MINIATURIZED DUAL-BAND WI-FI ANTENNA FOR MOBILE APPLICATION

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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

Faculty of Electronics and Computer Technology and Engineering
Universiti Teknikal Malaysia Melaka

2024

UNIVERSITI TEKNIKAL MALAYSIA MELAKA
FAKULTI TEKNOLOGI DAN KEJURUTERAAN ELEKTRONIK DAN KOMPUTER

BORANG PENGESAHAN STATUS LAPORAN
PROJEK SARJANA MUDA II

Tajuk Projek : Miniaturized Dual-Band Wi-Fi Antenna for Mobile Application

Sesi Pengajian : 2023/2024

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DEDICATION

This thesis is dedicated to University Teknikal Malaysia Melaka (UTeM), a beacon of knowledge and a catalyst for intellectual growth and innovation. This dedication is a testament to the transformative power of education and the profound impact UTeM has had on my intellectual and personal development. It is a tribute to the countless opportunities, invaluable experiences, and lasting friendships forged within these halls of learning. I am honored to be a part of UTeM's legacy and grateful for the platform it has provided me to explore, discover, and contribute to the world of knowledge. I dedicate this thesis to UTeM, as a token of appreciation for its role in shaping my academic journey and as a celebration of its commitment to fostering intellectual curiosity and advancement.

ABSTRACT

Miniaturized dual-band Wi-Fi antenna for mobile application is a collaboration project between UTeM and Intel to design a compact dual-band antenna in mobile application such as smartphones, tablets, and laptops. This thesis addresses the growing demand for compact and efficient dual-band Wi-Fi antennas operating at both 2.4 GHz and 5 GHz frequencies. The objective of this research is to design and optimize a miniaturized dual-band Wi-Fi antenna, operating at 2.4 GHz and 5 GHz, to meet the requirements of compact electronic devices. The scope of this study encompasses the design, simulation, fabrication, and testing of a meander line antenna for dual-band Wi-Fi applications. Meander line antennas are chosen for their ability to achieve compactness and multiband operation. The methodology involves a comprehensive study of meander line antenna configurations, parametric analysis, and optimization to achieve desired performance metrics. The antenna is fabricated and experimentally tested to validate simulation results and assess real-world performance. Measurements are conducted to evaluate parameters such as return loss, radiation pattern, and antenna gain. Result shows that the antenna achieved resonant frequencies at 2.328 GHz and 5.020 GHz with S-parameter of -40.74 dB and -39.17 dB. The research contributes to the ongoing efforts in antenna design for modern communication systems, addressing the challenges posed by size constraints in emerging electronic devices.

ABSTRAK

Antena Wi-Fi dwijalur miniatur untuk aplikasi mudah alih ialah projek kerjasama antara UTeM dan Intel untuk mereka bentuk antena dwijalur padat dalam aplikasi mudah alih seperti telefon pintar, tablet dan komputer riba. Tesis ini menangani permintaan yang semakin meningkat untuk antena WiFi dwi-jalur yang padat dan cekap yang beroperasi pada kedua-dua frekuensi 2.4 GHz dan 5 GHz. Objektif penyelidikan ini adalah untuk mereka bentuk dan mengoptimumkan antena Wi-Fi dwi-jalur kecil, beroperasi pada 2.4 GHz dan 5 GHz, untuk memenuhi keperluan peranti elektronik padat. Skop kajian ini merangkumi reka bentuk, simulasi, fabrikasi, dan ujian antena talian berliku untuk aplikasi Wi-Fi dwi-jalur. Antena talian berliku dipilih kerana keupayaannya mencapai kekompakan dan operasi berbilang jalur. Metodologi ini melibatkan kajian menyeluruh tentang konfigurasi antena talian berliku, analisis parametrik dan pengoptimuman untuk mencapai metrik prestasi yang diingini. Antena direka dan diuji secara eksperimen untuk mengesahkan keputusan simulasi dan menilai prestasi dunia sebenar. Pengukuran dijalankan untuk menilai parameter seperti kehilangan pulangan, corak sinaran, dan kekuatan antena. Keputusan menunjukkan bahawa antena mencapai frekuensi resonans pada 2.328 GHz dan 5.020 GHz dengan parameter S -40.74 dB dan -39.17 dB. Penyelidikan ini menyumbang kepada usaha berterusan dalam reka bentuk antena untuk sistem komunikasi moden, menangani cabaran yang ditimbulkan oleh kekangan saiz dalam peranti elektronik yang baru muncul.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to all those who have contributed to the completion of this thesis on "Miniaturized Dual-Band Wi-Fi Antenna for Mobile Application."

First and foremost, I am immensely thankful to my supervisor, Dr. Maizatul Alice Binti Meor Said, for her invaluable guidance, support, and encouragement throughout this research endeavor. Her expertise, insightful feedback, and unwavering commitment have been instrumental in shaping the direction and quality of this thesis.

I am also thankful to Dr. Amyrul Azuan Bin Mohd Bahar for his guidance and the collaborative effort between UTeM and Intel, which provided a unique opportunity for me to work on the miniaturized dual-band Wi-Fi antenna project. The resources, mentorship, and industry insights provided by this collaboration greatly enriched the research experience.

Next, I would also like to extend my heartfelt appreciation to the faculty members of University Teknikal Malaysia Melaka (UTeM), whose knowledge and teachings have significantly enriched my understanding of antenna design and wireless communication systems. Their passion for academic excellence has been a constant source of inspiration.

I am also grateful to the staff and technicians at the PSM laboratory and MRG laboratory for their assistance during the fabrication and measurement processes. Their technical expertise and support have been crucial in conducting the experiments and obtaining reliable results.

I would like to acknowledge the contributions of my colleagues and friends who have provided valuable discussions and shared their knowledge and experiences, enhancing the depth of my research.

Lastly, I express my heartfelt gratitude to my family for their unconditional love, unwavering support, and understanding throughout my academic journey. Their constant encouragement and belief in my abilities have been the driving force behind my perseverance.

To all those mentioned above and to anyone else who has directly or indirectly contributed to the successful completion of this thesis, I extend my sincere appreciation. Their support and collaboration have been invaluable.

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LIST OF SYMBOLS AND ABBREVIATIONS

IoT	:	Internet of Things
GHz	:	Giga Hertz
MLA	:	Meandered Line Antenna
RFID	:	Radio Frequency Identification
PIFA	:	Planar Inverted F Antenna
SRR	:	Split Ring Resonator
CRLH	:	Composite Right/Left-Handed
mm	:	Millimeter
dB	:	Decibel
FR4	:	Flame Retardant 4
SMA	:	SubMiniature version A
VSWR	:	Voltage Standing Wave Ratio
dBi	:	Decibels isotropic

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CHAPTER 1

INTRODUCTION

a. Background Study

The proliferation of mobile devices and the increasing demand for wireless connectivity have reshaped the way we communicate, access information, and interact with the digital world. Wi-Fi technology has emerged as a vital solution for wireless internet access and local network connectivity, enabling seamless communication and data transfer in various environments. However, the design and implementation of Wi-Fi antennas for mobile applications present unique challenges that must be addressed to meet the growing demands of users.

Mobile devices, such as smartphones, tablets, and wearables, have become essential companions in our everyday lives. These devices require compact and space-efficient antennas to provide reliable wireless connectivity while occupying minimal physical space. However, designing antennas for mobile applications is a complex task due to the limitations imposed by the small form factor, multi-band operation, and the need to maintain high performance in terms of gain, bandwidth, and radiation efficiency.

The miniaturization of antennas has been a subject of extensive research to overcome these challenges. Researchers have explored various miniaturization techniques, such as compact antenna geometries and advanced materials, to reduce the physical size of antennas without compromising their performance. These techniques aim to achieve compactness, multi-band operation, and efficiency in mobile Wi-Fi antennas.

b. Motivation

The motivation behind this research stems from the pressing need to develop miniaturized dual-band Wi-Fi antennas specifically tailored for mobile applications. By addressing the challenges of limited space, dual-band operation, high performance, and environmental considerations, this research aims to contribute to the development of antennas that can provide seamless and reliable wireless connectivity within the constraints of mobile devices.

The successful implementation of miniaturized dual-band Wi-Fi antennas for mobile applications holds significant implications. It can enhance the performance and user experience of mobile devices by enabling faster and more reliable wireless connectivity. This, in turn, can support a wide range of applications, including streaming multimedia content, cloud-based services, real-time communication, and Internet of Things (IoT) connectivity.

Moreover, the research in this area aligns with the broader efforts to advance wireless communication technology. By exploring innovative miniaturization techniques, optimizing antenna performance, and addressing the specific challenges of mobile applications, this research contributes to the advancement of wireless connectivity and its integration into mobile devices.

c. Problem Statement

The rapid growth in mobile device usage and the increasing demand for wireless connectivity have necessitated the development of compact and efficient Wi-Fi antennas specifically designed for mobile applications. However, designing antennas for mobile devices poses significant challenges due to the limited available space and the need to maintain optimal performance across multiple Wi-Fi frequency bands.

The primary problem addressed in this thesis is the design and implementation of a miniaturized dual-band Wi-Fi antenna that can meet the stringent requirements of mobile applications. This problem encompasses the following key challenges:

1. Limited Space: Mobile devices, such as smartphones and wearables, have strict size constraints, necessitating the design of antennas that occupy minimal physical space. Achieving compactness while maintaining optimal performance is a significant challenge.
2. Dual-Band Operation: Wi-Fi communication typically operates in both the 2.4 GHz and 5 GHz frequency bands. Designing an antenna that can efficiently cover both frequency bands while maintaining adequate bandwidth, gain, and radiation efficiency poses a challenge.

