi Cylindrical Slots and Directors for Microwave Imaging Applications

The antenna design is proposed by Guruswamy et al. (2019) to detect breast cancer by using microwave imaging systems [12]. This paper describes the modification of the basic design of the Vivaldi antenna by adding hemi-cylindrical slots on the edges of the antenna to increase the electrical length and energy focus on the center of the aperture. Figure 2.2 and Figure 2.3 below show the basic design and the proposed design of Vivaldi antenna.

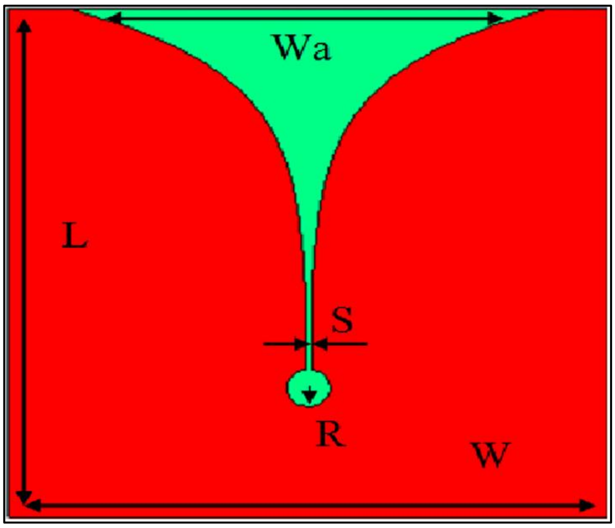


Figure 2.2 Reference Design [12].

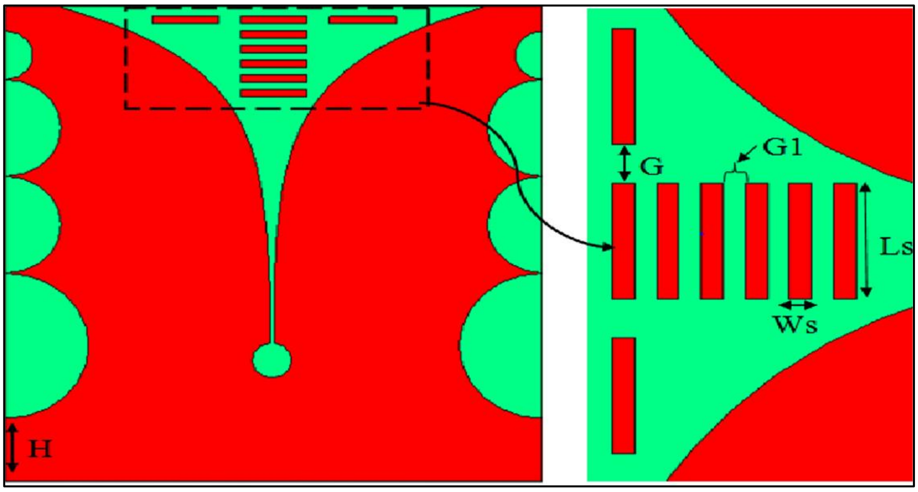


Figure 2.3 Vivaldi Antenna with Hemi Cylindrical Slots and Directors (VAHCSD)[12].

The proposed Vivaldi antenna design is printed on FR4 substrate with dielectric constant of 4.3, loss tangent of 0.025 and thickness of 0.8mm. Table 2.1 below shows the design parameters of the proposed antenna structures.

Table 2.1 Dimension Parameters of VAHCSD [12].

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
L	49	H	6.75
W	48.4	G	2
Wa	38.2	G1	0.75
S	0.4	Ws	0.75
R	1.8	Ls	6

The proposed antenna is designed and simulated in Computer Simulation Technology (CST) software. Figure 2.4 and Figure 2.5 below show the return loss and the radiation pattern of the proposed antenna.

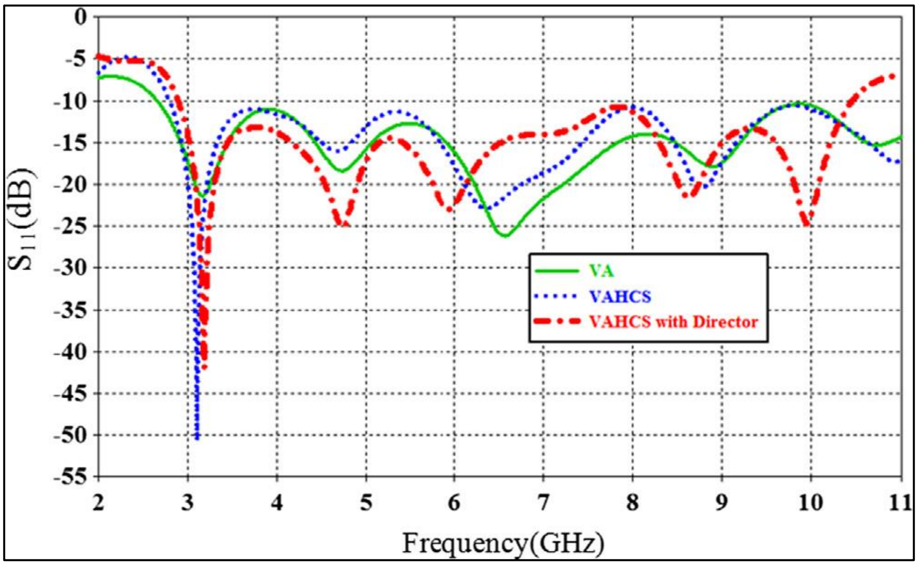


Figure 2.4 Return loss of VA, VAHCS and VAHCS with director [12].

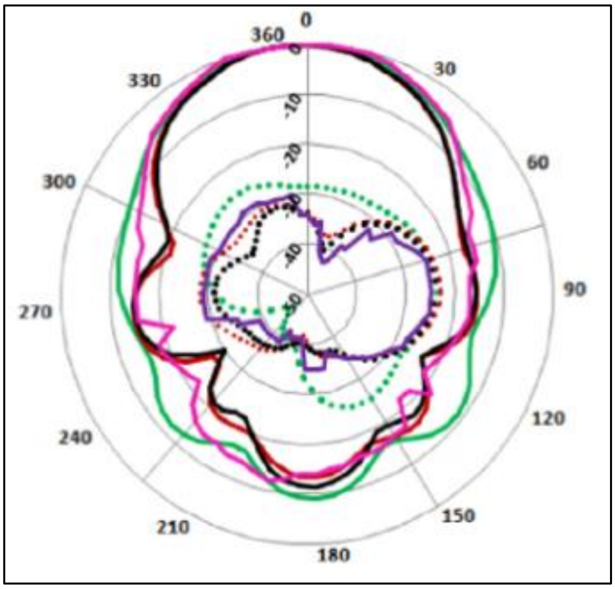


Figure 2.5 Radiation Pattern of Proposed Antenna at 6GHz [12].

Based on Figure 2.4, the return loss value is below -10dB from 2.9 to 10.4 GHz. By adding the hemi cylindrical slots and directors, the resonant frequencies are at 3.18GHz, 4.73 GHz, 5.94 GHz, 8.65 GHz, and 9.97 GHz. The radiation patterns show a directional pattern in Figure 2.5.

2.3.2 Dispersion Characterization of a UWB Vivaldi Antenna in Time and Frequency Domain

In this article, the researcher investigated a Vivaldi antenna for ultra-wideband applications with a thorough dispersion analysis [15]. The antenna design has an impedance bandwidth of 1.45 GHz to 5.35 GHz. At 4.5 GHz, the radiation pattern achieves a peak gain of 10.5 dBi. The antenna design is fabricated using a Taconic RF-35 substrate with a dielectric constant of 3.5, loss tangent of 0.0018 and a thickness of 1.52mm. The Vivaldi antenna are being designed and simulated using ANYSS HFSS software. Figure 2.6 and Table 2.2 below show the antenna design with its dimension parameters.

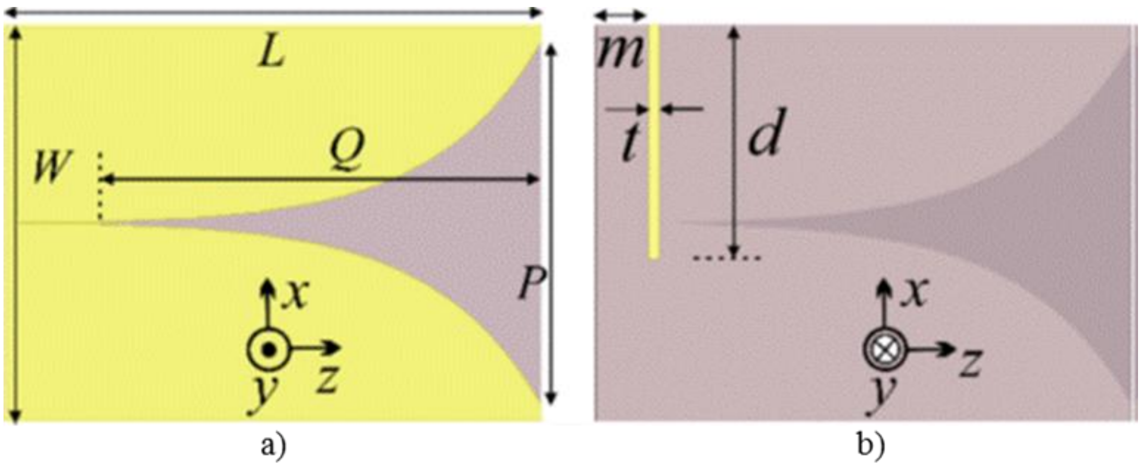


Figure 2.6 Vivaldi Antenna Design with Dispersion Analysis: a) Top view, b) Bottom view [15].

Table 2.2 Dimension Parameters of VA Design with Dispersion Analysis [15].

Parameter	Value (mm)	Parameter	Value(mm)
L	195	m	19.5
W	145	t	3.38
Q	165	d	85.5
P	132.78		

As a result, the Vivaldi antenna design with dispersion analysis has the resonant frequency at 2.5 GHz and the antenna can operate excellently in the frequency range of 1.5 to 5.5GHz as shown in Figure 2.7. Figure 2.8 below shows the radiation pattern of the proposed antenna design at 2GHz.

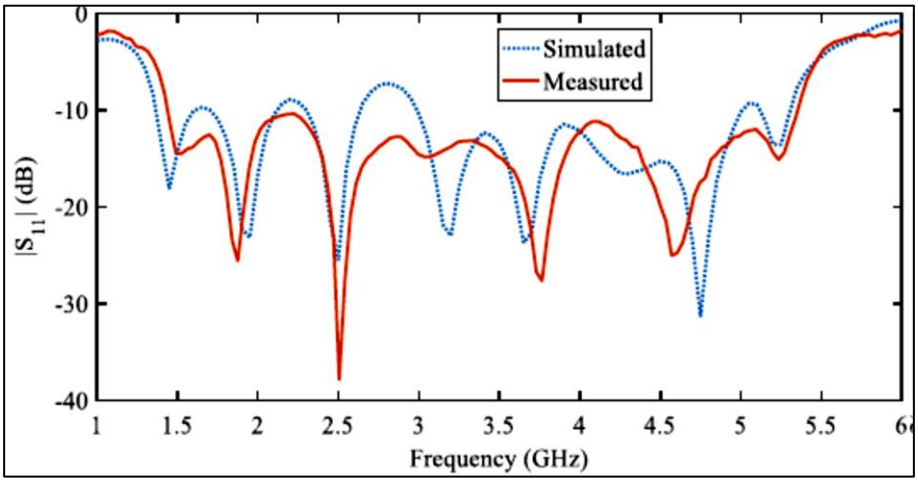


Figure 2.7 Return Loss Plot of the Antenna [15].

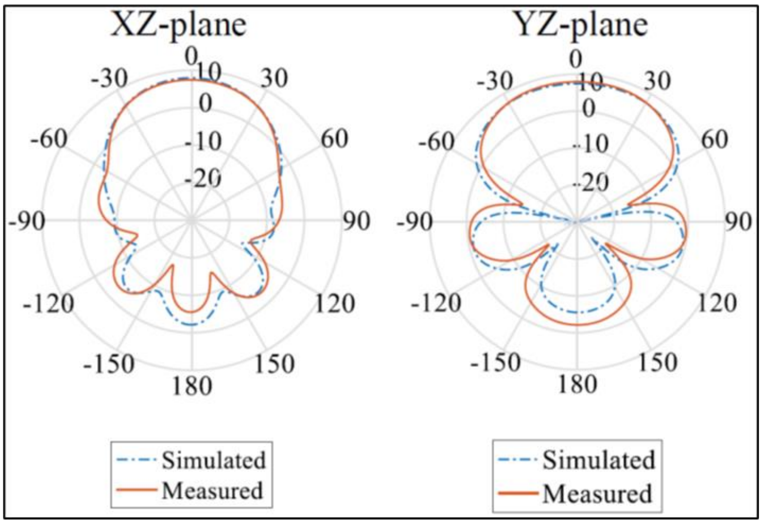


Figure 2.8 Radiation Pattern at 2GHz [15].

2.3.3 An L-Band Ultra-Wide Band Vivaldi Antenna with Wide Beam Angle

In this article, the antenna design is proposed to realize the miniaturization and wide beam of the antenna in the low frequency band by adapting a rounding technique [17]. The antenna design can operate at frequencies ranging from 1.01 GHz to 2.37 GHz. The antenna has potential to be applied in the missile borne field and mobile applications. FR-4 substrate is being used in the antenna design with dielectric constant of 4.3 and thickness of 1.6mm. Figure 2.9 and Table 2.3 below show the Vivaldi antenna design with its dimension parameters from this article.

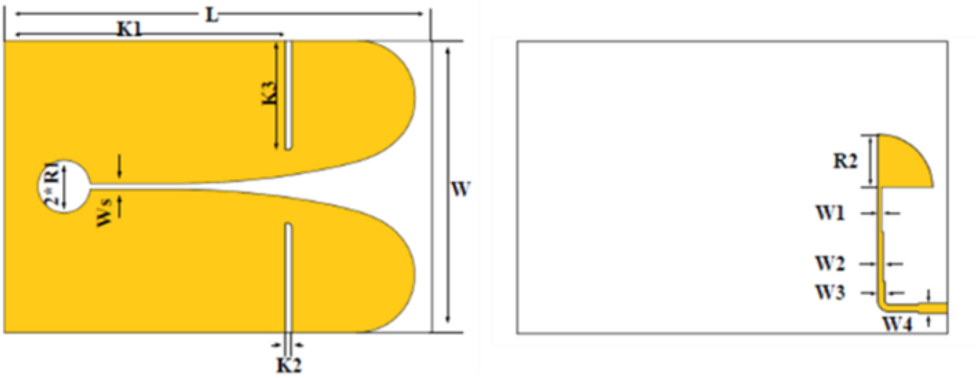


Figure 2.9 L-Band UWB Vivaldi antenna: a) Top view, b) Bottom view [17].

Table 2.3 Dimension Parameters of L-Band UWB Vivaldi Antenna [17].

Parameter	Value (mm)	Parameter	Value (mm)
L	231	W2	1.1
W	154	W3	1.8
Ws	1.4	W4	3.1
R1	14	K1	167
R2	24	K2	1.5
W1	0.7	K3	65

The proposed Vivaldi antenna are being designed and simulated using CST software. Figure 2.10 and Figure 2.11 below shows the return loss and the radiation pattern at 1.4GHz. Based on the results below, it has a resonant frequency of 1.25 and 2.1 GHz with directional radiation pattern.

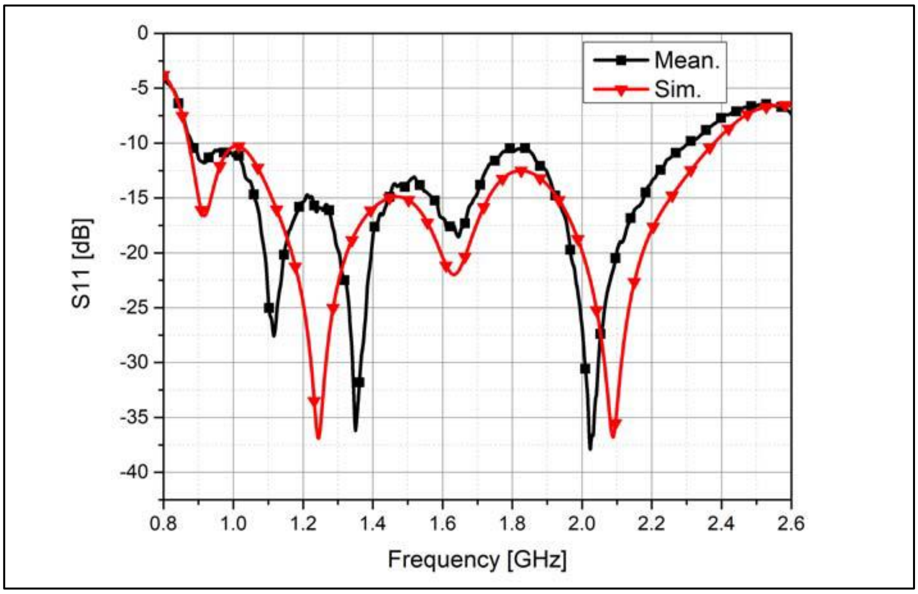


Figure 2.10 S_{11} of UWB L-Band Vivaldi Antenna [17].