3. High Performance: Mobile applications demand high-performance antennas to ensure reliable wireless connectivity. The antenna should exhibit good impedance matching, high gain, and efficient radiation characteristics while minimizing signal losses and interference.
4. Environmental Considerations: Antennas in mobile devices are subject to various environmental factors, including nearby objects, human body effects, and electromagnetic interference. The antenna design should be robust and capable of maintaining stable performance in the presence of these factors.

Addressing these challenges is crucial for enabling seamless and reliable wireless connectivity in mobile devices, enhancing user experience, and supporting the increasing demand for data-intensive applications.

Hence, the objective of this thesis is to design, analyze and implement dual-band Wi-Fi antenna that addresses spatial constraints, exhibits excellent performance in both the 2.4 GHz and 5 GHz frequency ranges, and remains resilient against environmental influences. By addressing these challenges, the research aims to contribute to the development of compact and efficient Wi-Fi antennas tailored specifically for mobile applications, facilitating enhanced wireless connectivity and improved user experience in mobile devices.

1. Objectives / Aims

Aim:

Investigation on different approach towards miniaturizing dual band Wi-Fi antenna.

Objectives:

1. To design a miniaturized dual-band Wi-Fi antenna at 2.4 GHz and 5 GHz by using CST Studio Software.
2. To investigate the antenna performance including operating frequencies and results produced.

2. Scope of Project

The scope of this project encompasses the design, analysis, and implementation of a miniaturized dual-band Wi-Fi antenna for mobile applications. The project aims to address the challenges associated with limited space, dual-band operation, high performance, and environmental considerations in the design of Wi-Fi antennas for mobile devices.

The project will involve the following key activities:

1. Literature Review: Conduct an extensive review of existing miniaturized antenna designs, miniaturization techniques, and relevant research on compact antennas for mobile applications. This review will serve as the foundation for the design approach.

2. Design and Simulation: Develop a novel miniaturized dual-band Wi-Fi antenna design using advanced simulation tools. The design will incorporate various miniaturization techniques, such as compact antenna geometries, high permittivity substrates, and metamaterial-inspired structures. The simulation will include optimization iterations to achieve the desired antenna performance metrics.
3. Fabrication and Measurement: Fabricate the designed antenna and conduct experimental measurements to validate its performance. Measurements will include impedance matching, radiation pattern characterization, and gain evaluation. The antenna will be tested under various environmental conditions, considering factors such as nearby objects and electromagnetic interference.
4. Performance Evaluation: Analyze the measured data and evaluate the performance of the miniaturized dual-band Wi-Fi antenna in terms of bandwidth, gain, radiation efficiency, and robustness to environmental factors. Compare the results with established performance standards and assess the suitability of the antenna for mobile applications.

The scope of this project is limited to the design and implementation of the miniaturized dual-band Wi-Fi antenna itself. Integration of the antenna into specific mobile device architectures or wireless communication systems is beyond the immediate scope but can be considered for future research or application.

Additionally, the project focuses on Wi-Fi communication in the 2.4 GHz and 5 GHz frequency bands, which are widely used for wireless connectivity. However, it does not address other frequency bands or wireless communication protocols.

The project will be conducted within the available resources, including simulation software, fabrication facilities, measurement equipment, and the necessary expertise. Any constraints or limitations imposed by these resources will be considered during the project execution.

In summary, the scope of this project encompasses the design, analysis, and implementation of a miniaturized dual-band Wi-Fi antenna for mobile applications. The project aims to overcome the challenges associated with limited space, dual-band operation, high performance, and environmental considerations. The project will contribute to the development of compact and efficient Wi-Fi antennas, enabling enhanced wireless connectivity in mobile devices.

CHAPTER 2

LITERATURE REVIEW

a. Introduction

Designing antennas for mobile applications presents several challenges, including the limited available space, the need for multi-band operation, and the requirement for high performance in terms of gain, bandwidth, and radiation efficiency. The miniaturization of antennas has been a subject of extensive research to address these challenges. Miniaturization techniques aim to reduce the physical size of the antenna while maintaining or enhancing its electrical performance. The literature review provides a comprehensive overview of existing research and relevant studies conducted in the field of miniaturized antennas for mobile applications, with a specific focus on dual-band Wi-Fi antennas. The review encompasses various aspects, including miniaturization techniques, compact antenna geometries, advanced materials, and performance evaluation metrics.

b. Miniaturization Techniques

Miniaturization techniques play a crucial role in designing compact antennas for various applications, including mobile devices. These techniques enable the reduction of antenna size while maintaining or even improving its electrical performance. A thorough understanding of miniaturization techniques is essential for developing efficient and space-saving antennas.

i. Compact Antenna Geometries

One of the widely studied miniaturization techniques is based on compact antenna geometries. These geometries introduce additional electrical path lengths within a limited physical space, effectively reducing the overall antenna size [1]. One widely studied compact antenna geometry is the meandered structure. Meandered line antennas (MLA) utilize a zigzag pattern in the conductor, effectively increasing the electrical length of the antenna within a given physical space. This extended electrical path allows for resonant operation at lower frequencies, enabling compactness while maintaining or enhancing radiation efficiency. Meandered structures have been utilized in a range of applications, including wireless communication systems, RFID tags, and miniaturized satellite antennas [2]. Figure 2.1 shows the structure of meandered line antenna

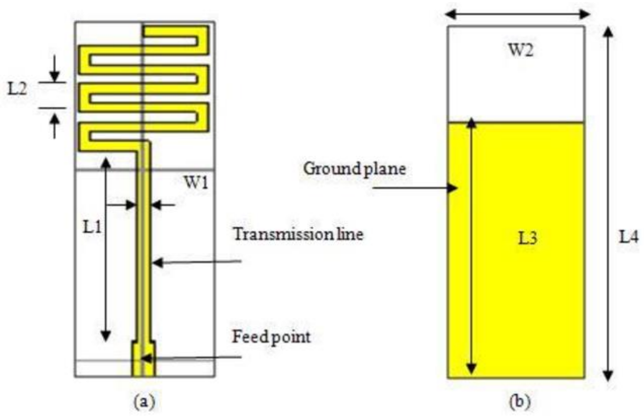


Figure 2.1: Meandered structure antenna

ii. Fractal Geometries

Fractal geometries are another category of compact antenna geometries that have gained significant attention in recent years. Fractals exhibit self-similarity patterns, meaning that they possess similar structures at different scales. The contours offer the advantage of achieving a greater electrical length within a reduced volume [3]. The electrical length of an antenna plays a vital role in determining its resonant frequency, making it a critical factor in antenna design. By having an enhanced electrical length, the resonance frequency is reduced, effectively reducing the size of the antenna. Notable examples of fractal antennas include the Sierpinski triangle, Koch curve, and Minkowski Island. These antennas exhibit multi-band and wideband operation, making them suitable for various frequency ranges [4]. Table 2.1 shows the self-similarity dimension of well-known fractal geometries.

Table 2.1: Self-similarity dimension of well-known fractal geometries

Fractal geometry	Scale factor (s)	No. of self-similar copies (N)	Dimension (D_s)
Sierpinski Gasket	$\frac{1}{2}$	3	1.5850
Sierpinski Carpet	$\frac{1}{3}$	8	1.8927
Koch Curve	$\frac{1}{3}$	4	1.2619
Hilbert Curve	$\frac{1}{2}$	4	2

Fractal antennas, however, have certain limitations. These include increased complexity in design and manufacturing due to fractal creation, lower gain in certain cases, numerical limitations, and diminishing benefits after a few iterations.

iii. Planar inverted F Antennas (PIFA)

Planar inverted F antennas (PIFAs) are compact antennas commonly used in mobile devices due to their size and multi-band capabilities. The origins of the inverted-F antenna can be traced back to the 1950s when it was initially developed as a bent-wire antenna. However, its most popular application today is as a planar inverted-F antenna (PIFA) in mobile devices due to its space-saving characteristics. PIFAs are commonly manufactured using the microstrip format, which is a widely adopted technology that allows for the production of printed RF elements similar to those found on printed circuit boards for mounting various components [5]. PIFAs consist of a planar structure with a shorting plate, which allows for reduced physical dimensions while maintaining multi-band operation. The shorting plate acts as a capacitance, enabling the antenna to resonate at multiple frequencies simultaneously. PIFAs are often integrated into the internal structure of mobile devices, making them a popular choice for space-constrained applications [6]. Figure 2.2 depicts the parameters that play a role in determining the resonant frequency of a Planar Inverted-F Antenna (PIFA). These parameters encompass not only the length and width of the patch, but also factors like the dimensions of the ground plane, the width of the feed and short plate, and the positioning of the top patch in relation to the ground plane [7]. It's important to note that while these parameters are mentioned, there are other factors to consider as well.