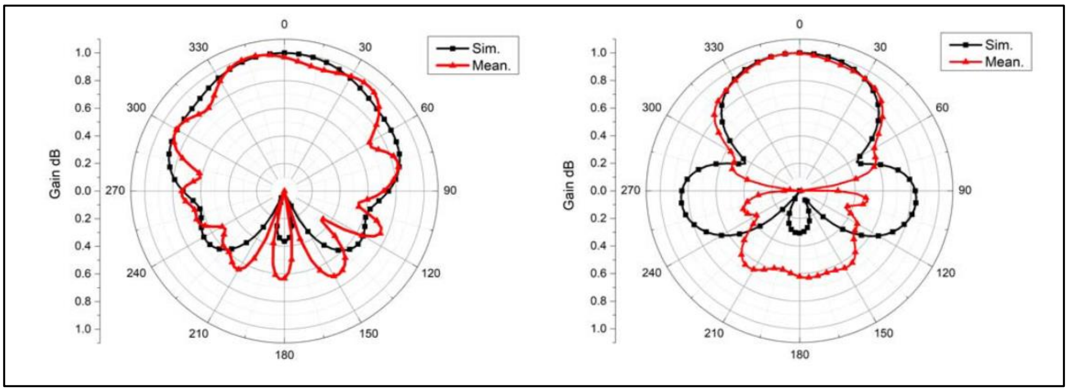


Figure 2.11 Radiation pattern E-plane and H-plane at 1.4GHz [17].

2.3.4 Design of a Vivaldi Antenna with Wideband Reduced Radar Cross Section

In this article, a low radar cross section (RCS) is proposed to achieve a reasonable RCS reduction without affect the performance of the antenna [18]. Object shaping method are being applied in this project by using circle slot on the antenna. The circle slot can minimize the scattering along the surface of the antenna. Taconic RF-60 are being used as substrate in the antenna design with a dielectric constant of 6.15, loss tangent of 0.0038 and thickness of 0.5mm. Figure 2.12 and Figure 2.13 below shows the design of the antennas.

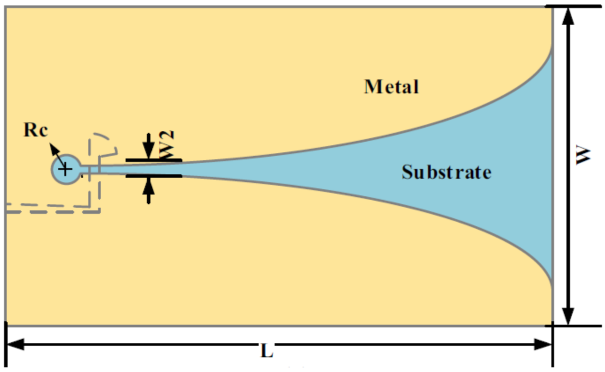


Figure 2.12 Reference Design [18].

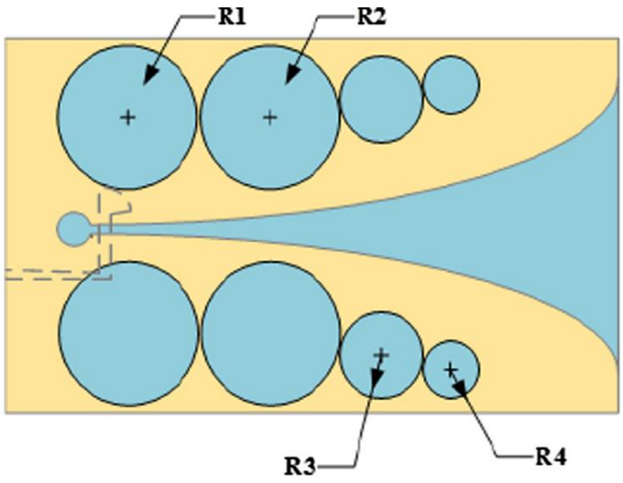


Figure 2.13 Reduced RCS Vivaldi Antenna [18].

The proposed antenna is being designed and simulated using CST software. Based on the simulation result, the antenna can operate in 7GHz to 11GHz and can provide 11dB of radiation gain. Figure 2.14 and Figure 2.15 below shows the simulation results of the proposed antenna design.

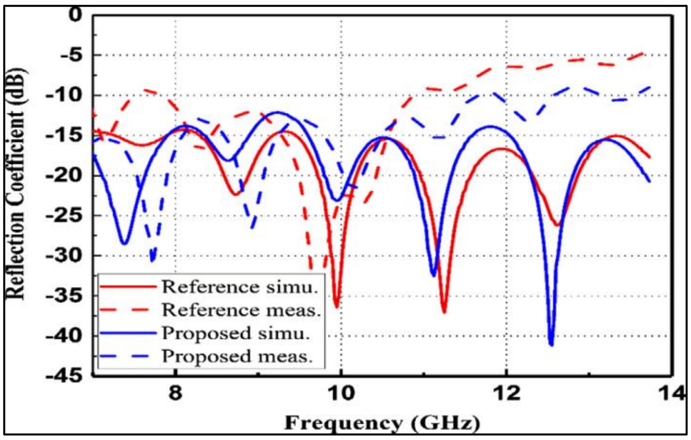


Figure 2.14 Reflection Coefficient of Reference and Proposed Antenna [18].

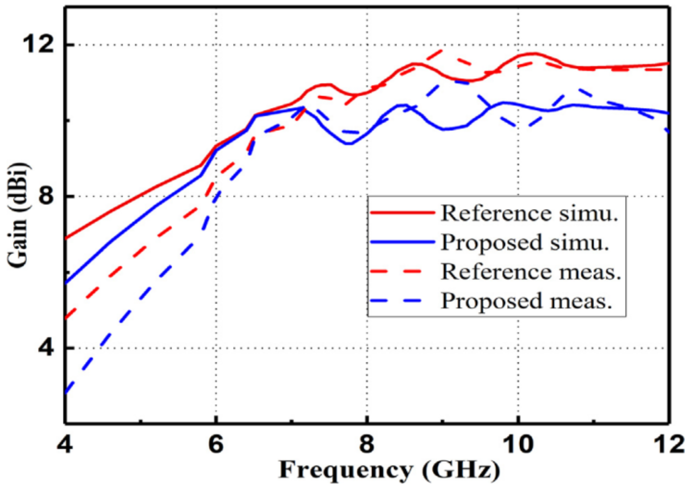


Figure 2.15 Gain Comparison of Reference and Proposed Antenna [18].

2.4 Non-destructive Measurement System Development

The non-destructive measurement system applies the principle of the free-space method (FSM). The FSM measurement setup consists of a Vector Network Analyzer (VNA), two units of antenna (transmitter and receiver), and a material sample to be measured for its dielectric properties, which can be called Material Under Test (MUT). Previous research article on FSM will be reviewed to study the concept of the measurement system.

2.4.1 Free-Space Characterization of Radar Absorbing Non-Magnetic Materials in the W-Band

The free space measurement setup for characterization of radar absorbing non-magnetic materials at W-band frequency is presented in this article. The measurement setup includes two horns with lens antennas, as well as a micrometer-precision positioning fixture for calibration [16].The focused beam lens are used to minimize the diffraction to the sample edges. Figure 2.16 below shows the free space W-band setup.

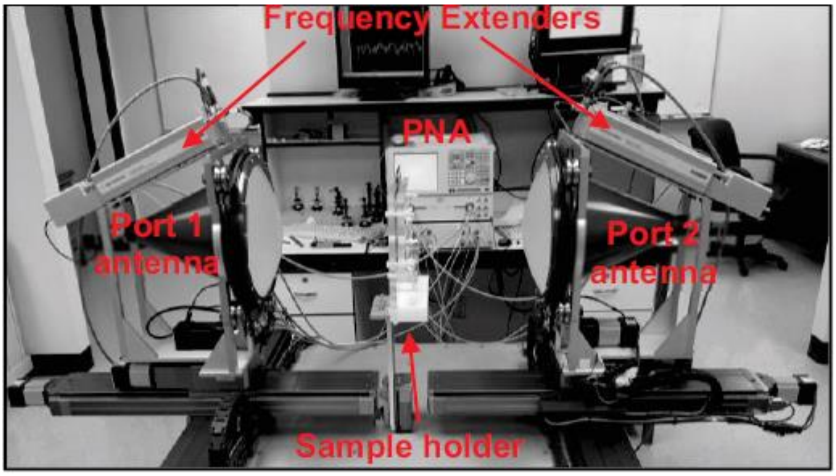


Figure 2.16 W-band Free Space System Setup [16].

The characterization of the sample material under test depends on the precision measurement of the S-parameters. Therefore, the calibration is required to reduce the measurement error. The calibration of the free space measurement setup applies the Thru-Reflect-Line (TRL) method. Figure 2.17 below shows the illustration of the TRL calibration.

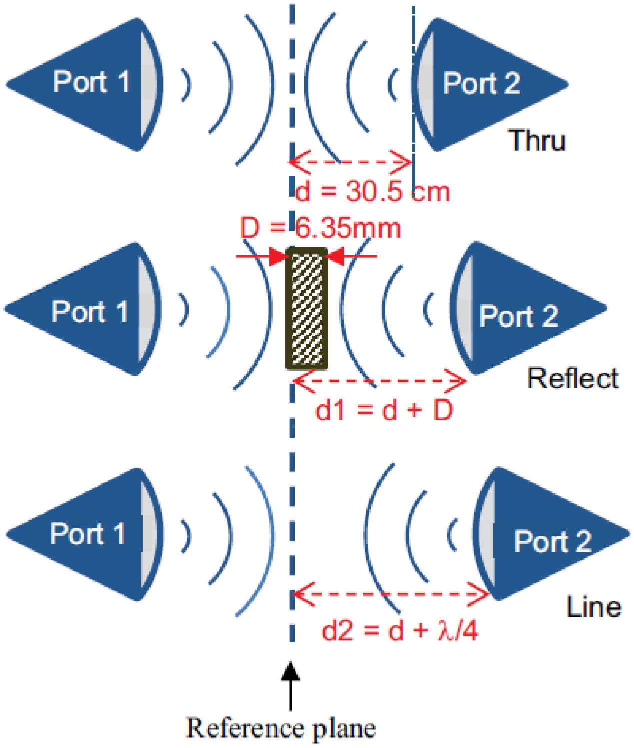


Figure 2.17 Free Space TRL Calibration [16].

Based on the Figure 2.17 above, the 'Thru' calibration is done by pointing the two antennas focused on the reference plane. The distance between the antenna and the reference plane is 30.5 cm. Then, in the 'Reflect' calibration, the gold-plated mirror with a thickness of 6.35mm was placed in between the two antennas. The focal lens of the port 2 antenna was moved by a distance d1=d+D from the reference plane because of the thickness of the mirror. Lastly, in the 'Line' calibration, the mirror was removed, and the port 2 antenna was moved by a distance d2=d+λ/4 from the reference plane.

The quartz samples are used to be characterised in the free space measurement system to test the accuracy of the permittivity extraction. Figure 2.18 below shows the comparison between the measured and calculated S-parameters of a 6.42mm thick quartz sample.

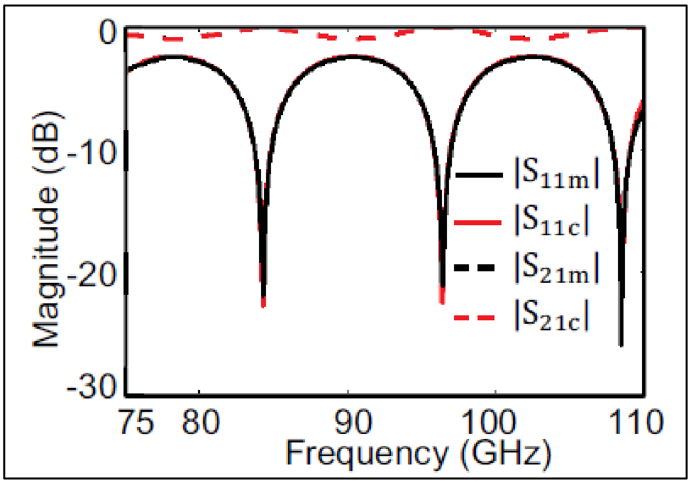


Figure 2.18 Measured and Calculated S-parameters of a Quartz Sample [16].

The measured S-parameters are gained from the PNA E3816A network analyser and validated with a custom-made MATLAB gating code (calculated S-parameter). According to the graph in Figure 2.18, the calculated and measured S-parameters are in good agreement.

2.5 Summary

Based on the article [15], there are theoretical approaches to designing the Vivaldi antenna. By using the mathematical equations that are shown in eq. 2.1 and eq. 2.2, we can design the radiating structure of a Vivaldi antenna with a desired frequency range. Besides that, several Vivaldi antenna designs from the research articles have been reviewed. There are many methods and techniques that have been presented to achieve the desired antenna output in the research. For example, they are using the slot tapering method and changing the shape of the radiating structure of the antenna. Furthermore, the development of a non-destructive system from the research article has been reviewed. The measurement setup of the non-destructive system has been explained in the article [16]. It is important to perform the calibration of the measurement setup to achieve an accurate measurement and minimize any potential error.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will cover all the methodology approaches to achieve the objective of this project. This project is divided into three phases which are the design and analysis phase, fabrication phase, and the antenna testing phase as shown in Figure 3.1. Each phase is dependent and needs to be completed sequentially to complete this project.

In the design and analysis phase, it is consisting of the literature review, validating the design technique, Vivaldi antenna design type analysis, the analysis of the effect of the cavity radius and feeding type analysis. Then, the antenna is fabricated in the following phase. Lastly, the fabricated antenna has been tested to evaluate its performance.

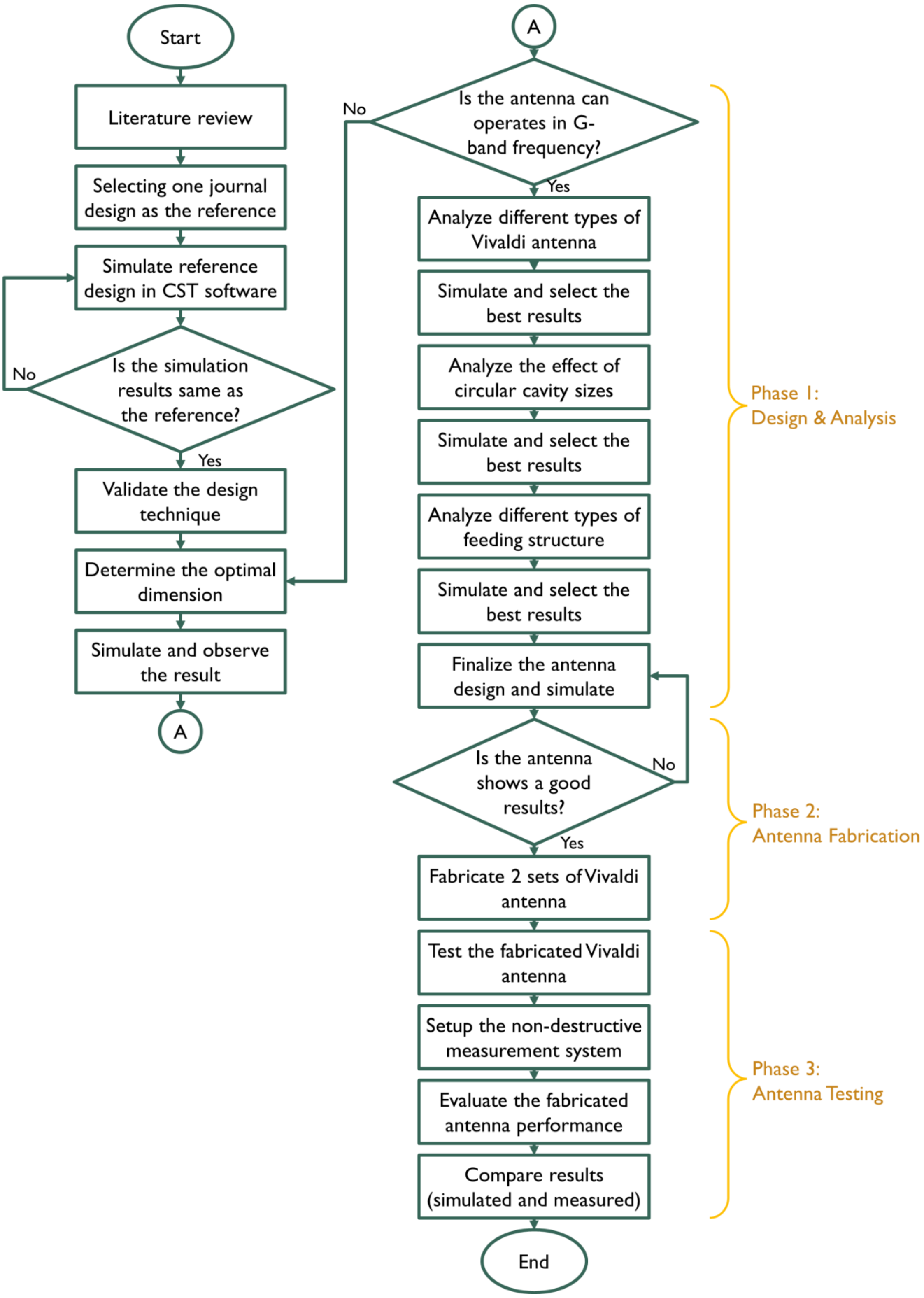


Figure 3.1 Methodology Flowchart.