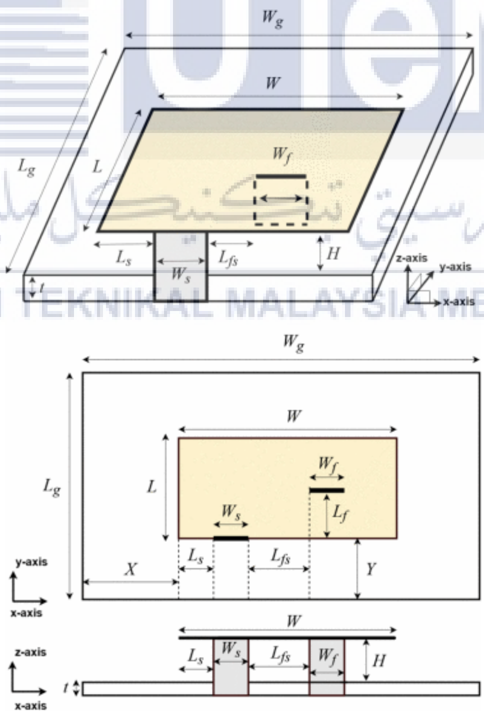


Figure 2.2: Schematic of PIFA with top and side view

iv. Advanced Materials

Advanced materials also play a significant role in antenna miniaturization. Metamaterial-inspired structures have emerged as a promising avenue for miniaturization [8]. Metamaterials are artificially engineered structures that exhibit unique electromagnetic properties not found in natural materials. By manipulating the geometry and composition of metamaterials, it is possible to control and enhance antenna performance. High permittivity substrates, such as ceramics or composites with high dielectric constants, enable the reduction of the wavelength within the substrate material [9]. This reduction allows for smaller physical dimensions while maintaining antenna performance. Additionally, the utilization of metamaterial-inspired structures, including split ring resonators (SRRs) and composite right/left-handed (CRLH) transmission lines, has demonstrated the potential for compact and efficient antenna designs [10]. By utilizing high permittivity substrates, antennas can achieve miniaturization without sacrificing electrical efficiency. Figure 2.3 shows the example of metamaterial antenna.

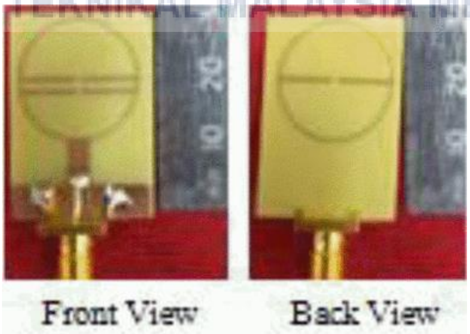


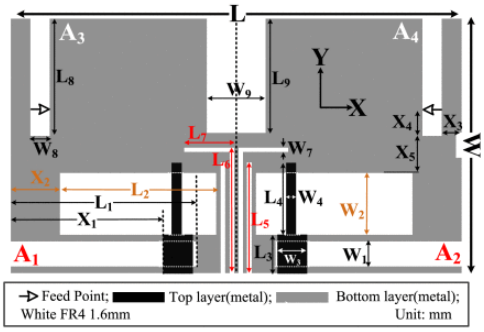
Figure 2.3: Example of Metamaterial Antenna

c. Performance Evaluation Metrics

When evaluating the effectiveness of miniaturized dual-band Wi-Fi antennas, several metrics are taken into account. These metrics encompass impedance matching, return loss, bandwidth, gain, radiation efficiency, and radiation pattern. Impedance matching ensures optimal power transfer between the antenna and the transmission line [11], while return loss quantifies the reflection of electromagnetic waves from the antenna [12]. Bandwidth measures the frequency range within which the antenna operates effectively [13]. Gain reflects the antenna's capacity to emit electromagnetic energy in a specific direction, and radiation efficiency takes into consideration losses in the radiating elements and structure [14]. Lastly, the radiation pattern describes the spatial distribution of the radiated energy.

d. Recent Research on Miniaturizing Antenna

The investigation reveals a significant body of research focused on the development of miniaturized antennas using various approaches. In a specific study by S. Soltani, P. Lotfi, and R. D. Murch (2017), a novel compact dual-band multiple-input-multiple-output (MIMO) slot antenna for WLAN applications is presented [15]. This antenna operates at two distinct frequency bands, 4.9-5.725 GHz with four ports and 2.4-2.5 GHz with two ports. The dual-band operation is achieved through the integration of a dual-band dual-port MIMO antenna and two single-band antennas dedicated to the 5 GHz band. The compact design, occupying a volume of $46 \times 20 \times 1.6\, mm^3$, is realized using an FR-4 printed circuit board. The achieved return loss is -15 dB for the 2.4 GHz band and -27 dB for the 5 GHz band. These excellent return loss values indicate the antenna's effective impedance matching and its ability to deliver maximum power to the system. The proposed antenna's compact form factor and robust performance make it well-suited for applications requiring simultaneous operation at 2.4 GHz and 5 GHz frequencies. The design details of the antenna are illustrated in Figure 2.4 and S-parameter is shown in Figure 2.5.



W	20	W_1	2	W_2	4	X_1	16	W_3	3
L	46	L_1	17.6	L_2	16	X_2	5	L_3	3
W_4	0.4	L_5	9	W_7	0.5	W_8	2	W_9	6
L_4	5	L_6	10	L_7	5	L_8	9.2	L_9	10
X_3	2	X_4	2	X_5	3.75	FR4(1.6mm)		Unit: mm	

Figure 2.4: Schematic of the proposed dual-band multiport antenna

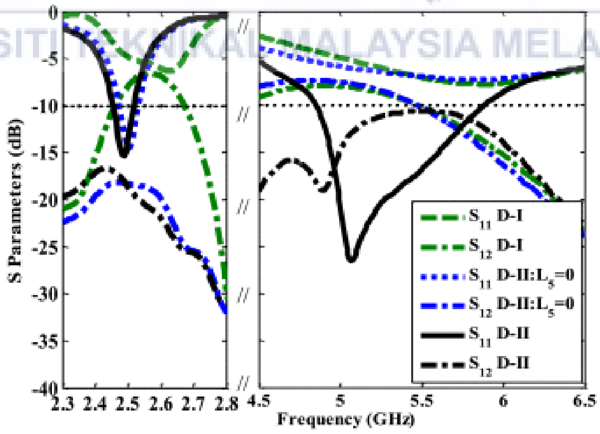
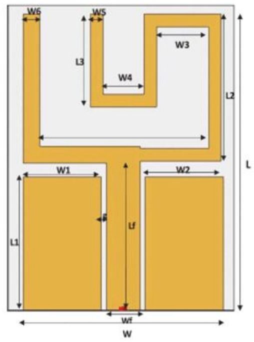


Figure 2.5: S-parameters results of the proposed MIMO antenna

Adnan Ghaffar, Xue Jun Li and Boon-Chong Seet (2018) introduced a planar monopole antenna with dual-band and overall compact size of $18 \times 12 \times 1.5\ mm^3$ [16] The study introduces a novel design for a dual-band printed monopole antenna, showcasing a compact structure optimized for efficient performance in the 2.4 GHz and 5.2 GHz frequency bands. The antenna is constructed using an inexpensive and readily available FR4 substrate material. The material specifications include a relative dielectric constant of 4.4, a dielectric loss tangent of 0.02, and a thickness of 1.5 mm. These parameters play a crucial role in determining the electrical characteristics of the antenna. The antenna achieves dual-band operation through carefully designed elements. The length of the radiation strip corresponds to a quarter wavelength, covering the lower frequency band of 2.4 GHz, while folded loops with an L-shape branch generate the higher frequency band of 5.2 GHz. The structure of the proposed antenna is strategically designed to be compact, utilizing folding techniques to minimize size while mitigating coupling effects between the antenna components. This design consideration enhances the antenna's efficiency and performance. The antenna's structural details, substrate material, and design parameters are presented in Figure 2.6, providing a comprehensive insight into the configuration and key components. The S parameter for the antenna simulation is shown in Figure 2.7.



Parameter	L	W	W_f	L_f	g	L_1	L_2
Unit (mm)	12	17.5	2	8.7	0.3	7.9	8.67
Parameter	L_3	W_1	W_2	W_3	W_4	W_5	W_6
Unit (mm)	5.49	4.7	4.7	3.13	2.45	0.75	1

Figure 2.6: Layout of the design antenna and its parameters

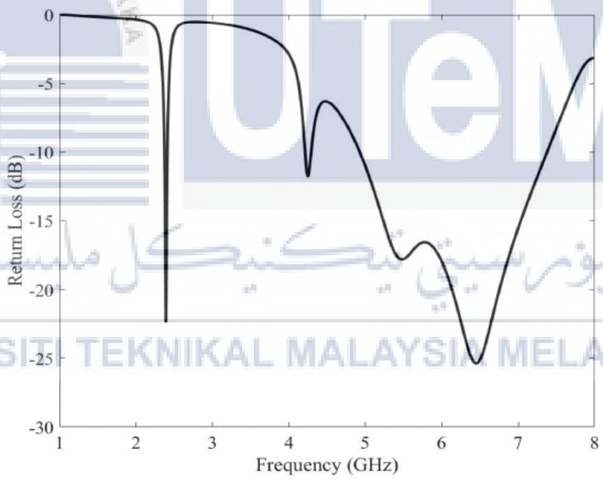


Figure 2.7: Simulated result of S parameter

E. Rashidi, J. Nourinia, Ch. Ghobadi, B. Azarm, M. Majidzadeh, and P. Hatami collaborated in 2020 to propose a dual band 2.4/5.5 GHz WLAN performance through a highly isolated MIMO configuration dual-band Multiple Input Multiple Output (MIMO) antenna [17]. The antenna design, outlined in their study, features two monopole antennas situated beside each other from a top view. Each monopole incorporates a 50Ω microstrip line-fed radiating patch, formed by joining three L-shaped elements, providing dual-band functionality at 2.4 and 5.5 GHz WLAN frequency bands. A rectangular-shaped ground on the backside and a parasitic rectangular structure contribute to the overall design. The proposed MIMO antenna occupies a compact total area of $25 \times 45 \times 1.6\ \text{mm}^3$, emphasizing efficiency in size for applications with spatial constraints. The inclusion of a parasitic rectangular structure between the two constituent antennas on the backside serves the purpose of isolation enhancement, minimizing interference and crosstalk between antennas. Detailed analysis and validation of the antenna's performance metrics have been conducted, including impedance bandwidth, group delay, radiation pattern, gain, and total active reflection coefficient. Notably, the antenna achieves a 10dB impedance bandwidth at 2.4 and 5.5 GHz, indicating stable and wideband performance across the specified frequency ranges. The antenna achieved a good return loss value of -25db at 2.4 GHz and -35db at 5 GHz. Figure 2.8, Figure 2.9 and Figure 2.10 depict the proposed MIMO antenna design, fabricated MIMO antenna and S-parameter for the antenna.