3.2 Phase 1: Design and Analysis

In the first phase, various designs are to be analysed to find the optimal dimension of the Vivaldi antenna that can operate efficiently at the 5GHz frequency. The process is started by validating the design techniques to justify the method of designing the Vivaldi antenna and to find the starting point of the antenna design. Next, three different Vivaldi antenna structures have been referred to in the literature review and are being used in the making of antenna design to observe the results. Then, the circular cavity radius in the antenna design is changed into four sizes to study the effect on the antenna's performance. After that, three different feeding structures were applied to the antenna design to observe the effect on the antenna's performance. Finally, several alterations have been made to the dimension parameters of the antenna design to achieve the desired objective.

3.2.1 Validate the Design Technique

After observing and studying various Vivaldi antenna designs, one of the designs from the literature review was chosen as a reference and simulated again to justify the antenna design technique in the CST software. To validate the technique in designing the Vivaldi antenna, the simulation results from the reproduced design must be approximately the same as the simulation results from the reference article.

The reference Vivaldi antenna design are taken from Figure 2.6. In the simulation, the dimensions of the Vivaldi antenna design are followed exactly as in the Table 2.2. The simulation steps are divided into two parts, which are designing the Vivaldi antenna and simulation setup in the CST software. Figure 3.2 and Figure 3.3 below describe the step and process of Vivaldi antenna simulation in CST software.

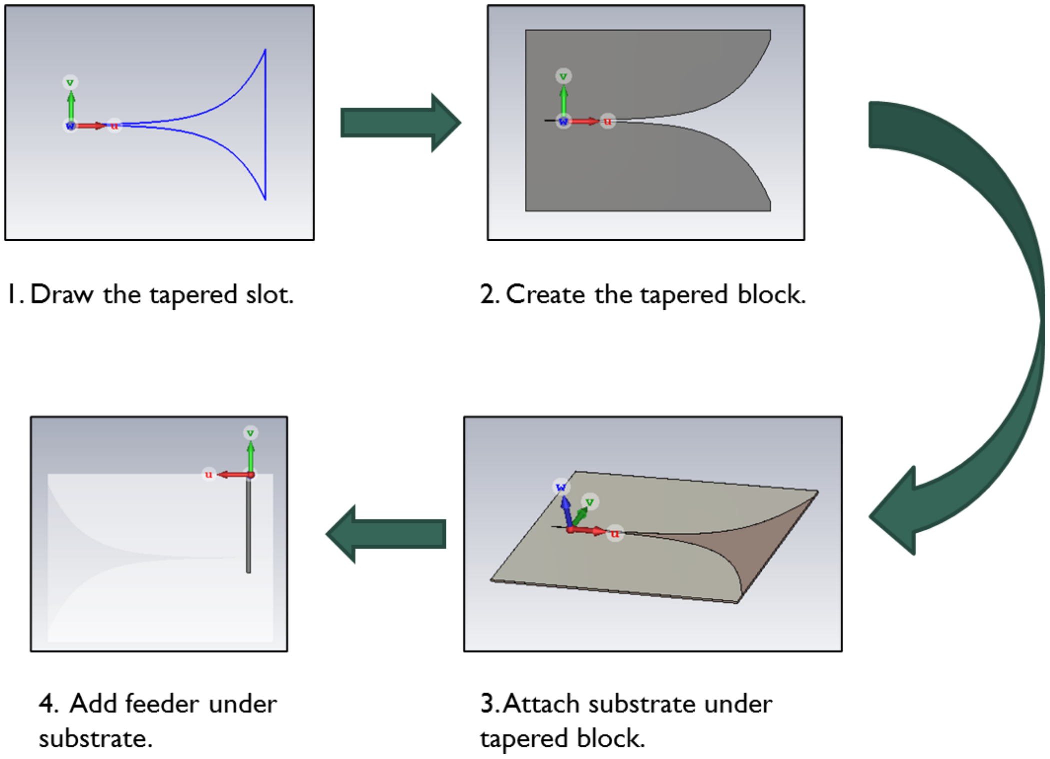
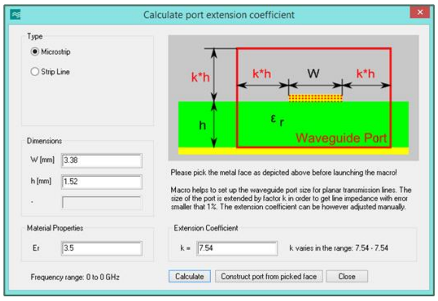


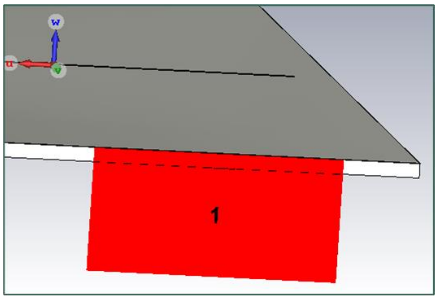
Figure 3.2 Steps for Designing Vivaldi Antenna in CST.

Based on Figure 3.2, the first step on designing the Vivaldi antenna is to draw the tapered slot. Then, create a block and subtract the tapered slot by using the Boolean function. After that, create a substrate block under the tapered block. Finally, add the feeder under the substrate block.

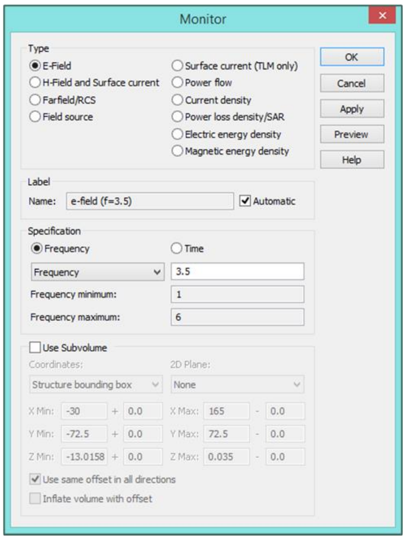
After finished the antenna design, set up the simulation as shown in Figure 3.3. Firstly, calculate the port extension coefficient by using the Macros tools. Then, create the waveguide port. Lastly, select the desired output display and run the simulation.



1. Calculate port extension coefficient



2. Create the Waveguide Port



3. Select the desired output display and then run the simulation.

Figure 3.3 Simulation Setup Steps in CST.

After that, the referenced Vivaldi antenna design is being reproduced again without following the dimension parameters from the reference article. The dimension parameters of the design are determined by using the mathematical modelling and predicting method. According to research [12], there are mathematical equations involved in designing the antenna to calculate several parameters. Equation 3.1 and 3.2 below is the equation for aperture width, W_a and aperture length, L_a.

$$W_a = \frac{c}{2f_L \times \sqrt{\varepsilon_r}} \tag{3.1}$$

$$L_a = \frac{c}{f_L \times \sqrt{\varepsilon_r}} \tag{3.2}$$

Where c is the velocity of light, f_L is the lower frequency and ε_r is the dielectric constant of the substrate.

The tapered exponential curve equation is expressed as eq. 3.3

$$y = \pm s e^{rx} \tag{3.3}$$

Where s is the constant and r is the taper rate of the curve. The taper rate of the curve can be expressed as eq. 3.4

$$r = \frac{1}{L_a} ln\left(\frac{W_a}{2s}\right) \tag{3.4}$$

After completing the calculation of the dimension parameters, the new design has been created, and then proceeds with the simulation of the antenna design in the CST software. Figure 3.4 below shows the theoretical design followed with the dimension parameters in Table 3.1.

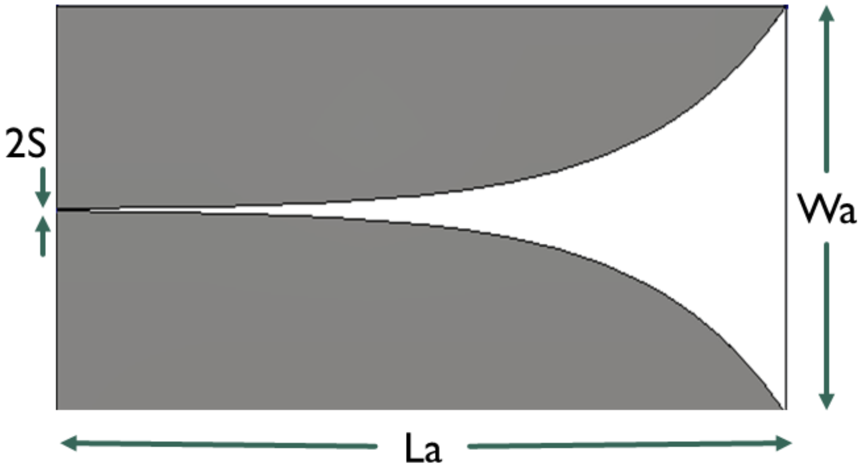


Figure 3.4 Theoretical Vivaldi Antenna Design.

Table 3.1 Dimension Parameters of Theoretical Vivaldi Antenna Design.

Parameter	**Value (mm)**
L_a	160.36
W_a	80.18
s	0.2
r	0.033

3.2.2 The Analysis of Different Vivaldi Antenna Types

Three different designs of the Vivaldi antenna have been created and simulated in the CST. This analysis aims to find an antenna design that has a resonant frequency of 5GHz. The basic Vivaldi antenna, the Vivaldi antenna with cavity, and the rounded-end Vivaldi antenna with cavity are among the designs.

3.2.2.1 Design of Basic Vivaldi Antenna

The first design is the basic Vivaldi antenna that is referred to as the Vivaldi antenna designed by Hasan et al.(2018)[15]. The material used for the substrate in this antenna design is FR-4 with a dielectric constant of 4.3, a loss tangent of 0.025, and a thickness of 1.5mm. Figure 3.5 and Table 3.2 below show the basic Vivaldi antenna design with its dimension parameters.

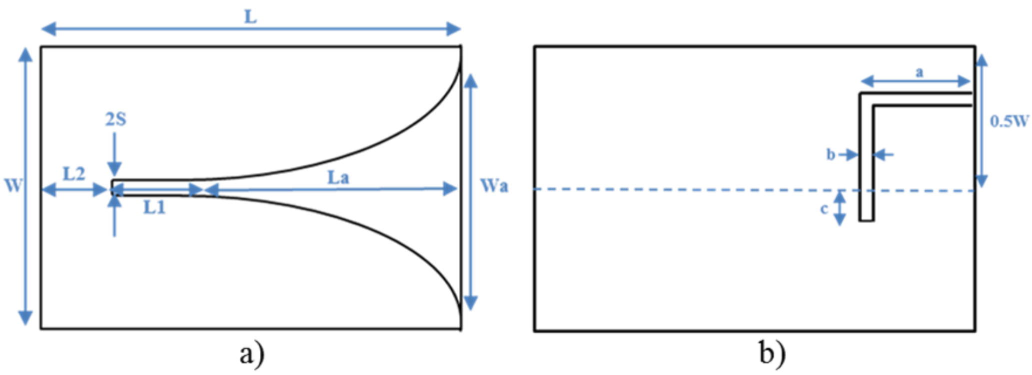


Figure 3.5 Basic Vivaldi Antenna: a) Top view, b) Bottom view.

Table 3.2 Dimension Parameters of Basic Vivaldi Antenna.

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
L	63.7	L_1	8
W	56	L_2	10.7
s	0.2	a	15.7
r	0.105	b	1.8
L_a	45	c	7.5
W_a	45.1		

3.2.2.2 Design of Vivaldi Antenna with Cavity

In the second design, the circular tapered slots are added at the throat of the aperture and called as the cavity. Based on Guruswamy et al. (2019)[12], the circular cavity can minimize the reflections from microstrip line to slot line transition and exhibits better impedance characteristics. The material used for the substrate in this antenna design is FR-4 with a dielectric constant of 4.3, a loss tangent of 0.025, and a thickness of 1.5mm. Figure 3.6 and Table 3.3 below show the Vivaldi antenna with cavity design with its dimension parameters.

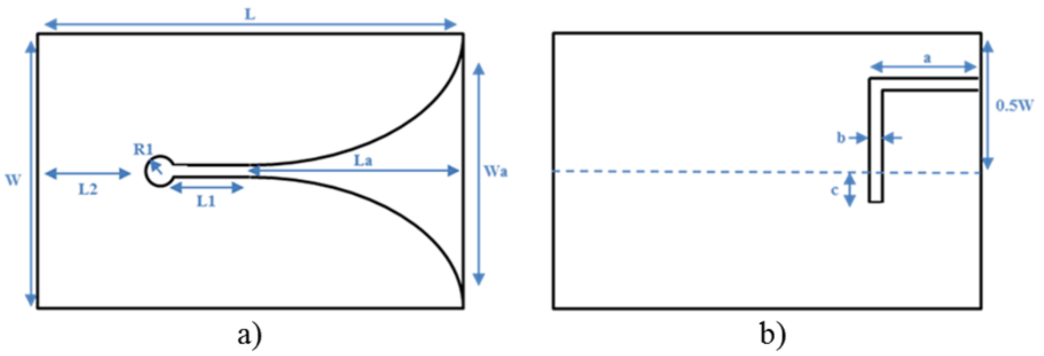


Figure 3.6 Vivaldi Antenna with Cavity (VAC): a) Top view, b) Bottom view.

Table 3.3 Dimension Parameters of VAC.

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
L	63.7	L_1	8
W	56	L_2	10.7
s	0.2	a	15.7
r	0.105	b	1.8
L_a	45	c	7.5
W_a	45.1	R_1	1.8

3.2.2.3 Design of Rounded-end Vivaldi Antenna with Cavity

In the third design, the end of the antenna tapered slot is rounded. Based on Li et al. (2020)[17], the rounded end can increase the electrical strength and reduce the size of the antenna. The material used for the substrate in this antenna design is FR-4 with a dielectric constant of 4.3, a loss tangent of 0.025, and a thickness of 1.5mm. Figure 3.7 and Table 3.4 below show the Vivaldi antenna with cavity design with its dimension parameters.

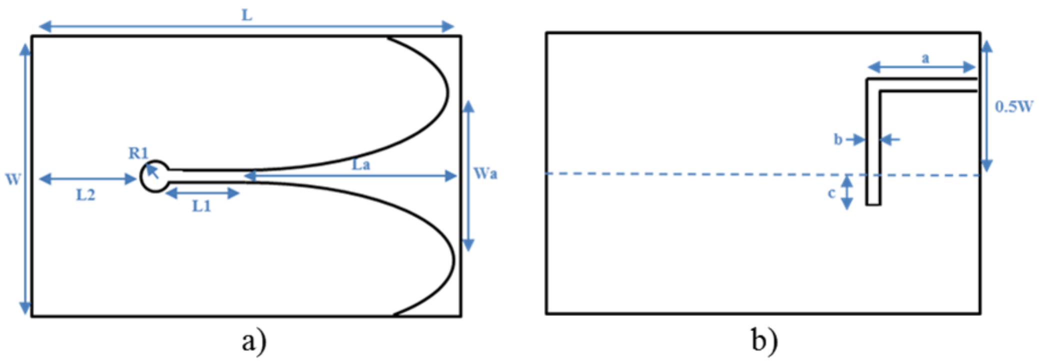


Figure 3.7 Rounded-end Vivaldi Antenna with Cavity (VACR): a) Top view, b) Bottom view.

Table 3.4 Dimension Parameters of VACR.

Parameter	Value (mm)	Parameter	Value (mm)
L	63.7	L_1	8
W	56	L_2	10.7
s	0.2	a	15.7
r	0.105	b	1.8
L_a	45	c	7.5
W_a	45.1	R_1	1.8

3.2.3 The Effect of Circular Cavity Radius

From the previous analysis, the Vivaldi antenna with cavity (VAC) is selected because it achieves a resonance frequency closer to 5GHz compared with other Vivaldi antenna types. The following analysis is to observe the effect of the radius size of the circular cavity. Based on Guruswamy et al. (2019) experiment work [12], the accurate cavity radius can perform the better impedance characteristics. Different radiuses of circular cavities are simulated in this analysis to figure out how well the antenna works. The radius, R_1, has been set at 1.8mm, 2.2mm, 2.6mm, and 3.0mm in the simulation.

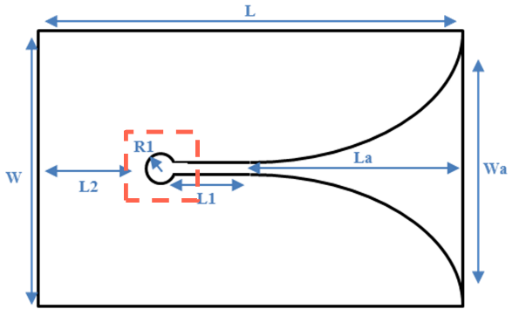


Figure 3.8 Circular Cavity.

After selected the best circular cavity outcomes, Table 3.5 below shows the updated dimension parameters of the VAC.

Table 3.5 Updated Dimension Parameters of VAC.

Parameter	Value (mm)	Parameter	Value (mm)
L	63.7	L_1	8
W	56	L_2	10.7
s	0.2	a	15.7
r	0.105	b	1.8
L_a	45	c	7.5
W_a	45.1	**R_1**	**2.6**

3.2.4 The Analysis of Different Feeding Types

From the previous analysis, the VAC with a cavity radius size of 2.6 mm was selected because it has the best performance of all the radius sizes. In the following analysis, different types of feeding structures are simulated in the CST to investigate if the different shapes of feeding can affect the antenna's performance. Based on Khusna et al. (2019)[19], the variety of feeding structures is one of the factors in the Vivaldi antenna design process. Three different feeding types will be tested in this analysis: rectangular, circular, and shell pattern. Figure 3.9, Figure 3.10 and Figure 3.11 below show the types of feeding structures.

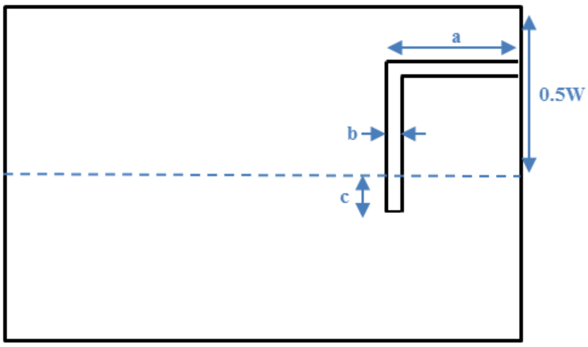


Figure 3.9 Rectangular Feeding.

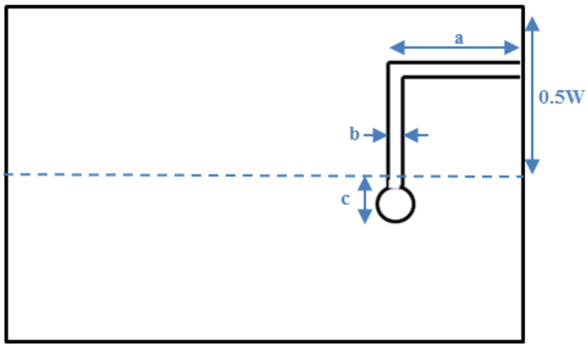


Figure 3.10 Circular Feeding.

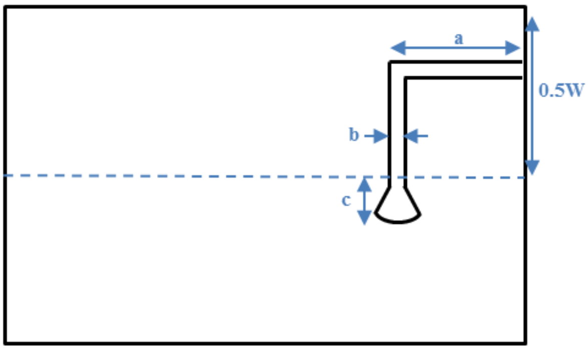


Figure 3.11 Shell Feeding.

3.2.5 Dimension Alteration of the Antenna Design

From the previous analysis, the Vivaldi antenna with shell feeding type is chosen because the overall S_{11} parameter of the return loss is below -10dB. However, some alterations to the dimension parameters in Table 3.5 were made in order for the antenna operate efficiently at a 5GHz frequency. In the finished design, the antenna width (W), extended from 56mm to 80.6mm; the throat length (L_1), extending from 8 mm to 18 mm;

and the aperture length (L_a), extended from 45mm to 50mm. Figure 3.12 and Table 3.6 below show the final design of the Vivaldi antenna with its dimension parameters.

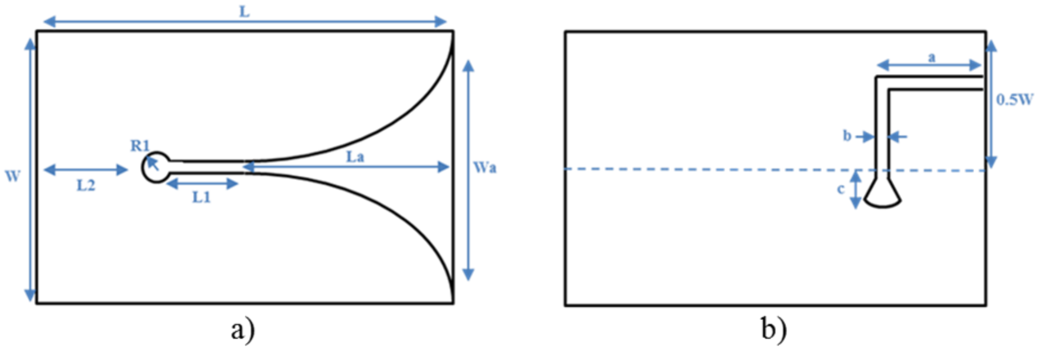


Figure 3.12 Final Design: a) Top view, b) Bottom view.

Table 3.6 Dimension Parameters of Final Design.

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
L	83.9	**L_1**	**18**
W	**80.6**	L_2	10.7
s	0.2	a	15.7
r	0.105	b	1.8
L_a	**50**	c	7.5
W_a	76.23	R_1	2.6

3.3 Phase 2: Antenna Fabrication

The second phase starts when the Vivaldi antenna design has been finalized. In this phase, the proposed design of the Vivaldi antenna is fabricated using the etching methods. The etching method provides ease of fabrication, time-saving and low cost. The etching method involves with the use of chemicals. Hence, all safety precautions for handling the chemicals have been followed.

Before starting the process of etching the antenna, preparing all the equipment and the components are necessary. The equipment and components included in this process are the double-sided FR-4 printed circuit board (PCB), ferric chloride solution (etching chemical), glossy photo paper, scrubber, and heating equipment. Figure 3.13 and Figure 3.14 below show the double-sided FR-4 PCB and the ferric chloride solution.

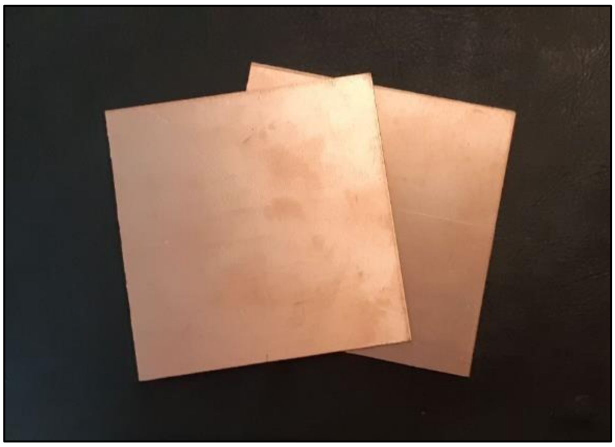


Figure 3.13 Double-sided FR-4 PCB Board.

Figure 3.14 Ferric Chloride Solution.

The first step of the etching process is cleaning up the PCB. Scrub the upper and lower side of the board with the scrubber and rinse it with water to clean away the residue. Figure 3.15 below shows the condition of the PCB after it has been cleaned.

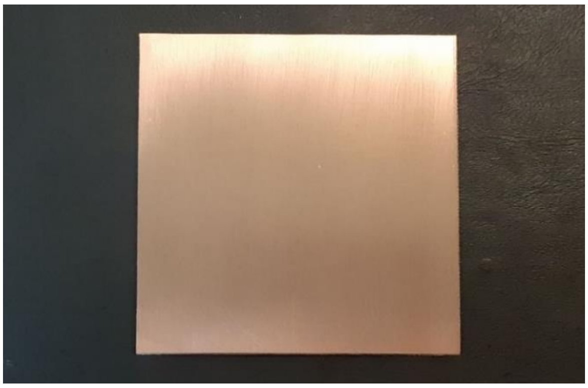


Figure 3.15 Cleaned PCB.

The second step is transferring the antenna design's layout from the printed paper to the PCB. Patch the printed layout on the top and bottom of the PCB and heat it with the heating equipment as shown in Figure 3.16. The heating process is taken about 10 minutes to transfer the ink from the paper to the PCB.

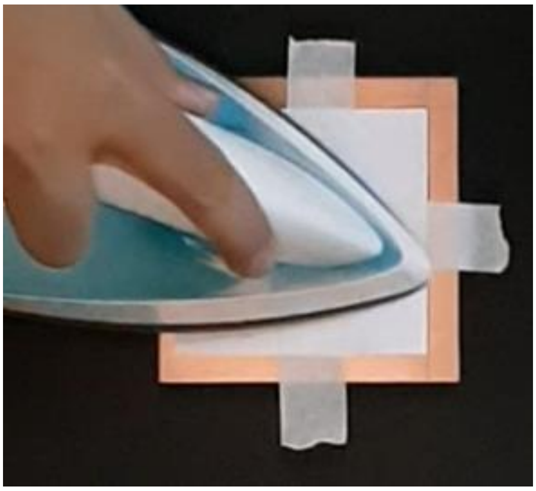
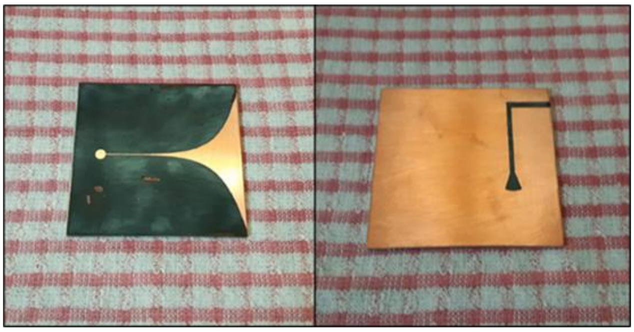


Figure 3.16 Heating Process.

After that, submerge the PCB in the clean water as in Figure 3.17 and leave for about 10 minutes. Then, slowly scrub the paper away from the PCB and it gets as shown in Figure 3.18.

Figure 3.17 PCB Submerged in Water.



a) b)

Figure 3.18 PCB with the Layout Ink: a) Top view, b) Bottom view.

The third step is the etching process. This process is to eliminate the unwanted copper on the PCB. Pour the etching chemical into the container. Then, submerge the PCB with the layout ink into the etching chemical as shown in Figure 3.19. Leave it until all the unwanted copper has been eliminated.

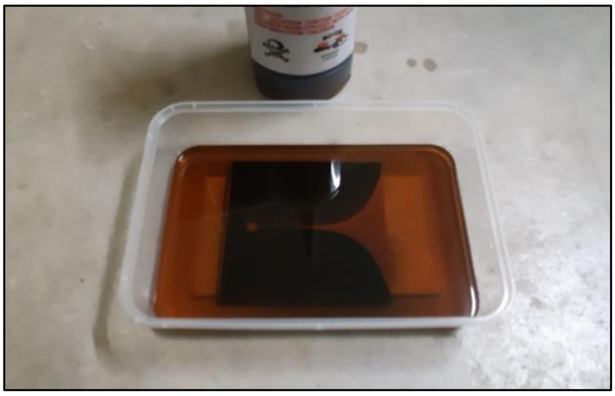
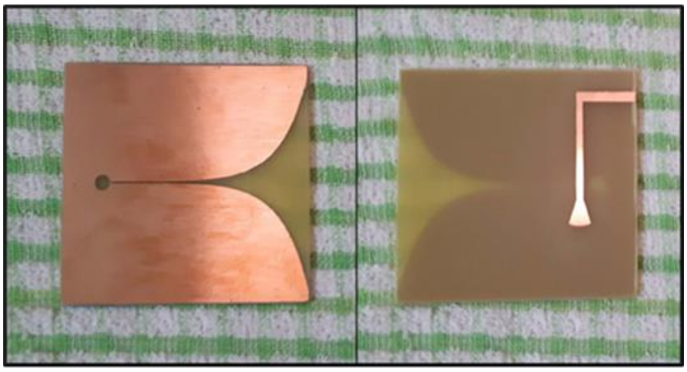


Figure 3.19 PCB Submerge into the Etching Chemical.

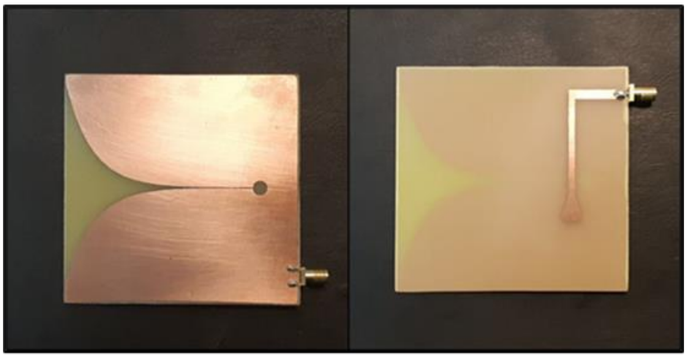
After that, rinse the PCB with clean water and scrub the top and bottom layers of the PCB to remove the ink. Figure 3.20 below shows the etched Vivaldi antenna.



a) b)

Figure 3.20 Etched Vivaldi Antenna: a) Top view, b) Bottom view.

Finally, attach the SMA connector to the Vivaldi antenna. Solder the SMA connector to the feeding part of the Vivaldi antenna. Now, the fabrication of the Vivaldi antenna has been completed. Figure 3.21 below shows the fabricated Vivaldi antenna.



a) b)

Figure 3.21 Fabricated Vivaldi Antenna: a) Top view, b) Bottom view.

3.4 Phase 3: Antenna Testing

In the third phase, the fabricated antennas should be tested in order to analyse and evaluate the antenna performance by comparing the test results with the simulation results. The antenna was tested by its return loss (S_{11}). The Vivaldi antenna has been tested using the E5071C ENA vector network analysis from Agilent Technologies. Figure 3.22 below illustrates that the antenna is under test.

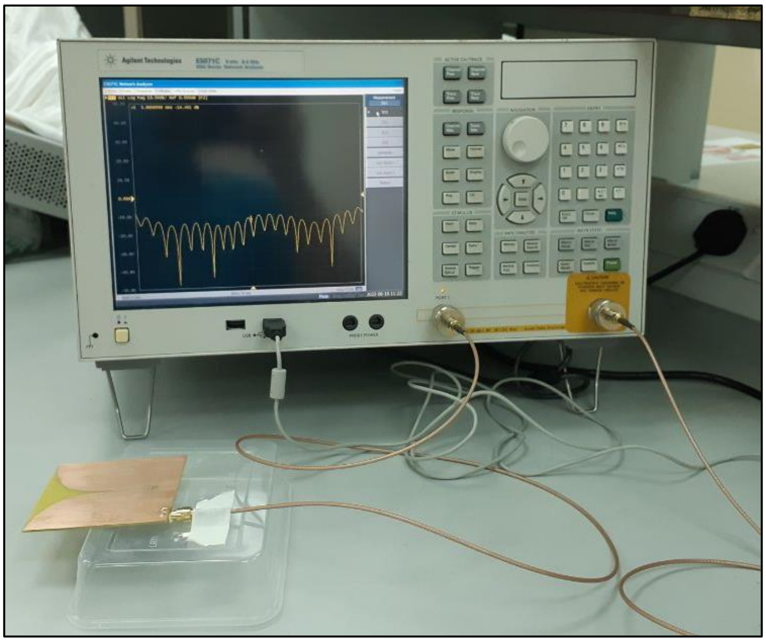


Figure 3.22 Antenna Testing.

After the antenna's performance has been evaluated, the non-destructive measurement system will be set up as in Figure 3.23 to test the insertion loss (S_{21}) of the two-port measurement system. There are two conditions for the measurement setup: without a material sample and with a material sample. The purpose is to figure out if any different readings occurred on the results.

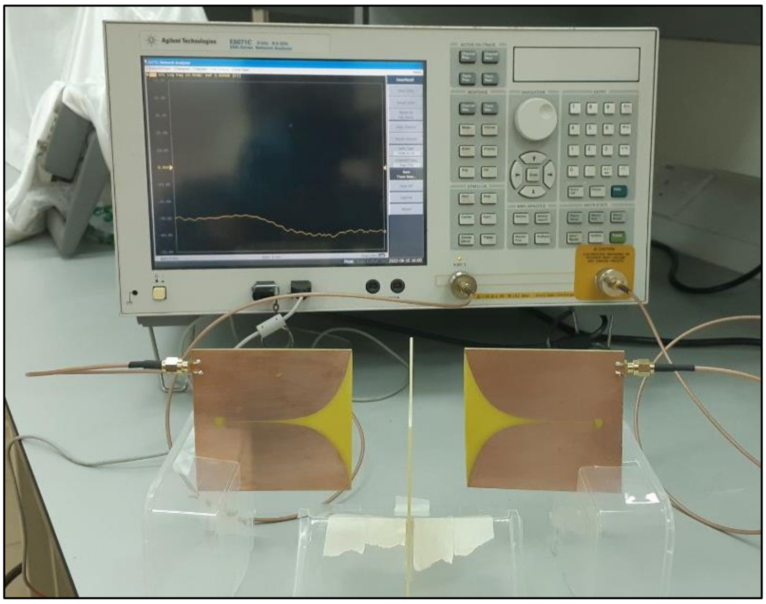


Figure 3.23 Non-destructive Measurement Setup.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will discuss the results from the experimental and simulation of all the Vivaldi antenna designs discussed in the previous chapter. Starting from the simulation designs until the antenna testing, the results to be discussed are the return loss, the voltage standing wave ratio (VSWR), the gain, and the antenna design's radiation pattern.

4.2 Results from Phase 1: Design and Analysis

In the first phase, the simulation in CST software was carried out on validating the design technique, design type analysis, the effect of the cavity radius, and the feeding type analysis. Also, the final design of the Vivaldi antenna with the optimal dimensions has been simulated, and the results will be discussed in this section.

4.2.1 Simulation Results from Reproducing Reference Design

As mentioned in the previous chapter, the reproducing antenna design dimension parameters are followed exactly as stated in Table 2.2 and have been simulated in the CST software. Therefore, to validate the antenna design technique, the simulation results should be the same as the results produced in the reference antenna design. Figure 4.1 and Figure 4.2 below shows the comparison simulation results between the reference design and the reproducing antenna design.