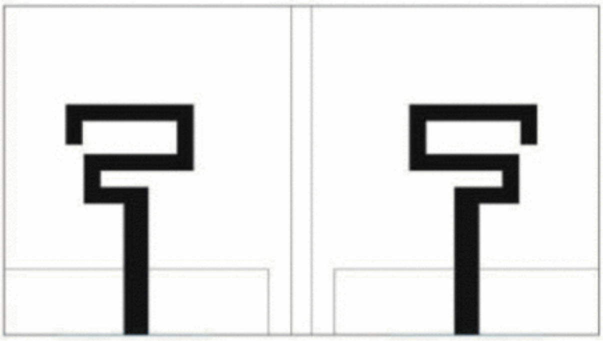


Figure 2.8: Proposed MIMO antenna design

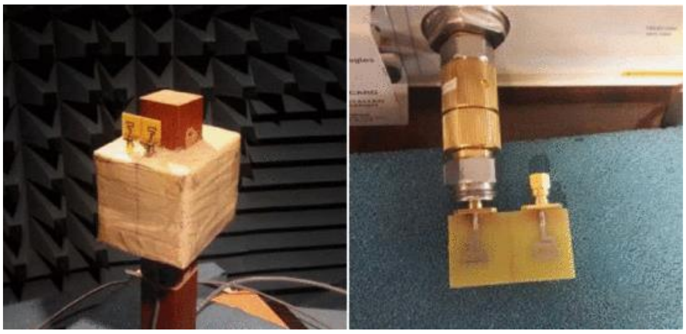


Figure 2.9: Fabricated MIMO antenna under S parameters measurement

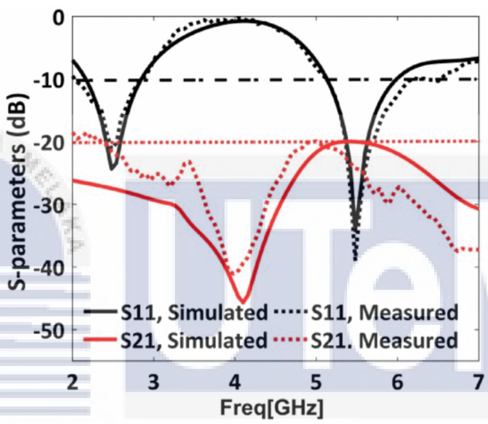


Figure 2.10: S-parameters of the MIMO antenna

Yasar Kaplan and Cem Gocen (2022) presented another effective design featuring a dual-frequency microstrip Wi-Fi antenna operating at 2.4 GHz and 5 GHz [18]. The antenna's feed is realized using a microstrip line, while the dielectric material employed is an FR-4 substrate with a thickness of 0.8 mm. Copper, with a thickness of 0.035 mm, serves as the conductive material. Microstrip antennas can be fed using various methods such as contact and non-contact feeding. Among these, the microstrip feeding method was employed in the design of this particular antenna. It is well-documented in literature that one technique influencing antenna performance is the incorporation of open slots at the feeding point. The proposed antenna exhibits resonant frequencies at 2.42 GHz and 5 GHz, with return loss values of -31.17 dB and -42.05 dB, respectively, at these frequencies. The bandwidth of the antenna spans 600 MHz (from 2.19 GHz to 2.75 GHz) for the 2.4 GHz band and 1250 MHz (from 4.74 GHz to 6 GHz) for the 5 GHz band. The realized gains are measured at 1.918 dBi and 2.303 dBi, respectively. Refer to Figure 2.11 and Figure 2.12 for a visual depiction of the antenna design and the simulated S-parameter of the antenna.

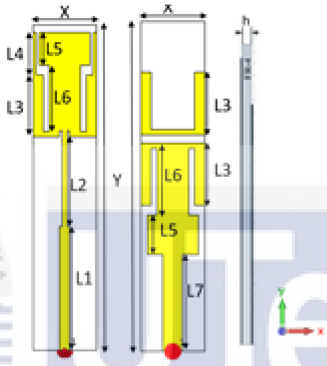


Figure 2.11: Design of Proposed Antenna

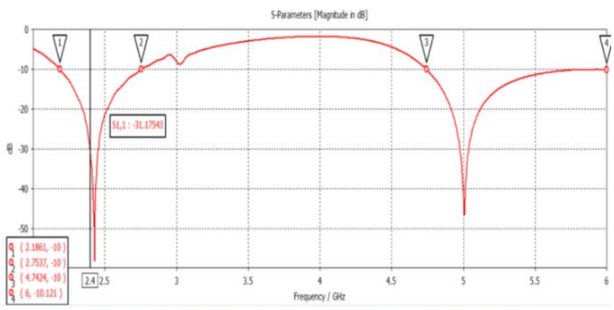
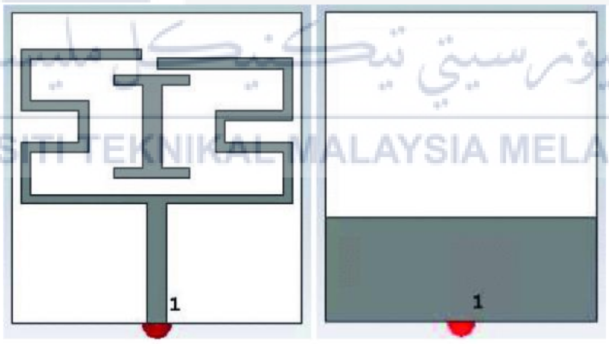


Figure 4. S_{11} Parameter of Proposed Antenna

Figure 2.12: Simulated S-parameter for the antenna

Sachin S Khade, Sidharth Tembhare, Pratik Gawali, Saharsh Jain, Rajat Ingole and Chitra V. Bawankar (2023) put forward a design for dual band Meander Line Antenna (MLA) for 5G and WLAN application utilizing an FR4 substrate with dimensions $30 \times 30 \times 1.6\, mm^3$ [19]. The proposed antenna addresses the challenge of limited range in 2.4 GHz connections by harnessing the higher speeds offered by the 5 GHz frequency. The radiating patch of the antenna comprises L-shaped elements interconnected on the top side, showcasing a unique approach to enhancing wireless communication while contributing to the overall performance of the antenna. The proposed antenna's performance is rigorously evaluated in terms of gain, radiation pattern, and return loss. The measured return loss at 2.4 GHz and 5 GHz is reported as -34.88 dB and -12.56 dB, respectively. This suggests effective impedance matching, meeting the stringent requirements of 5G applications. The design of proposed antenna and S-parameter are shown in Figure 2.13 and Figure 2.14.



(a) Front view (b) Back view

Figure 2.13: Layout of the proposed Meander line patch antenna

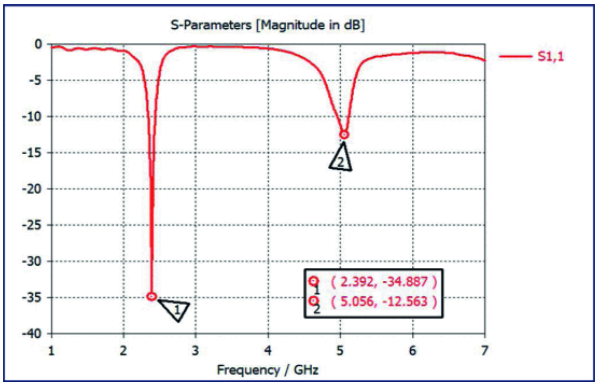


Figure 2.14: Simulated S-parameter for the MLA antenna

In a specific study by Weiquan Zhang, Yue Li, Kunpeng Wei and Zhijun Zhang (2023), two dual-band back-to-back planar inverted-F antennas (PIFAs) were presented for wireless local area network (WLAN) applications [20]. The system mainly consists of one substrate, one metal sheet, and three probes. The substrate is FR-4 with the dielectric constant of 4.4 and the loss tangent of 0.02. The overall size of the PIFA antenna is $50 \times 150 \times 11.1mm^3$. Lumped ports were applied to feed the antennas during the simulation. The microstrip lines are connected to the metal sheet through metal probes. To obtain dual-band PIFAs, Π -shaped slots are symmetrically etched on the metal sheet. Long and short slots are successively engraved on the ground to reduce the mutual coupling at the two independent bands in a guided way. The antenna achieved a return loss of approximately -28db at 2.45 GHz and -32db at 5.25 GHz. Figure 2.15 shows the design of proposed PIFA antenna while Figure 2.16 depicts the fabricated PIFA antenna. The simulation for S parameter is shown in Figure 2.17.