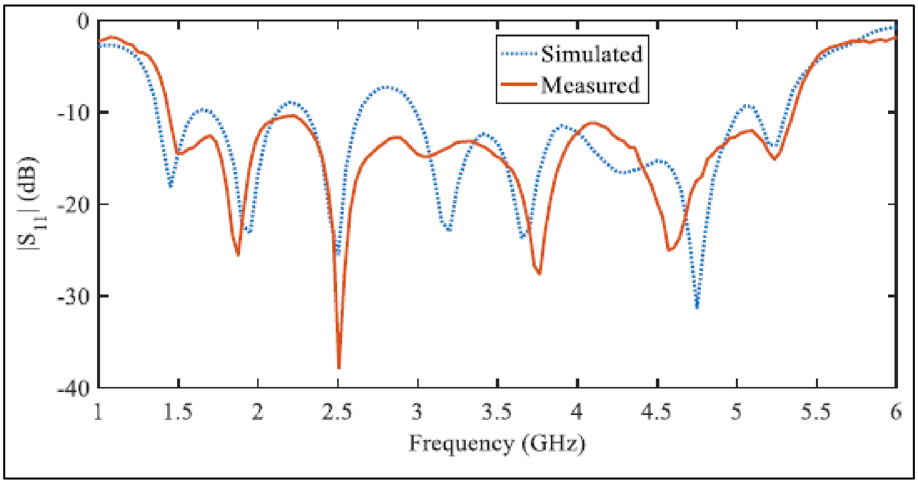


Figure 4.1 S_{11} Results from the Reference Design.

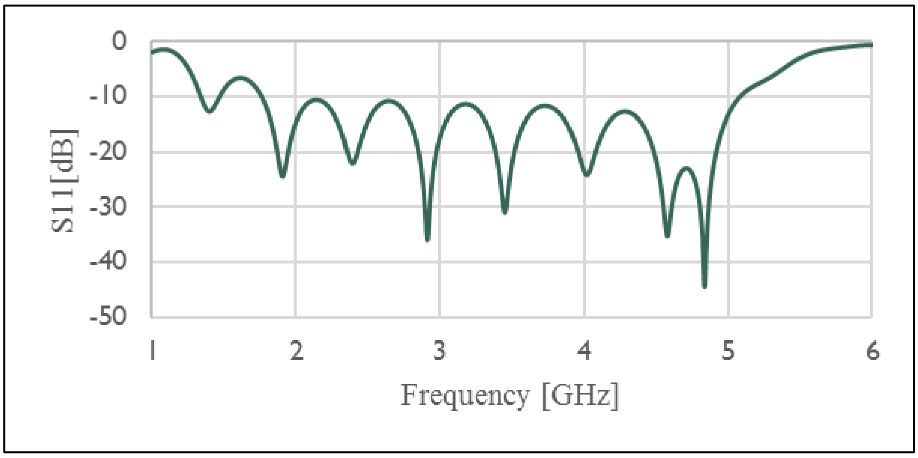


Figure 4.2 S_{11} Results from Resimulate the Reference Design.

Based on Figure 4.2, the return loss (S_{11}) and the radiation pattern from the reproduced design results show almost the same result as in the reference article as shown in Figure 4.1. Therefore, the design technique using CST software has been verified.

4.2.2 Simulation Results from Theoretical Design

In the previous chapter, a Vivaldi antenna design was created using mathematical modelling and predicting methods. This approach is one of the methods to determine the optimal dimension of the antenna design. Figure 4.3 below shows the return loss (S_{11}) and the radiation pattern of the theoretical design of the Vivaldi antenna.

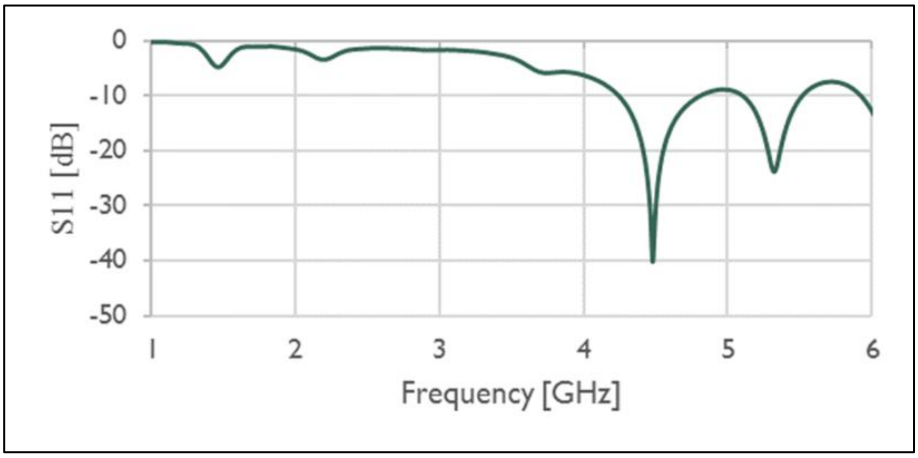


Figure 4.3 S_{11} Parameter of Theoretical Design.

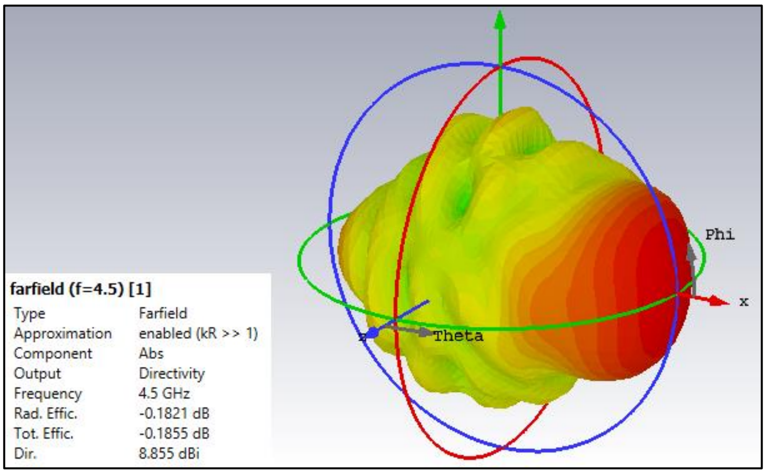


Figure 4.4 Radiation Pattern of Theoretical Design.

Based on Figure 4.3, the theoretical Vivaldi antenna design produces the resonant frequency of 4.5 GHz. However, the antenna performance did not show good results because the values of the return loss (S_{11}) were higher than -10dB. This means that the antenna transmits less energy due to the high reflection of energy. While in Figure 4.4, the gain produced at a 4.5GHz frequency is 8.855 dBi and the radiation pattern is directional. Therefore, the starting point for designing the Vivaldi antenna has been found.

4.2.3 Simulation Results from Design Type Analysis

Three types of Vivaldi antenna designs have been simulated, which are the Basic Vivaldi Antenna (VA), the Vivaldi Antenna with Cavity (VAC), and the Rounded-end Vivaldi Antenna with Cavity (VACR). Figure 4.5, Figure 4.6 and Figure 4.7 below show the radiation pattern of three types of Vivaldi antenna designs at 5GHz frequency.

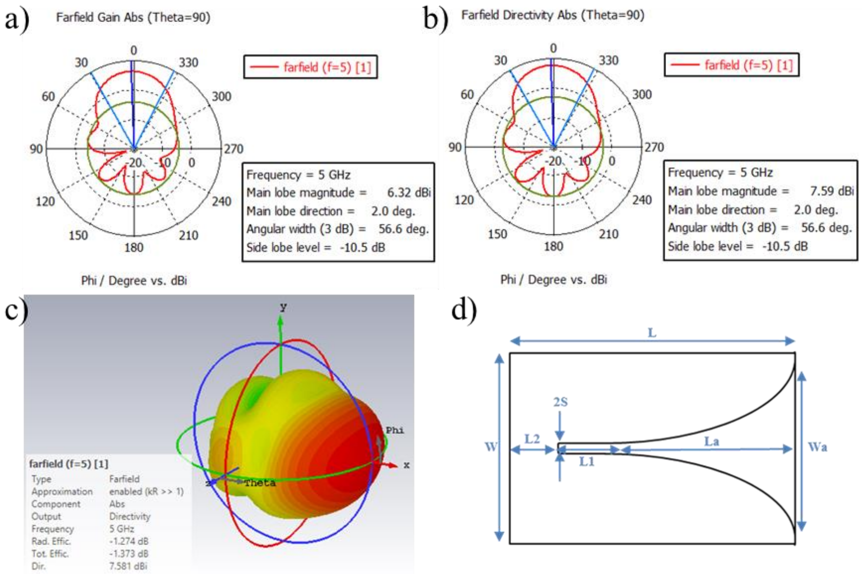


Figure 4.5 Radiation Pattern of VA: a) Gain, b) Directivity, c) 3D Pattern, d) Design Model.

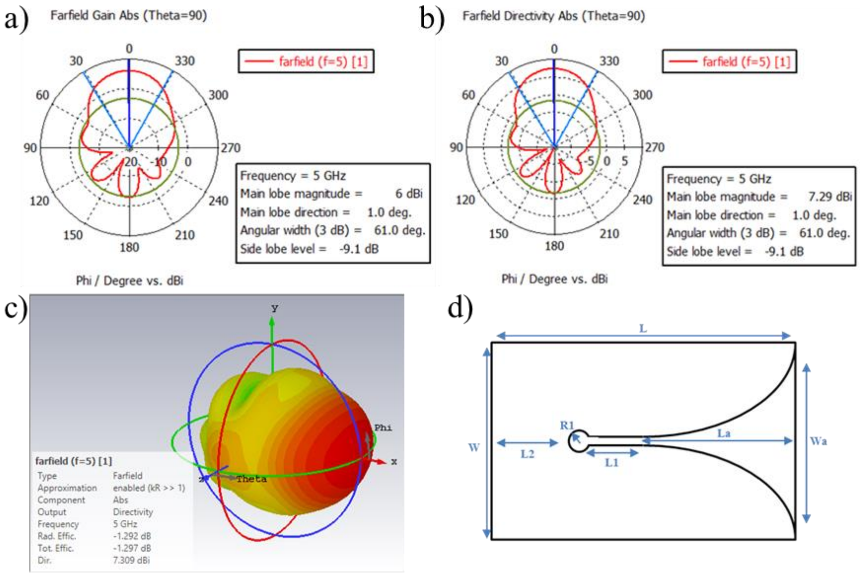


Figure 4.6 Radiation Pattern of VAC: a) Gain, b) Directivity, c) 3D Pattern, d) Design Model.

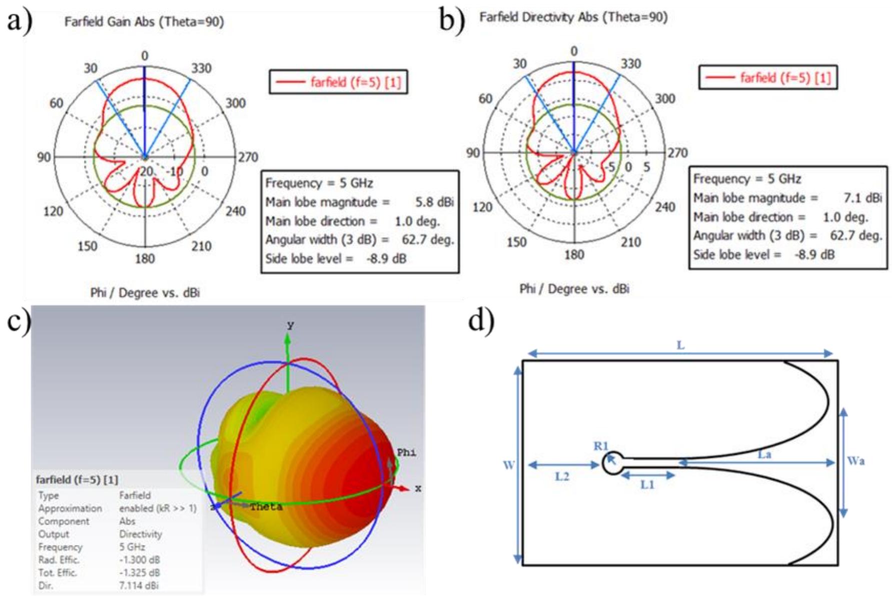


Figure 4.7 Radiation Pattern of VACR: a) Gain, b) Directivity, c) 3D Pattern, d) Design Model.

Based on the results above, the radiation pattern of the three antenna designs type shows a directional characteristic which means that the radiation is fired in one direction. Radiation pattern of basic design of Vivaldi antenna have the best result with the gain of 6.32 dBi and directivity of 7.39 dBi.

Next, take a look at the other simulation findings, specifically the gain, the return loss, and the voltage standing wave ratio (VSWR) for each of the three different types of designs. Figure 4.8, Figure 4.9 and Figure 4.10 below show the analysis results of the return loss, the VSWR, and the gain of the three antenna designs.

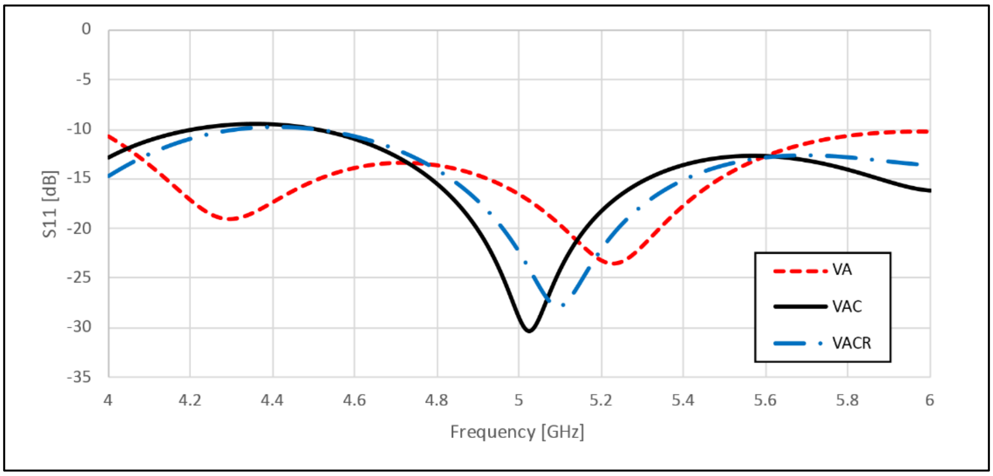


Figure 4.8 Return Loss of Design Type Analysis.

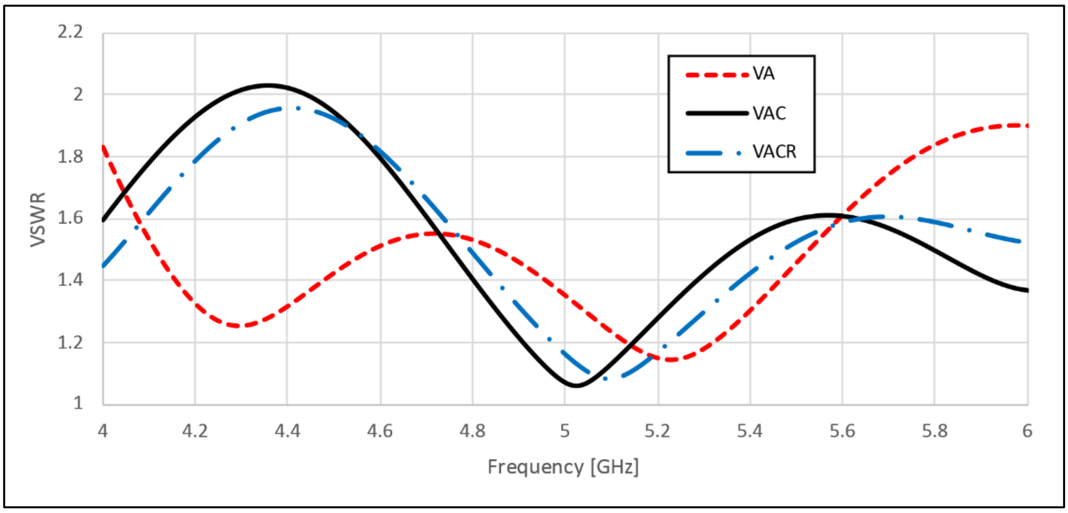


Figure 4.9 VSWR of Design Type Analysis.

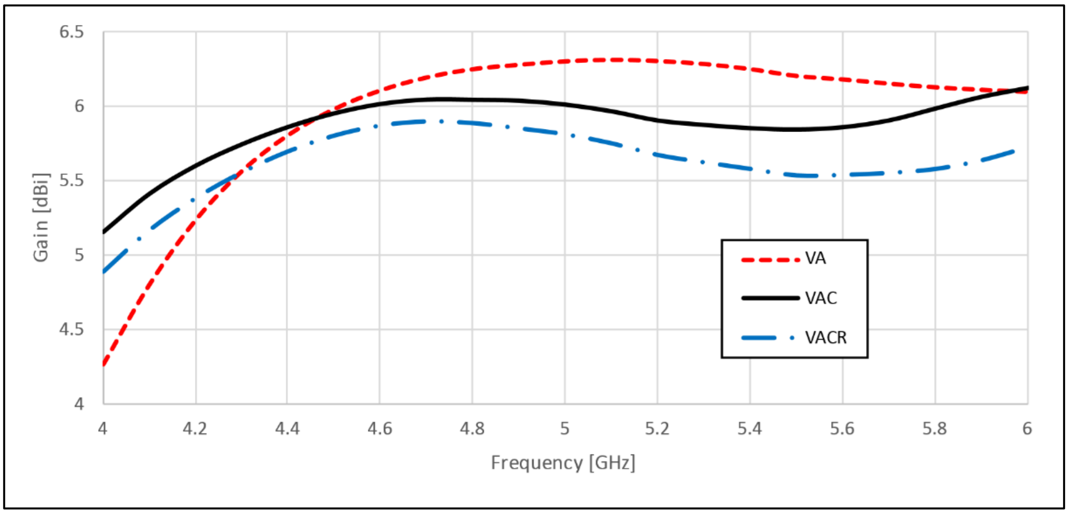


Figure 4.10 Gain of Design Type Analysis.