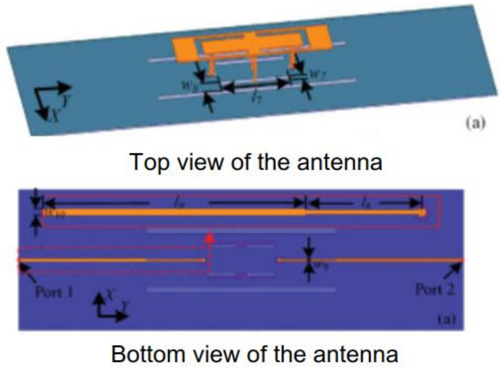


Figure 2.15: Design of the proposed PIFA antenna

Figure 2.16: (a) Top and (b) bottom views of the prototype

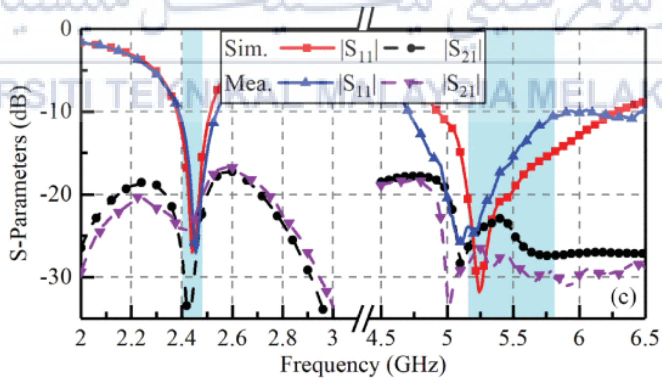


Figure 2.17: Simulated S-parameter for PIFA antenna

e. Research Gaps

The literature review also identified research gaps and areas for further investigation. While several miniaturization techniques and compact antenna geometries have been explored, there is still room for innovation and refinement. Additionally, the integration of advanced materials and metamaterial-inspired structures into miniaturized antenna designs warrants further exploration. Furthermore, the evaluation of miniaturized dual-band Wi-Fi antennas in real-world scenarios, considering factors such as nearby objects and environmental effects, requires additional investigation. Table 2.2 below shows the comparison and limitation of recent research done.

Table 2.2: Limitation and gap of recent antenna research

Author, year	Type of Antenna	Limitation
S. Soltani, P. Lotfi, and R. D. Murch (2017)	A Dual-Band Multiport MIMO Slot Antenna for WLAN Applications	-Multiple ports are required based on the number of antennas used in the system -Hard to integrate multiple antennas into small devices
Adnan Ghaffar, Xue Jun Li and Boon-Chong Seet (2018)	Compact Dual-Band Broadband Microstrip Antenna at 2.4 GHz and 5.2 GHz for WLAN Applications	-Consist of two branches to achieve resonant frequencies at 2.4 GHz and 5 GHz which make it

		harder to achieve smaller size
E. Rashidi, J. Nourinia, Ch. Ghobadi, B. Azarm, M. Majidzadeh, and P. Hatami (2020)	Dual Band 2.4/5.5 GHz WLAN Performance through a Highly Isolated MIMO Configuration	-Multiple port require base on the number of antennas used in the system -Hard to integrate multiple antennas into small devices
Y. Kaplan and C. Göçen (2022)	A Dual-Band Antenna Design for 2.4 and 5 GHz Wi-Fi Applications	-Gain for the antenna is too low and does not meet the requirement criteria
S. S. Khade, S. Tembhare, P. Gawali, S. Jain, R. Ingole and C. V. Bawankar (2023)	Dual Band Meander Line Antenna for 5G and WLAN Application	-Consist of two branches to achieve resonant frequencies at 2.4 GHz and 5 GHz which make it harder to achieve smaller size
W. Zhang, Y. Li, K. Wei and Z. Zhang (2023)	Dual-Band Decoupling for Two Back-to-Back PIFAs	-Consume a lot of space (height) which is not suitable for the use of mobile application

f. Summary

In summary, the literature review provided a comprehensive overview of the existing research on miniaturized dual-band Wi-Fi antennas for mobile applications. It synthesized the findings from studies related to miniaturization techniques, compact antenna geometries, advanced materials, and performance evaluation metrics. The review identified research gaps and sets the foundation for the subsequent design, analysis, and implementation of a novel miniaturized dual-band Wi-Fi antenna for mobile applications. Based on the literature review done, meandered line antenna approach is chosen as the main methodology to complete this thesis.

CHAPTER 3

METHODOLOGY

a. Introduction

The research study will be carried out in one year and can be divided into five work packages, namely: (1) Literature review, (2) design a miniaturized dual-band Wi-Fi antenna, (3) develop and fabricate the antenna, (4) evaluate the performance of the designed antenna and (5) report, paper and journal writing. The flow of the work packages and project's research methodology are shown in Figure 3.1 and Figure 3.2.

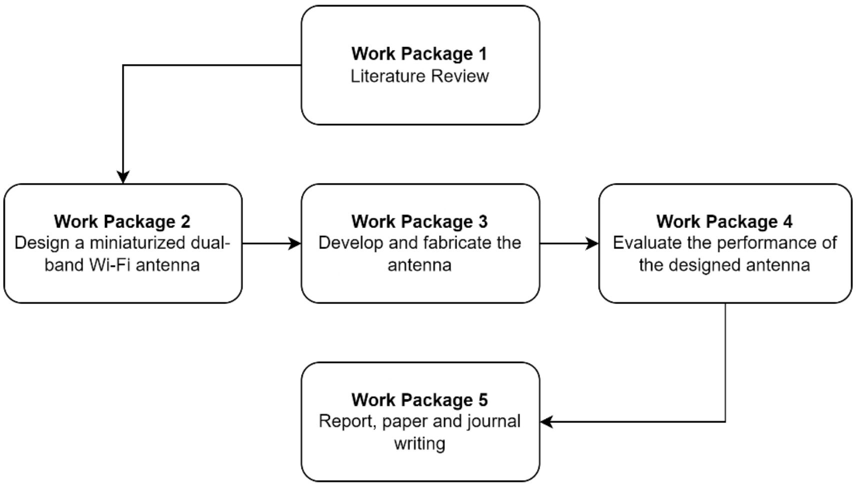


Figure 3.1: Flow chart of the project

b. Project's Research Methodology Flow Chart

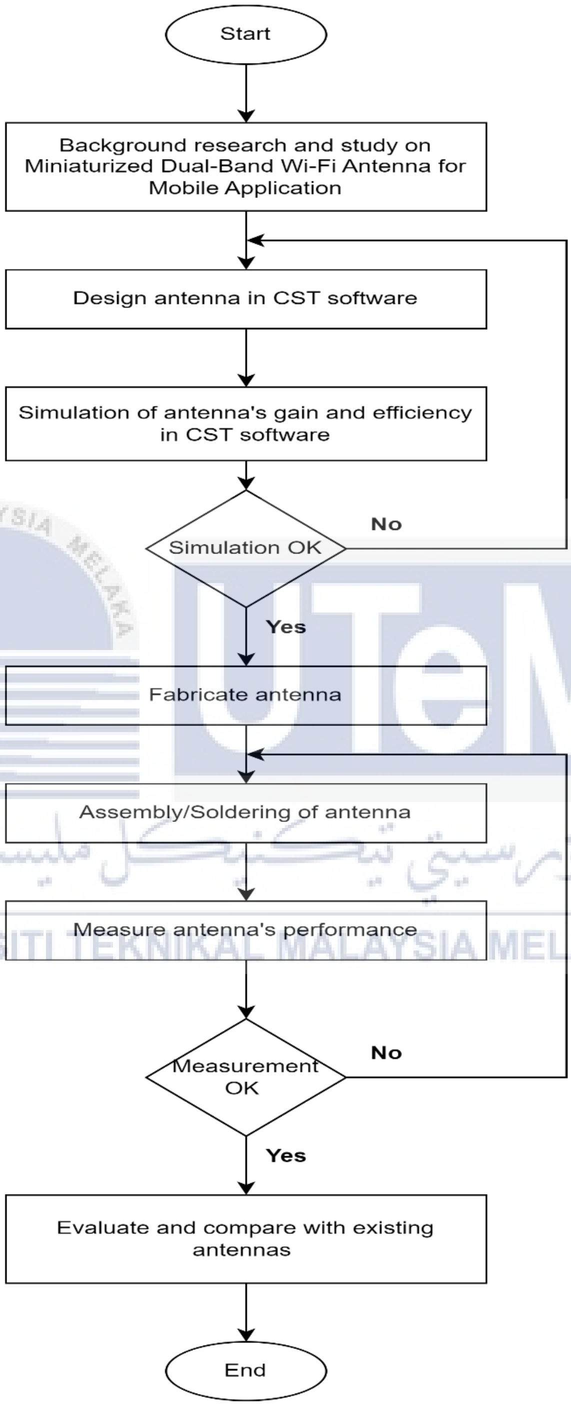


Figure 3.2: Project's Research Methodology Flow Chart

i. Detail Description of The Research Methodology

1. Background research and study on miniaturized dual-band Wi-Fi antenna for mobile application
   - Do research and study on 2.4 GHz and 5 GHz Wi-Fi antennas.
   - Discover a way to combine 2.4 GHz and 5 GHz into dual band Wi-Fi antenna
   - Find out the method used to miniaturize the Wi-Fi antenna

2. Install Computer Simulation Technology (CST) software
   - Download and install CST Studio Suite 2022 from its official website.
   - Go through the introduction and tutorial of CST software

3. Design antenna in CST software
   - Design 2.4 GHz and 5 GHz antenna according to specification provided by Intel.
   - Design a dual band Wi-Fi antenna combining 2.4 GHz and 5 GHz bandwidth with minimum size

4. Simulation of antenna
   - The antenna design is simulated using CST software to test its performance such as gain and efficiency
   - The maximum antenna gain is 3dBi for 2.4 GHz and 5dBi for 5 GHz.
   - If the simulation result is not satisfied, the antenna needs to be redesigned for better performance

5. Fabricate antenna & assembly/soldering
    - The antenna was fabricated on FR-4 substrate and assembly process should be applied to the antenna.

6. Measure antenna's performance
    - Fed power to the antenna feed pads and measured the strength of the radiated electromagnetic field, gain and efficiency.
    - If the expected measurement is not acquired, further troubleshooting should be done to find the cause of the problem.

7. Evaluate and compare with existing antenna
    - The antenna is compared to current antenna existed on the market to prove its improvement

c. Technical Design

i. Components used in the projects

1. FR-4 substrate

FR-4, commonly known as Flame Retardant 4, is an ideal substrate material extensively utilized in the design and fabrication of antennas for Wi-Fi applications. Its unique properties make it well-suited for creating high-performance Wi-Fi antennas.

FR-4 substrates for Wi-Fi antennas are comprised of a woven fiberglass cloth impregnated with epoxy resin. This combination provides exceptional electrical insulation, which is crucial for maintaining signal integrity and minimizing interference in wireless communication systems. The low dielectric constant, ranging from 3.8 to 4.8 and low dissipation factor of FR-4 help to reduce signal loss, ensuring efficient transmission and reception of Wi-Fi signals [21].

In the realm of antennas, it is essential to have a substrate material that can withstand various environmental factors and mechanical stresses. FR-4 exhibits remarkable mechanical strength and dimensional stability, allowing Wi-Fi antennas to endure rigorous conditions encountered in real-world applications. The woven fiberglass reinforcement enhances the structural integrity of the substrate, making it resilient against vibrations, impacts, and other mechanical disturbances.

Wi-Fi antennas often operate in environments with fluctuating temperatures and thermal challenges. FR-4 possesses excellent thermal stability, enabling it to handle elevated temperatures associated with antenna operation. This characteristic ensures that the substrate retains its performance and structural integrity under demanding thermal conditions, thereby contributing to the longevity and reliability of Wi-Fi antennas [22].

Furthermore, FR-4 substrates used in Wi-Fi antennas are designed to be flame retardant. This feature provides an additional layer of safety, minimizing the risk of fire and protecting the integrity of the antenna. Compliance with flame retardancy standards, such as UL 94V-0, ensures that Wi-Fi antennas employing FR-4 substrates meet the necessary safety regulations.

The versatility and cost-effectiveness of FR-4 make it a preferred choice for manufacturing Wi-Fi antennas. It is available in various thicknesses, allowing for customization and optimization of antenna designs for specific Wi-Fi frequencies and applications. The machinability and processability of FR-4 facilitate the fabrication of complex antenna structures with precise geometries, ensuring optimal performance. Table 3.1 depicts the properties of FR-4 substrate and Figure 3.3 shows the FR-4 substrate.

Table 3.1:Properties of FR-4 Substrate

Parameter	Value
Temperature index	140 °C (284 °F)
Thermal conductivity, through-plane	0.29 W/(m·K), 0.343 W/(m·K)
Thermal conductivity, in-plane	0.81 W/(m·K), 1.059 W/(m·K)
Dielectric breakdown (A)	> 50 kV
Dielectric breakdown (D48/50)	> 50 kV
Dielectric strength	20 MV/m
Relative permittivity (A)	4.4
Relative permittivity (D24/23)	4.4
Dissipation factor (A)	0.017
Dissipation factor (D24/23)	0.018
Dielectric Constant (ε_r)	3.9 – 4.7, 4.4 @ 1 GHz (Supplier Isola)
Loss Tangent (tanδ)	0.02 – 0.03, 0.030 @ 1 GHz
Glass transition temperature	Can vary, but is over 120 °C

Figure 3.3: FR-4 Substrate

2. SMA Port

The SMA (SubMiniature version A) port plays a crucial role in antenna design, serving as a reliable and versatile coaxial RF connector. Characterized by its threaded coupling mechanism, the SMA connector ensures a secure and stable connection in applications ranging from DC to 18 GHz. SMA connectors come in male and female types, with the compact size of these connectors being particularly advantageous in antenna design where space constraints are common. The connectors are commonly used in antennas for wireless communication systems, such as Wi-Fi and cellular networks, due to their durability, adaptability, and ability to withstand repeated connect-disconnect cycles. Additionally, SMA connectors are employed in RF test and measurement equipment, offering flexibility in connecting various components [23]. The 50-ohm impedance version of SMA is prevalent in RF and antenna applications, contributing to signal integrity and reliable performance [24]. Figure 3.4 illustrates the SMA port used in the MLA antenna design.

Figure 3.4: SMA Jack PCB Mount (Female)

ii. Software Development

1. Computer Simulation Technology (CST) Studio Suite

CST Studio Suite is a comprehensive and industry-leading software package developed by Computer Simulation Technology (CST) for the design, simulation, and analysis of electromagnetic fields and their interactions with complex structures. It provides engineers and researchers with powerful tools to model and optimize electromagnetic systems across a wide range of applications.

One of the key strengths of CST Studio Suite is its advanced simulation capabilities. It employs numerical techniques, such as the finite integration technique (FIT) and finite element method (FEM), to accurately model and analyze electromagnetic phenomena in three-dimensional (3D) space [25]. These techniques enable engineers to simulate a wide range of electromagnetic effects, including electromagnetic interference (EMI), radiation patterns, scattering, signal propagation, and power distribution. Figure 3.5 shows the CST Studio Suite application.

Figure 3.5: CST Studio Suite 2022

2. Calculation

Calculation should be done first to find the dimension of the substrate, patch, inset and port of the antenna. For designing of a microstrip patch antenna, the resonant frequency and a dielectric medium for which antenna is to be designed has to be selected. The parameters to be calculated are as below:

1. Width of the patch [26]:

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (3.1)$$

2. Effective Dielectric Constant [26]:

This is based on the height, dielectric constant of the dielectric and the calculated width of the patch antenna.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right) \quad (3.2)$$

3. Effective Length [26]:

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \tag{3.3}$$

4. Length Extension [26]:

$$\Delta L = 0.412h\left[\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right] \tag{3.4}$$

5. Length of the patch [26]:

$$L = L_{eff} - 2\Delta L \tag{3.5}$$

6. Input Impedance of the Antenna [26]:

$$Z_{in} = 90\left(\frac{{\varepsilon_r}^2}{\varepsilon_r-1}\right)\left(\frac{L}{W}\right)^2 \tag{3.6}$$

7. Bandwidth of the Antenna [26]:

$$BW = 3.77f_o\left(\frac{\varepsilon_r-1}{{\varepsilon_r}^2}\right)\left(\frac{Wh}{L\lambda}\right)^2 \tag{3.7}$$

3. Design of Antenna in CST Studio Suite

The miniaturized dual-band Wi-Fi antenna is designed in the software using project template of antenna under the microwaves & RF / Optical. The workflow of the patch antenna should be set as for planar (Patch, Slot, etc). The antenna is designed in time domain and all of the unit parameters are set as default. The range of the frequency is set as 1 (min) to 7 (max) to make it easier for monitoring purpose of the S parameter graph, S_{11} for 2.4 GHz and 5 GHz. Parametric sweep is done to optimize the S_{11} curve and find the most suitable dimension of the patch. The design step of the patch antenna can be summarized as in Figure 3.6.

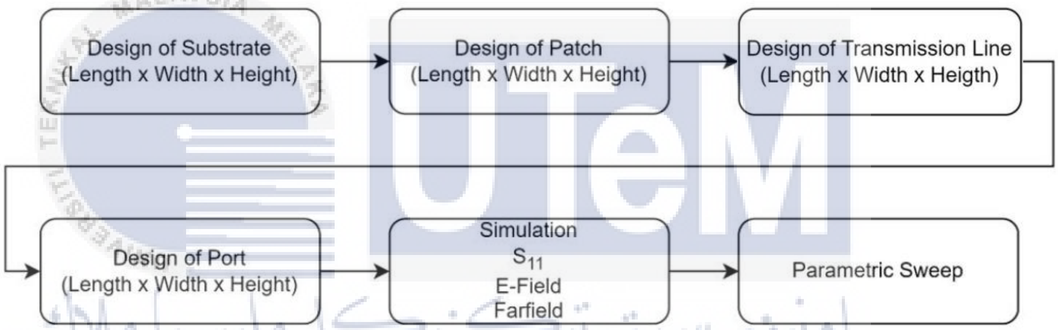


Figure 3.6: Procedure for Designing Wi-Fi Antenna

The MLA line is designed in CST Studio Suite 2022, the antenna consists of dielectric, meandered line patch and ground patch. Figure 3.7 and Figure 3.8 show the front and back view of the MLA. The port is constructed at the end of the transmission line as illustrated in Figure 3.9.