The results above show that the Basic Vivaldi Antenna (VA) has the most remarkable performance compared with other design types. However, the Vivaldi Antenna with Cavity (VAC) has the closest resonant frequency to 5GHz. Therefore, the VAC has been selected and will bring it to the next analysis.

4.2.4 Simulation Results from Cavity Radius Analysis

In this section, different sizes of the circular cavity radius have been tested in the VAC antenna type to investigate the impact of variable cavity radiuses have on the antenna's performance. Figure 4.11, Figure 4.12 and Figure 4.13 below show the radiation pattern of three different cavity sizes at 5GHz frequency.

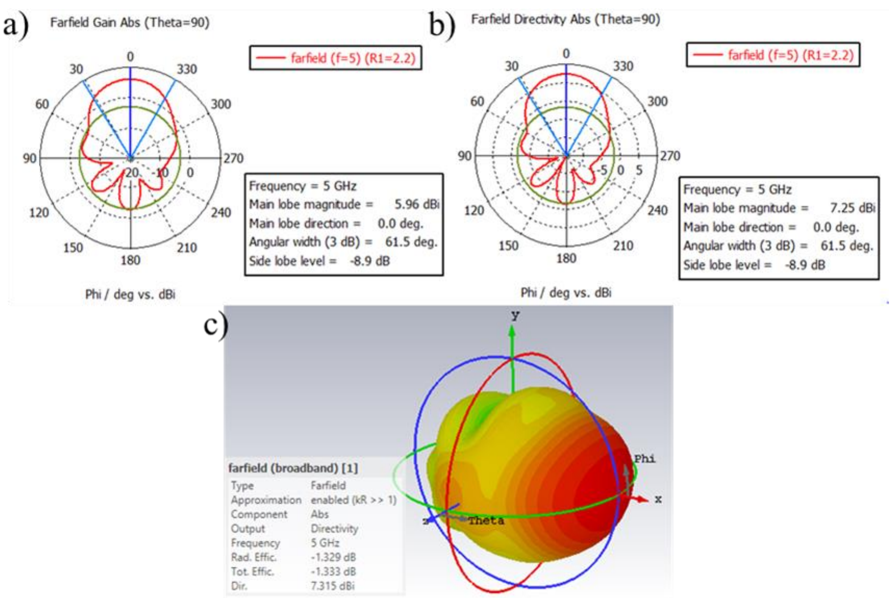


Figure 4.11 Radiation Pattern of 2.2mm Cavity Radius: a) Gain, b) Directivity, c) 3D Pattern.

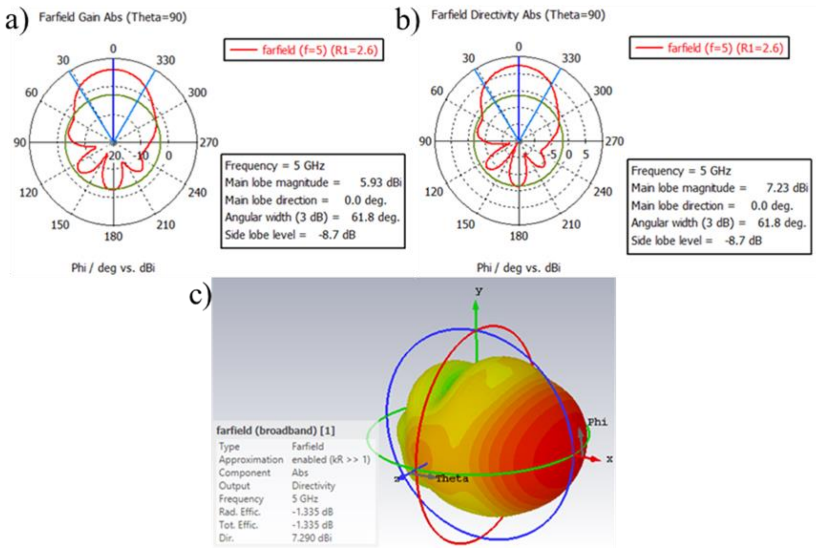


Figure 4.12 Radiation Pattern of 2.6mm Cavity Radius: a) Gain, b) Directivity, c) 3D Pattern.

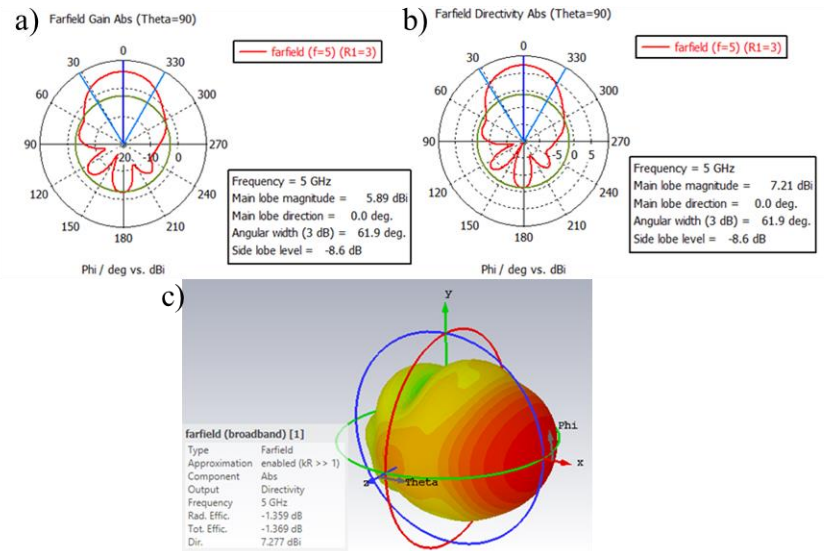


Figure 4.13 Radiation Pattern of 3.0mm Cavity Radius: a) Gain, b) Directivity, c) 3D Pattern.

According to the results shown above, each of the three different cavity sizes emits in a directional pattern. In comparing the performance, the cavity with a radius of 2.2mm has the best results, with a gain and directivity of 5.96 dBi and 7.25 dBi, respectively. Next, Figure 4.14, Figure 4.15 and Figure 4.16 below show the return loss, VSWR and gain analysis of three different cavity sizes.

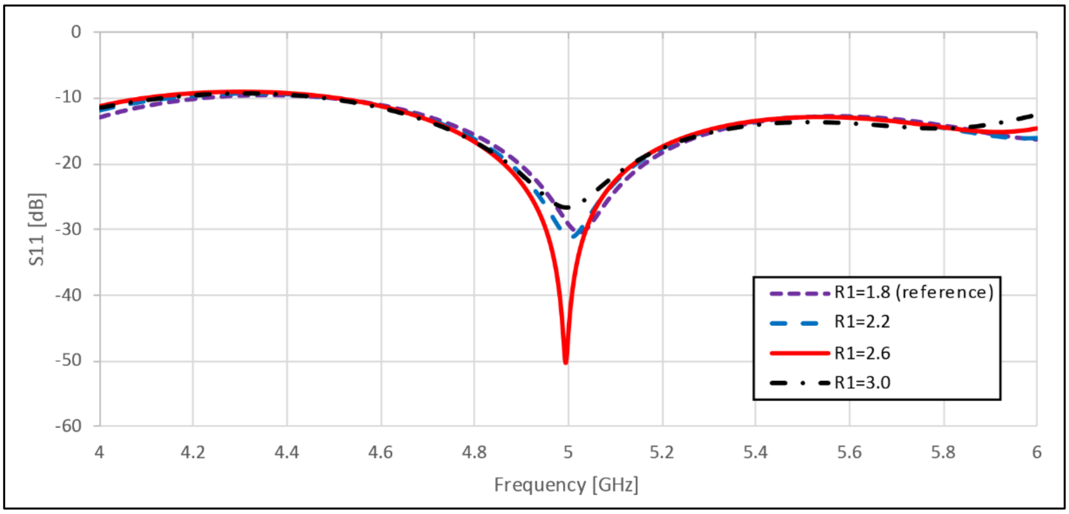


Figure 4.14 Return Loss of Cavity Radius Analysis.

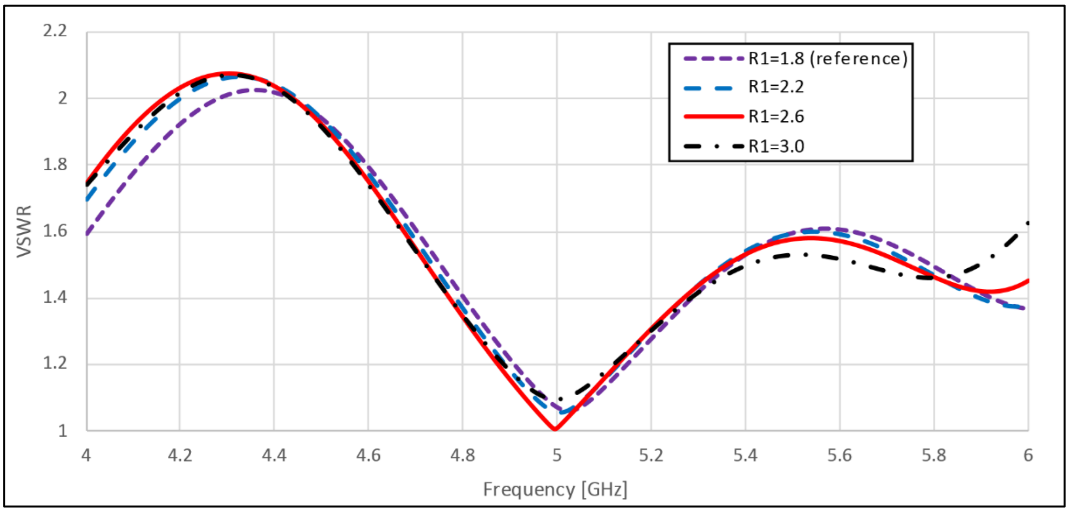


Figure 4.15 VSWR of Cavity Radius Analysis.

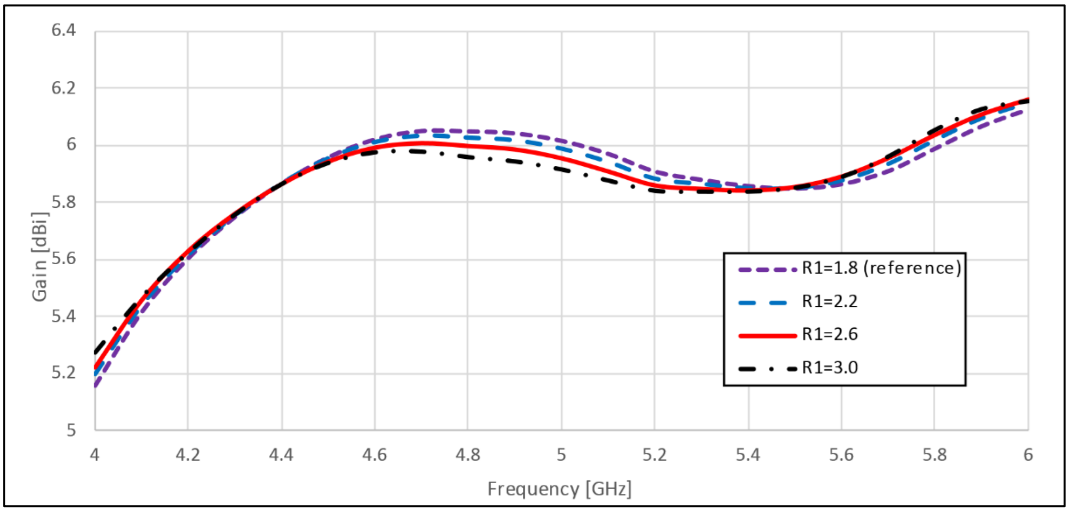


Figure 4.16 Gain of Cavity Radius Analysis.

The data presented above indicates that the VAC with a cavity radius of 2.6 mm has successfully reached the resonant frequency of 5 GHz. On the other hand, taking into consideration the return loss, the overall s11 is still greater than -10dB, and the VSWR is not between 1 and 2. Therefore, other approaches are still needed, and the VAC with the 2.6mm cavity radius will be brought into the next analysis.

4.2.5 Simulation Results from Feeding Type Analysis

In the next analysis, three different feeding patterns has been designed and simulated. These patterns are rectangular, circular, and shell feeding patterns. Figure 4.17, Figure 4.18 and Figure 4.19 below show the radiation pattern produced by three different feeding types at a frequency of 5GHz.

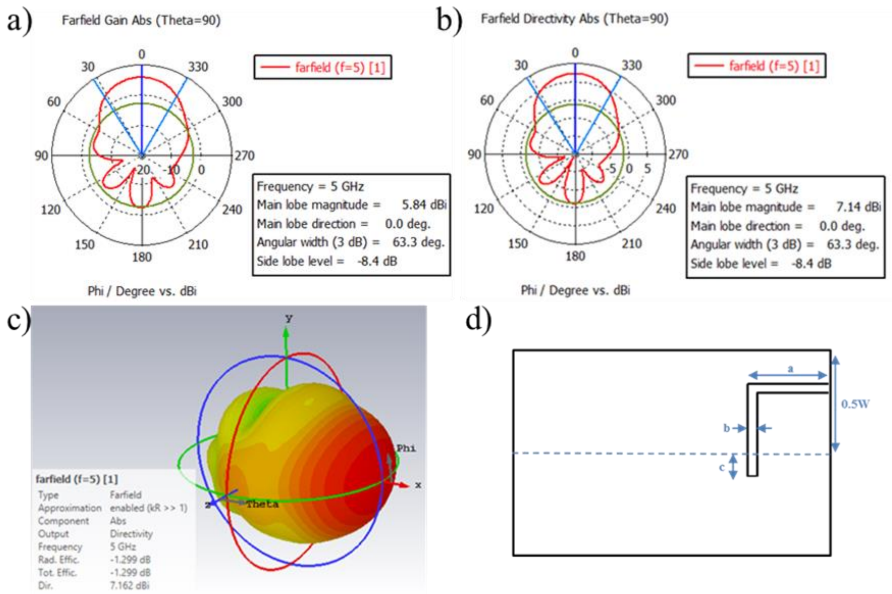


Figure 4.17 Radiation Pattern of Rectangular Feeding: a) Gain, b) Directivity, c) 3D Pattern, d) Feeding Model.

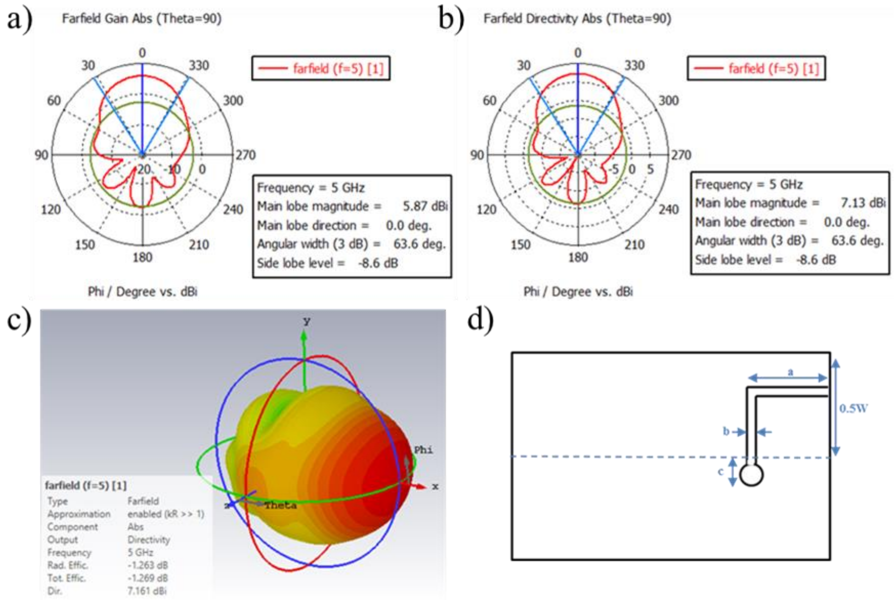


Figure 4.18 Radiation Pattern of Circular Feeding: a) Gain, b) Directivity, c) 3D Pattern, d) Feeding Model.

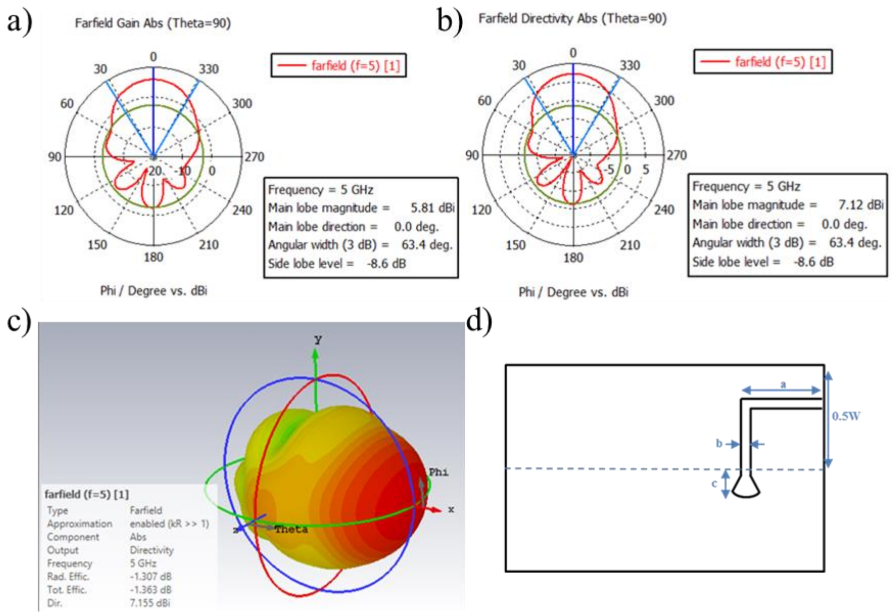


Figure 4.19 Radiation Pattern of Shell Feeding: a) Gain, b) Directivity, c) 3D Pattern, d) Feeding Model.

According to the results above, each of the feeding types radiates in a directional pattern. The radiation performance can be said almost the same because they only have a slight difference of gain and directivity value. Next, Figure 4.20, Figure 4.21 and Figure 4.22 below show the return loss, VSWR and gain analysis of three different feeding types.

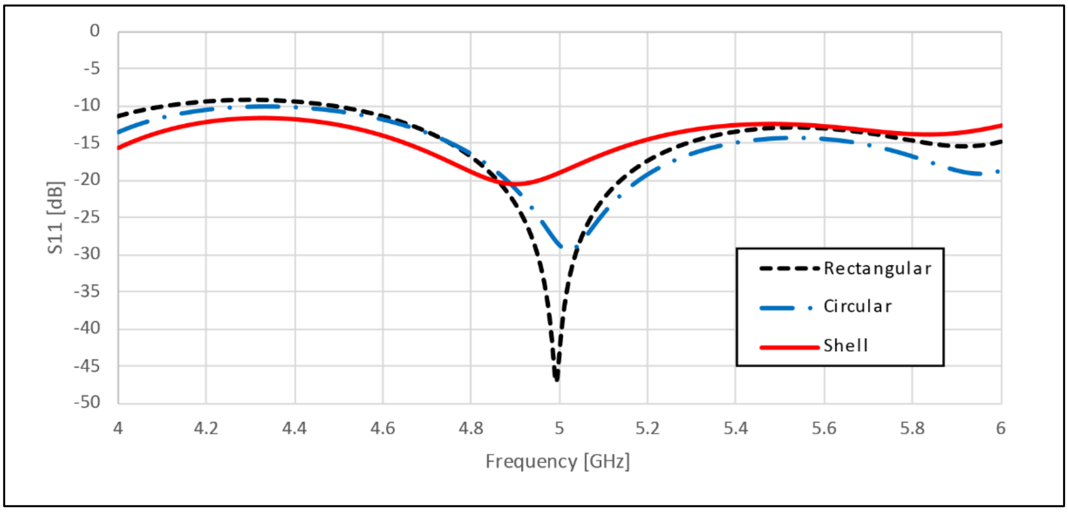


Figure 4.20 Return Loss of Feeding Type Analysis.

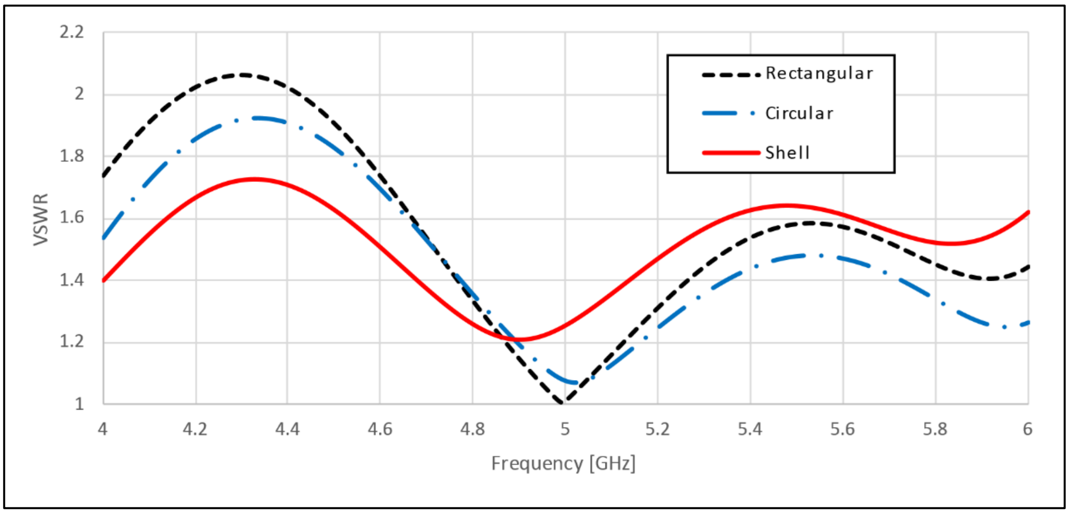


Figure 4.21 VSWR of Feeding Type Analysis.

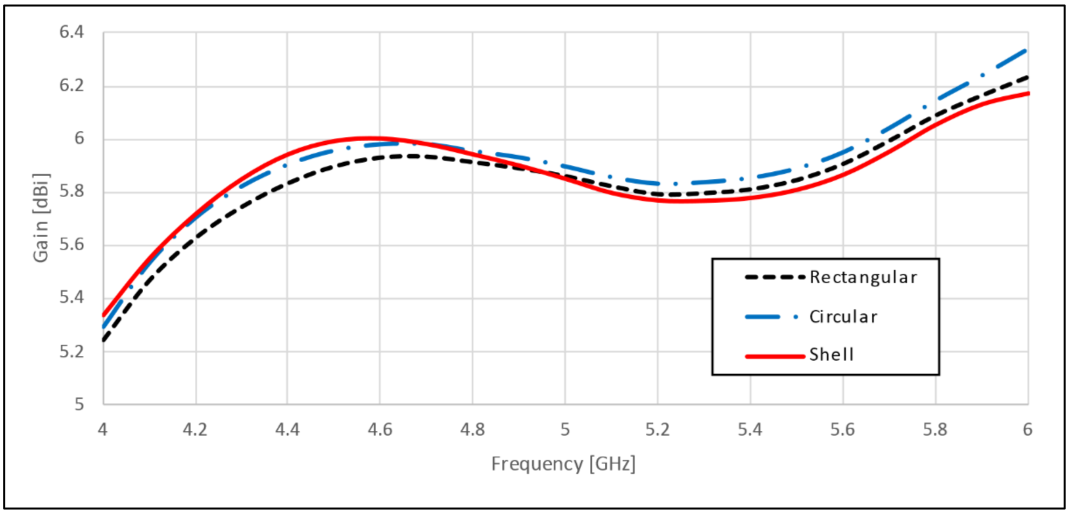


Figure 4.22 Gain of Feeding Type Analysis.

The return loss result above shows that the rectangular feeding type reaches the resonant frequency of 5GHz. However, the VSWR of the rectangular type is higher than 2. While the shell feeding type achieves a good overall VSWR and produces the highest gain. Therefore, the VAC with the shell feeding type is selected as the proposed Vivaldi design.

4.2.6 Simulation Results from Dimension Alterations

The proposed Vivaldi antenna design achieves a return loss below -10dB and a VSWR between 1 and 2, which meets the requirement of excellent performance of an antenna. However, the proposed antenna still does not achieve the resonant frequency at 5GHz. Therefore, several dimension changes were made in order for the antenna to operate efficiently at a 5GHz frequency. The dimension parameters that have been changed from Table 3.5 are the antenna's width (W), throat length (L1), and aperture length (La). Figure 4.23, Figure 4.24 and Figure 4.25 below show the radiation pattern at 5GHz.

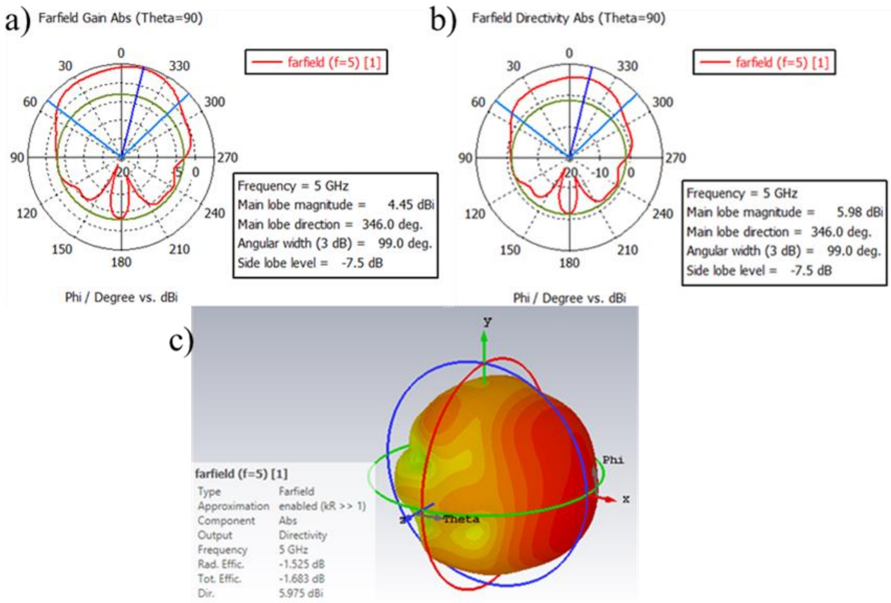


Figure 4.23 Radiation Pattern of First Alteration: a) Gain, b) Directivity, c) 3D Pattern.

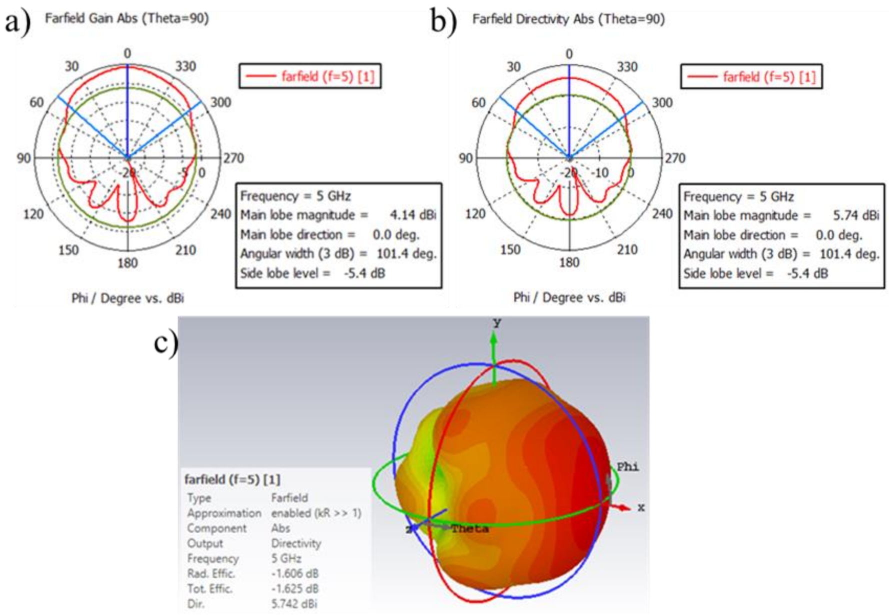


Figure 4.24 Radiation Pattern of Second Alteration: a) Gain, b) Directivity, c) 3D Pattern.

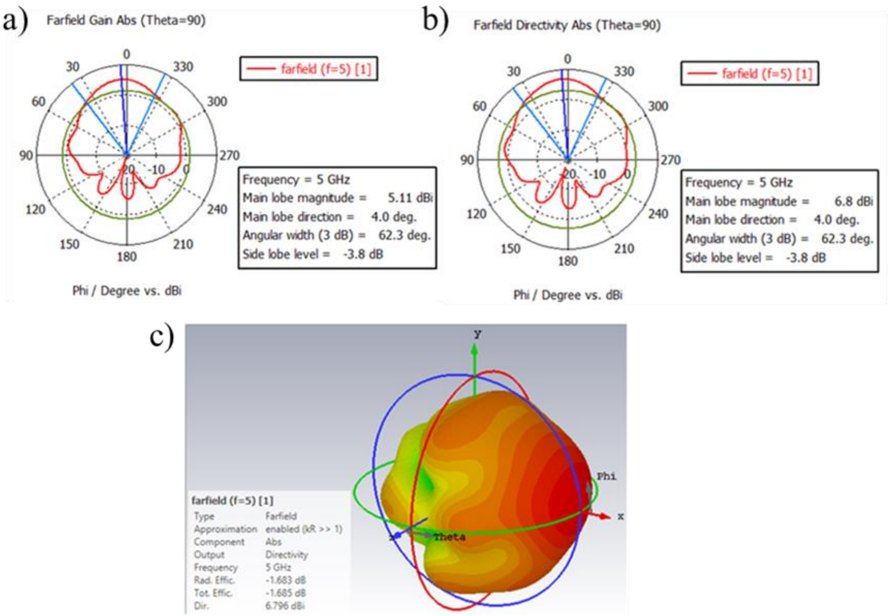


Figure 4.25 Radiation Pattern of Third Alteration: a) Gain, b) Directivity, c) 3D Pattern.

Based on the results above, in the first alteration, the gain drops to 4.45 dBi. Then, in the second alteration, the gain slightly drops to 4.14 dBi. However, the antenna's gain manages to increase in the third alteration to 5.11 dBi. Figure 4.26, Figure 4.27 and Figure 4.28 below show the return loss, VSWR and gain analysis of the dimension alteration.

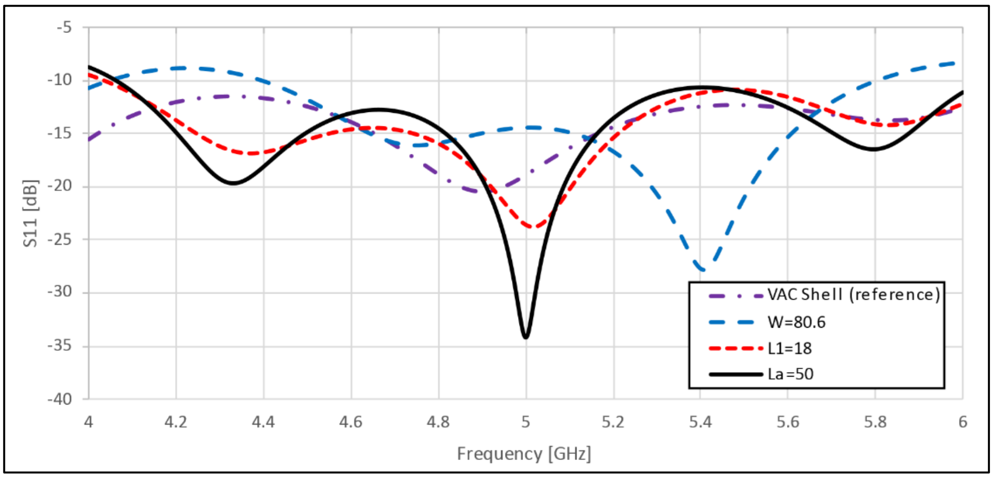


Figure 4.26 Return Loss of Dimension Alterations Analysis.

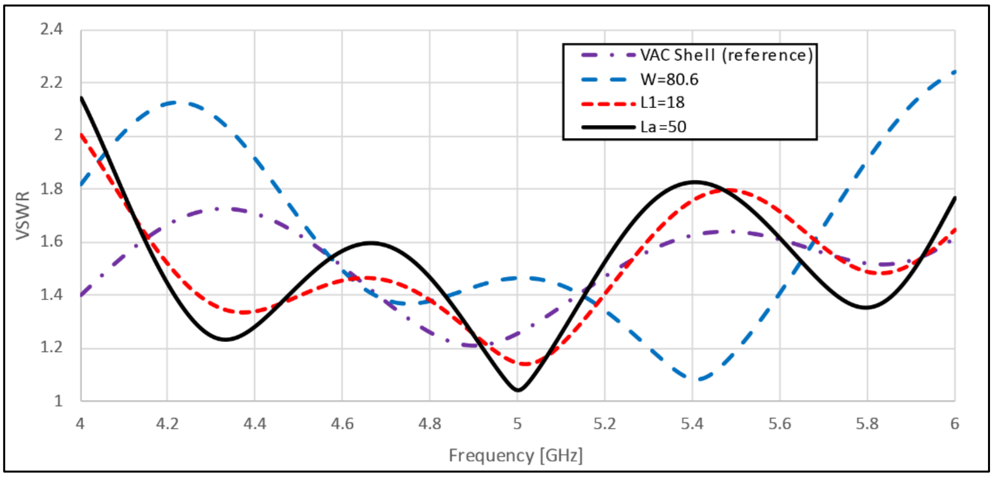


Figure 4.27 VSWR of Dimension Alterations Analysis.