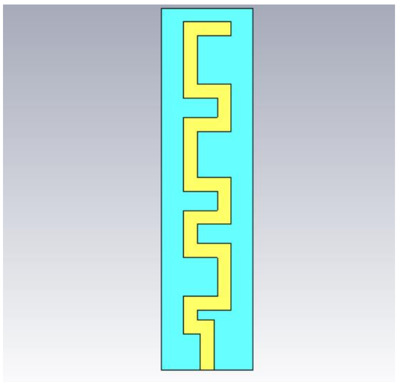


Figure 3.7: Front view of the proposed MLA

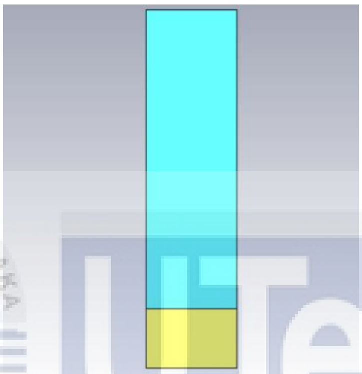


Figure 3.8: Back view of the proposed MLA

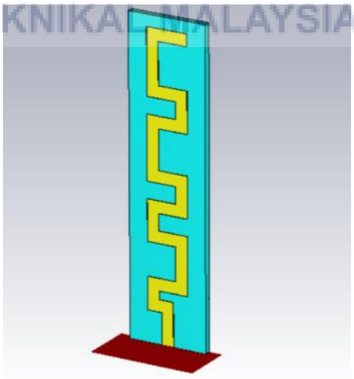


Figure 3.9: Port constructed at the end of transmission line

d. Fabrication Process

The MLA antenna is fabricated by undergoing the etching process on FR-4 board. The etching process for creating an antenna on an FR-4 board involves selectively removing unwanted copper material to define the antenna structure. The copper layer on the FR-4 serves as the conductive material for the antenna. Before transferring the antenna design onto the FR-4 board, a printed circuit board (PCB) layout is typically printed on a special transfer material known as a "transfer film" or "toner transfer paper" as shown in Figure 3.10. This step is often referred to as the toner transfer process. The transfer material acts as a carrier for the printed circuit pattern and helps transfer it to the surface of the FR-4 board during the fabrication process. Subsequently, the board undergoes the etching process inside an etching machine as shown in Figure 3.11. An etchant solution, often a mixture of ferric chloride or ammonium persulfate with water, is applied to the board, selectively dissolving the exposed copper areas. The etching reaction continues until the desired antenna pattern is revealed, with the toner acting as a resist to protect the intended conductive pathways. The etched board is then rinsed thoroughly to halt the etching process and remove any remaining etchant. The etched FR-4 board is then cut to remove excessive dielectric part that is not in the design dimension. Finally, a SMA port is soldered onto the end of the transmission line of the MLA. Figure 3.12 and Figure 3.13 depict the fabricated MLA with SMA port soldered onto its transmission line.

Figure 3.10: Printed MLA design on Transfer Film

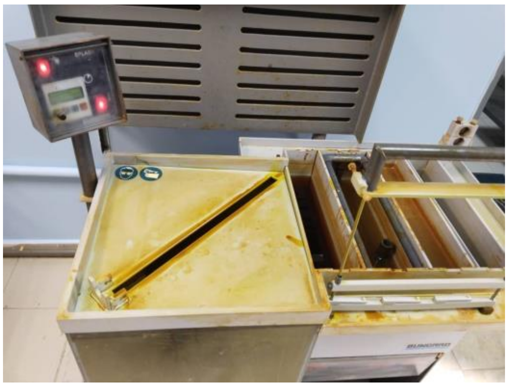


Figure 3.11: Etching Machine used to etch FR-4 into MLA antenna

Figure 3.12: Front View of the MLA

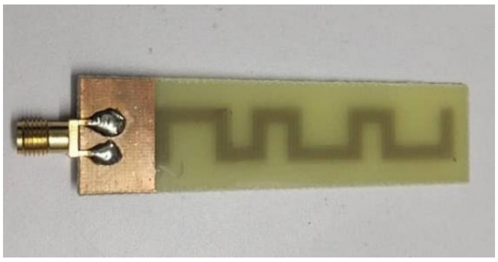


Figure 3.13: Back view of the MLA

e. Measurement Process

The fabricated MLA's return loss is measured using VNA as shown in Figure 3.14. The radiation pattern, gain and directivity of the antenna is measured inside chamber room. Figure 3.15 depicts the measurement setup of the MLA inside the chamber room.

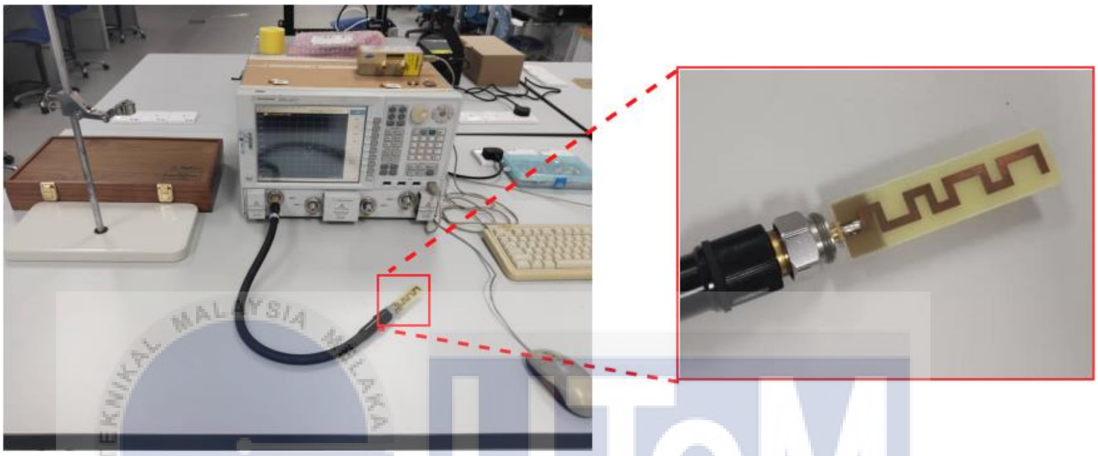


Figure 3.14: Measurement setup using VNA

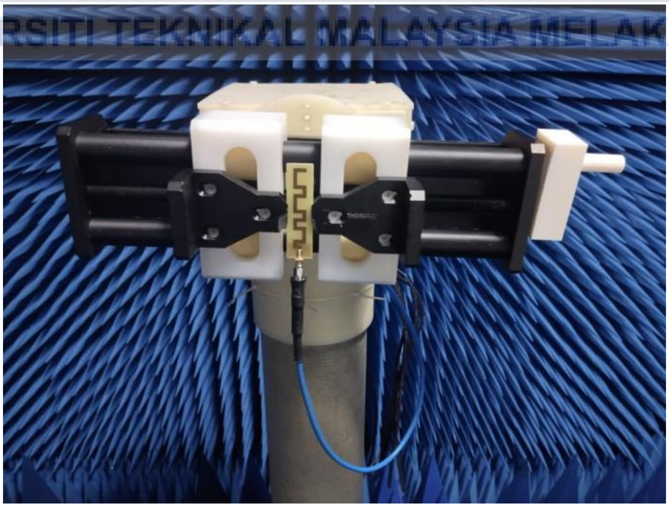


Figure 3.15: Gain and directivity measurement

CHAPTER 4

RESULTS AND DISCUSSION

a. Introduction

This section marks a pivotal phase in unraveling the intricate design and performance evaluation of the "Miniaturized Dual-Band WiFi Antenna." The preceding chapters meticulously delved into the theoretical underpinnings, design considerations, and simulation methodologies employed in crafting this innovative antenna. This section presents a comprehensive analysis of the antenna's performance across the dual frequency bands, shedding light on its efficacy in meeting the demands of contemporary wireless communication systems. Through a series of carefully designed experiments and simulations, the aim is to elucidate the antenna's key parameters, such as gain, radiation pattern, impedance matching, and other relevant metrics.

b. Return loss

The MLA consist of multiple section of zigzag line as shown in Figure 4.1. The dielectric has a thickness of 1.6mm and other parameters as depicted in Table 4.1. Each of this section will affect the return loss and gain of the antenna at resonant frequencies of 2.4 GHz and 5 GHz. Parametric sweep is done to observe the effect of the meander section changes towards the return loss and gain of the antenna at desired resonant frequencies as shown in Figure 4.2 to Figure 4.9. The final simulation result of return loss for designed antenna is illustrated in Figure 4.10. It shows that two operating bands are generated at 2.4 and 5 GHz frequency band. The antenna elements resonated between 2.34 – 2.47 GHz and 4.87–5.68 GHz with a minimum $|S_{11}| < -10$ dB. The optimized antenna shows the bandwidth of about 70 MHz on lower band of 2.4 GHz and about 80 MHz on upper band of 5 GHz that is compatible with WLAN standard. The maximum return loss for resonant frequency 2.4 GHz is -26.92dB and 5 GHz is -45.34dB.