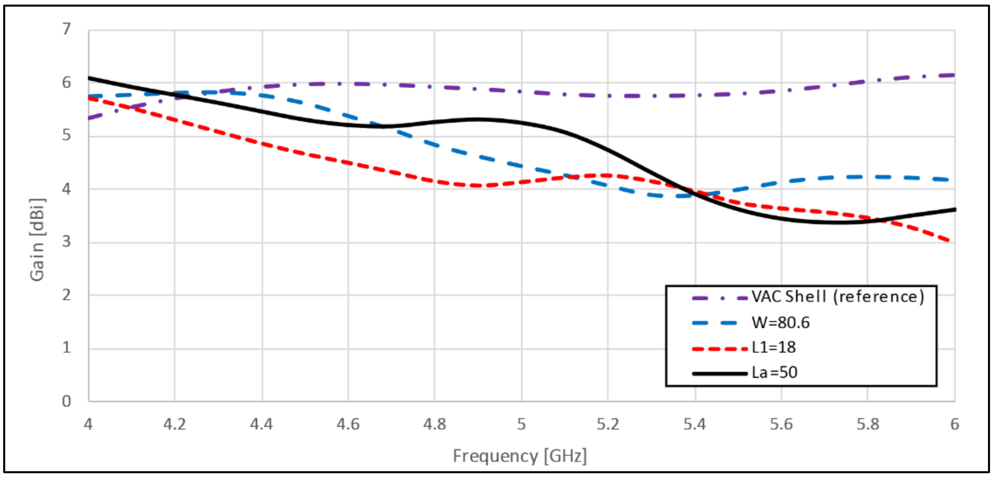
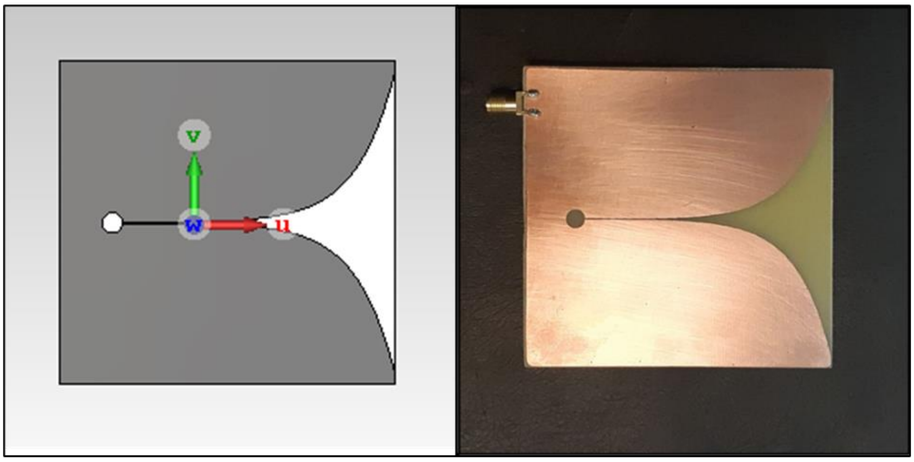


Figure 4.28 Gain of Dimension Alterations Analysis.

Based on the return loss analysis, the first alteration sharpens the antenna's resonant frequency at 5.4GHz. Then, the second alteration is shifting the resonant frequency to 5GHz. After that, by extending the aperture length to 50mm, the resonant frequency sharpens and reaches precisely 5GHz. Therefore, the proposed design has successfully achieved the resonant frequency at 5GHz with a return loss below -10dB and VSWR between 1 and 2 at the frequency ranges of 4.1 to 6 GHz.

4.3 Antenna Simulation VS Fabrication Results

The fabricated antenna as shown in Figure 4.29 (b) has been tested to evaluate its performance. The return loss (S_{11}) of the fabricated antenna has been measured using the vector network analyser and the results have been recorded. The evaluation has been done by comparing the measured results with the simulation results. The comparison results between the measured and simulated results are shown as in Figure 4.30.



a) b)

Figure 4.29 Design Model: a) Simulation, b) Fabrication.

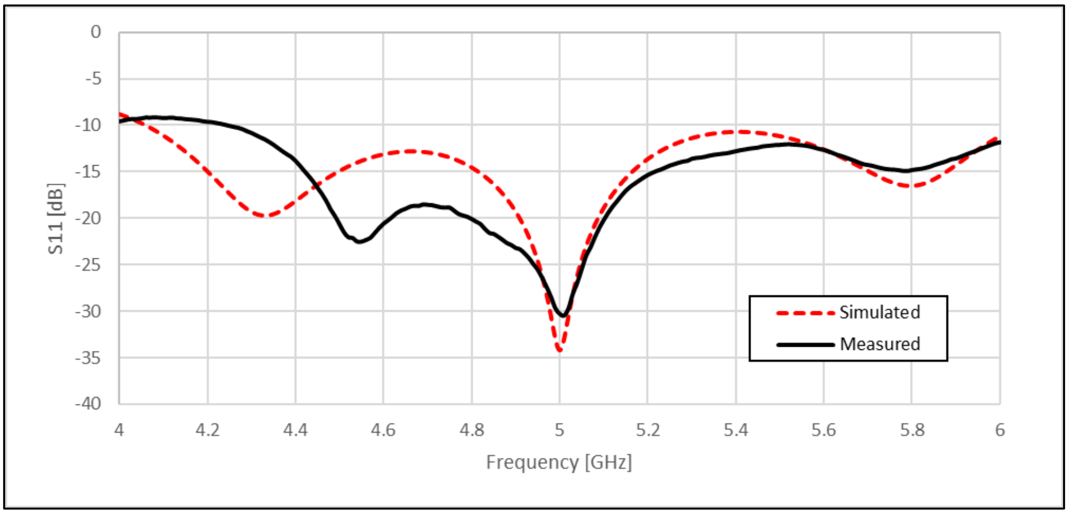


Figure 4.30 Simulated and Measured S_{11} of the Proposed Antenna.

According to the results above, it is evident that the measured results and simulated results are in good agreement, with some mismatch due to the fabrication error.

The measured results achieve a resonant frequency of 5GHz with the return loss below -10dB. Then, the non-destructive measurement system was set up as in Figure 4.31 with two conditions of setup: without material sample and with material sample. The insertion loss (S_{21}) has been measured and the results have been recorded. The comparison results between the measured and simulated results are shown as in Figure 4.32.

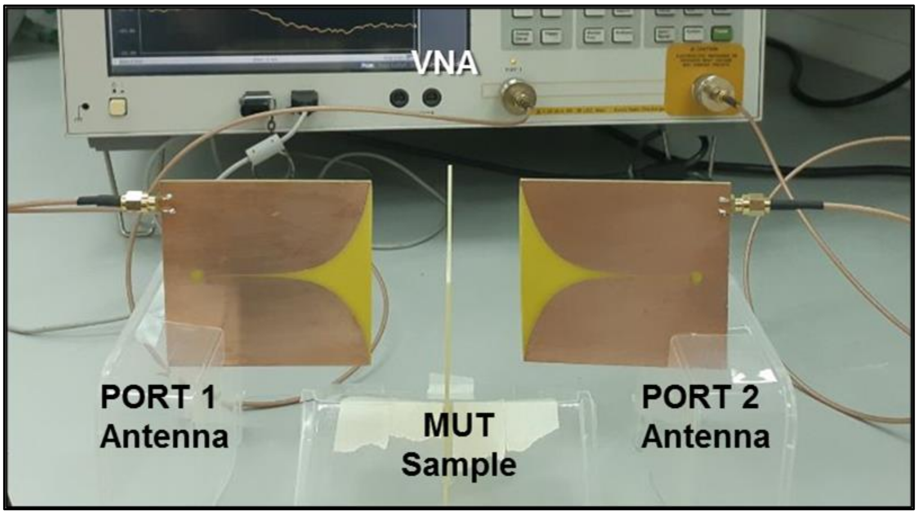


Figure 4.31 Non-destructive Measurement Setup.

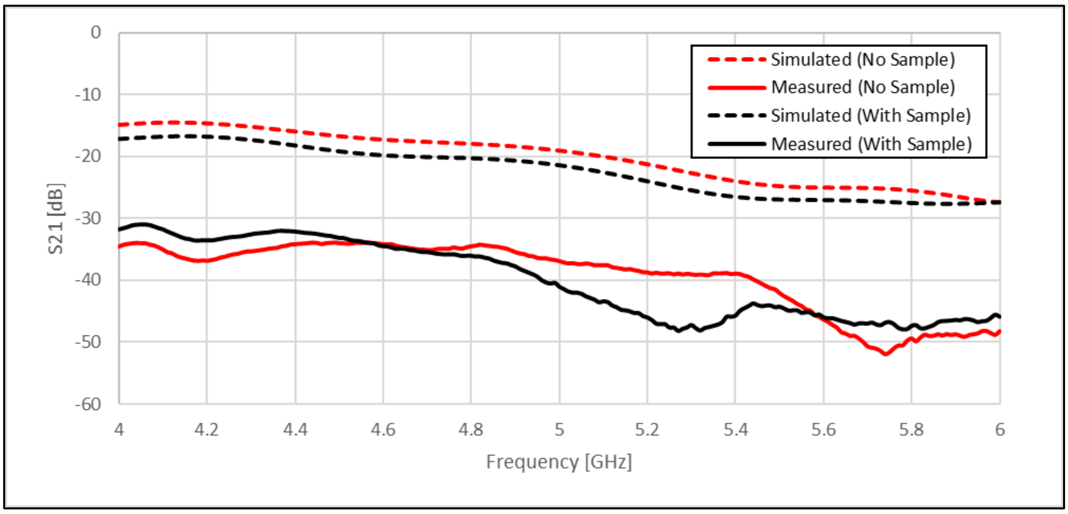


Figure 4.32 Simulated and Measured S_{21} of the Proposed Antenna.

Based on the results above, it shows different readings at 5GHz in the two conditions setup, whether in the simulation or in the measurement. It indicates that the measurement setup is able to characterise the material sample. A mathematical approach is needed to calculate the permittivity of the material sample by implement the S_{21} result.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter will conclude all the findings of the project's progress, including the recommendation that can be made for improvement in the future.

5.2 Conclusion

In conclusion, the design of the Vivaldi antenna for non-destructive measurement applications has been proposed. A variety of analyses have been done to complete the Vivaldi antenna design. The analysis that has been done in this project is the Vivaldi design type analysis, the effect of circular cavity radius analysis, and the feeding type analysis. Then, after making several dimension alterations, the optimal dimension of the Vivaldi antenna has been successfully established, and the proposed antenna works efficiently at a 5GHz frequency.

Besides that, two units of the proposed Vivaldi antenna have been successfully fabricated using the etching techniques. The antennas are made carefully by following the layout and dimension parameters of the proposed antenna layout.

As a result, the proposed Vivaldi antenna provides wide bandwidth, high directivity, and gain. In the frequency range of 4.1 to 6 GHz, the proposed Vivaldi antenna successfully achieves the overall return loss is shown to be below-10dB and the overall VSWR is between 1 and 2. This indicates that the proposed Vivaldi antenna can effectively transmit and receive the signal and meets the requirements for excellent performance of the antenna. Therefore, the proposed antenna can be used in the non-destructive measurement system, and it has been proved.

5.3 Recommendation

For future improvement, the performance of the Vivaldi antenna can be improved by manipulating the antenna design. The impedance matching can be improved by using tapering techniques [20]. Besides that, the gain of the antenna can be enhanced by using the microwave lens [21]. In terms of antenna fabrication, all the dimension parameters in the antenna design must be followed accurately to avoid fabrication error. Hence, use the appropriate tools, which can enhance the accuracy of the antenna fabrication.

REFERENCES

[1] D. Adamovic and F. Zivic, “Hardness and Non-Destructive Testing (NDT) of Ceramic Matrix Composites (CMCs),” *Encycl. Mater. Compos.*, pp. 183–201, Jan. 2021, doi: 10.1016/B978-0-12-819724-0.00074-4.

[2] J. G. Speight, “Monomers, polymers, and plastics,” *Handb. Ind. Hydrocarb. Process.*, pp. 597–649, Jan. 2020, doi: 10.1016/B978-0-12-809923-0.00014-X.

[3] D. El Khaled, N. Novas, J. A. Gazquez, R. M. Garcia, and F. Manzano-Agugliaro, *Fruit and vegetable quality assessment via dielectric sensing*, vol. 15, no. 7. 2015.

[4] S. Trabelsi, “Nondestructive Sensing of Water Activity from Measurement of the Dielectric Properties at Microwave Frequencies,” *IEEE Sensors Lett.*, vol. 4, no. 12, pp. 5–8, 2020, doi: 10.1109/LSENS.2020.3042749.

[5] F. H. Wee, P. J. Soh, A. H. M. Suhaizal, H. Nornikman, and A. A. M. Ezanuddin, “Free space measurement technique on dielectric properties of agricultural residues at microwave frequencies,” *SBMO/IEEE MTT-S Int. Microw. Optoelectron. Conf. Proc.*, no. I, pp. 183–187, 2009, doi: 10.1109/IMOC.2009.5427603.

[6] D. F. Williams, S. Member, J. E. Rogers, and C. L. Holloway, “Multiconductor Transmission-Line Characterization : Representations , Approximations , and Accuracy,” vol. 47, no. 4, pp. 403–409, 1999.

[7] K. Y. You and M. S. Sim, “Precision permittivity measurement for low-loss thin planar materials using large coaxial probe from 1 to 400 MHz,” *J. Manuf. Mater. Process.*, vol. 2, no. 4, 2018, doi: 10.3390/jmmp2040081.

[8] Z. Li, Z. Meng, A. Haigh, P. Wang, and A. Gibson, “Characterisation of water in honey using a microwave cylindrical cavity resonator sensor,” *J. Food Eng.*, vol. 292, no. August 2020, p. 110373, 2021, doi: 10.1016/j.jfoodeng.2020.110373.

[9] N. S. Knyazev and A. I. Malkin, “Dielectric permittivity and permeability measurement system,” *CEUR Workshop Proc.*, vol. 1814, pp. 45–51, 2017.

[10] Y. Qin, S. Liu, B. Wei, M. Li, C. Cai, and T. Hou, “Numerical simulation study of free space method for measuring sample permittivity,” *J. Phys. Conf. Ser.*, vol. 1871, no. 1, 2021, doi: 10.1088/1742-6596/1871/1/012003.

[11] Z. Lukeš, J. Láčík, and Z. Raida, “Optimized wideband horn antenna for millimeter-wave spectroscopy applications,” *J. Mol. Spectrosc.*, vol. 243, no. 2, pp. 227–233, 2007, doi: 10.1016/j.jms.2007.04.004.

[12] S. Guruswamy, R. Chinniah, and K. Thangavelu, “A printed compact UWB Vivaldi antenna with hemi cylindrical slots and directors for microwave imaging applications,” *AEU - Int. J. Electron. Commun.*, vol. 110, p. 152870, 2019, doi: 10.1016/j.aeue.2019.152870.

[13] L. N. Thalluri, A. R. Nallapu, R. Konda, S. S. Deep, and K. N. Harsha, “Design and Performance Analysis of Vivaldi Antenna for Medical Applications,” *Proc. 2020 IEEE Int. Conf. Commun. Signal Process. ICCSP 2020*, pp. 1021–1026, 2020, doi: 10.1109/ICCSP48568.2020.9182320.

[14] C. Tian, X. Zhang, and R. Luo, “A design of miniaturized Vivaldi antenna for UWB applications,” *2019 Int. Symp. Antennas Propagation, ISAP 2019 - Proc.*, no. c, pp. 30–32, 2019.

[15] M. N. Hasan, O. J. Babarinde, S. Das, and K. V. Babu, “Dispersion Characterization of a UWB Vivaldi Antenna in Time and Frequency Domain,” *2018 IEEE Indian Conf. Antennas Propagation, InCAP 2018*, 2018, doi: 10.1109/INCAP.2018.8770763.

[16] N. Vohra, L. R. Rodriguez-Aguilar, J. S. Batista, and M. El-Shenawee, “Free-Space Characterization of Radar Absorbing Non-Magnetic Materials in the W-Band,” *2020 94th ARFTG Microw. Meas. Conf. RF to Millimeter-Wave Meas. Tech. 5G Beyond, ARFTG 2020*, pp. 2020–2023, 2020, doi: 10.1109/ARFTG47584.2020.9071679.

[17] K. Li, M. Liu, and H. Zhang, “An L-Band Ultra Wide-Band Vivaldi Antenna with Wide Beam Angle,” *2020 13th UK-Europe-China Work. Millimetre-Waves Terahertz Technol. UCMMT 2020 - Proc.*, pp. 2–4, 2020, doi: 10.1109/UCMMT49983.2020.9296122.

[18] T. A. Khan, J. Li, Z. Li, M. Abdullah, J. Chen, and A. Zhang, “Design of a Vivaldi antenna with wideband reduced radar cross section,” *AEU - Int. J. Electron. Commun.*, vol. 95, pp. 47–51, 2018, doi: 10.1016/j.aeue.2018.08.011.

[19] E. M. Khusna, E. Setijadi, and G. Hendrantoro, “Parameter study of coplanar vivaldi antenna feeding structure,” *Proc. - 2019 Int. Semin. Intell. Technol. Its Appl. ISITIA 2019*, pp. 13–18, 2019, doi: 10.1109/ISITIA.2019.8937160.

[20] A. Gorai, A. Karmakar, M. Pal, and R. Ghatak, “A super wideband Chebyshev tapered antipodal Vivaldi antenna,” *AEU - Int. J. Electron. Commun.*, vol. 69, no. 9, pp. 1328–1333, 2015, doi: 10.1016/j.aeue.2015.05.017.

[21] M. S. Anwar, H. Abufanas, and A. Bangert, “3D printed dielectric lens for the gain enhancement of a broadband antenna,” *Int. J. RF Microw. Comput. Eng.*, vol. 30, no. 4, pp. 1–8, 2020, doi: 10.1002/mmce.22115.