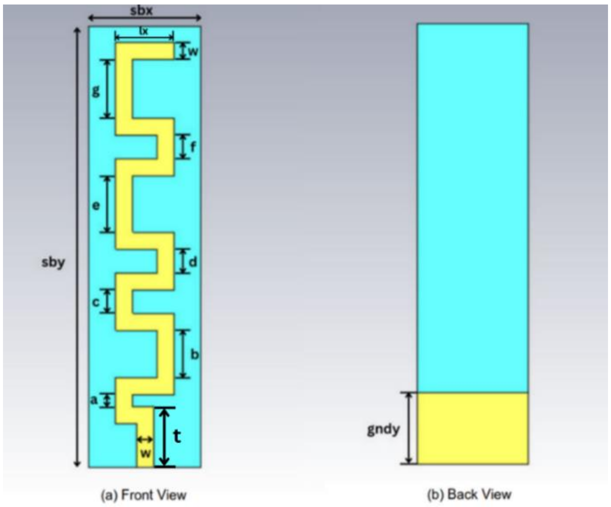


Figure 4.1: Parameters of proposed MLA design

Table 4.1: Parameters for the antenna

Parameter	Unit (mm)
sbx	19
sby	75
w	2.9
lx	10
a	2
b	8
c	4
d	4
e	10
f	4
g	10
t	7.5
gndy	12.3

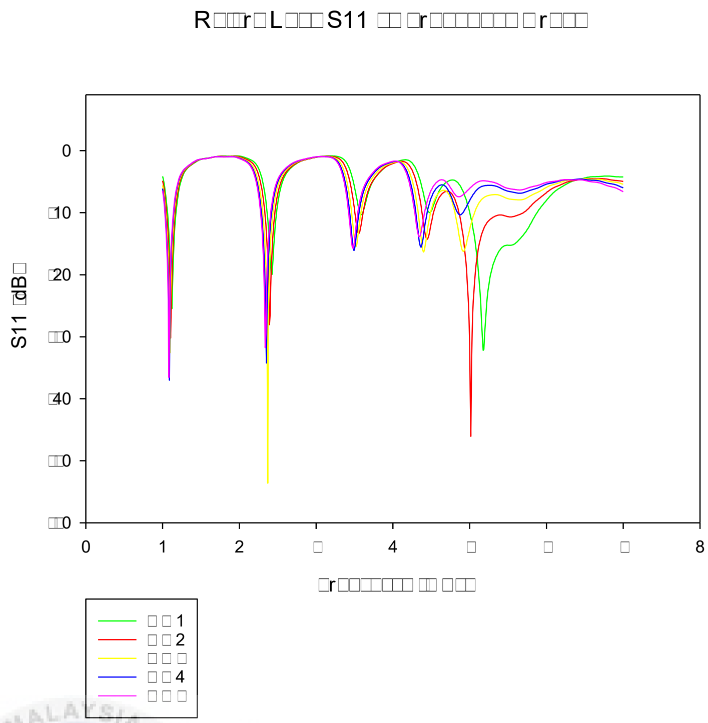


Figure 4.2: Parameter sweep 'a'

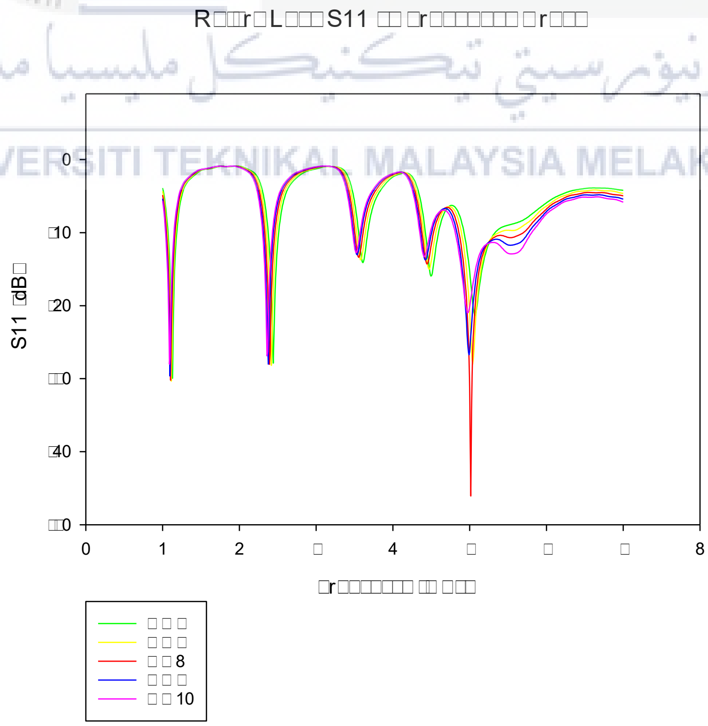


Figure 4.3: Parameter sweep 'b'

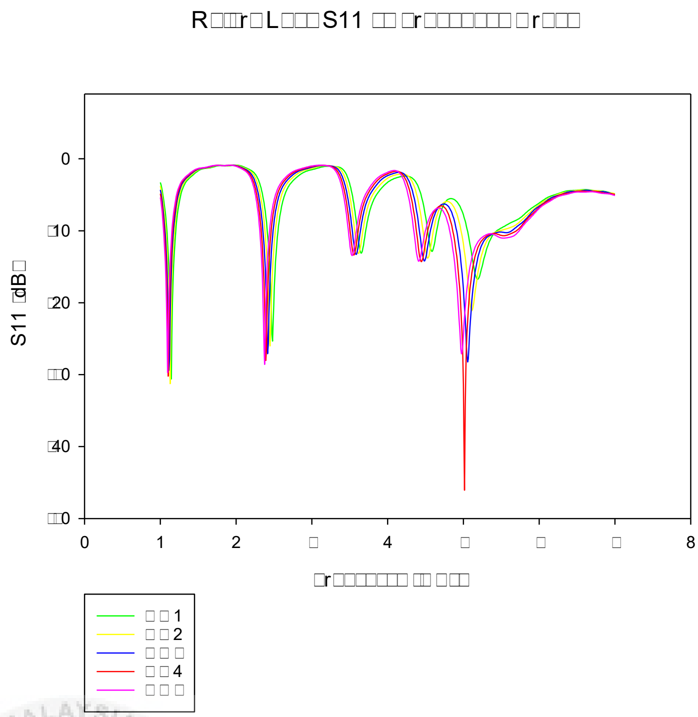


Figure 4.4: Parameter sweep 'c'

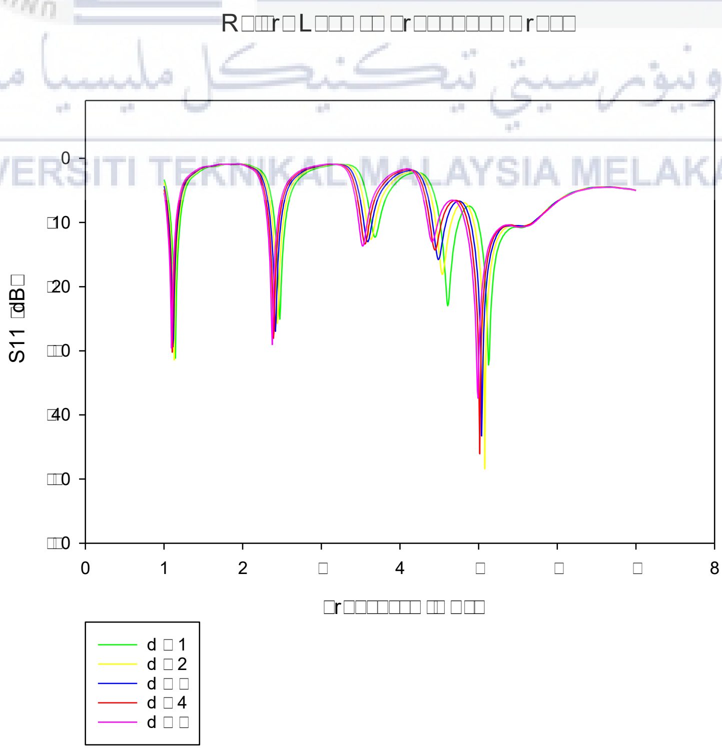


Figure 4.5: Parameter sweep ‘d’

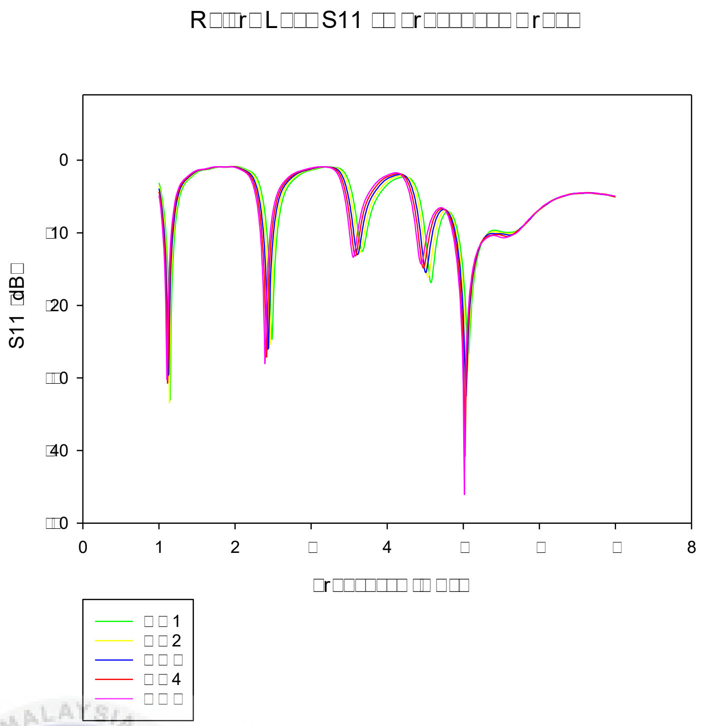


Figure 4.6: Parameter sweep 'e'

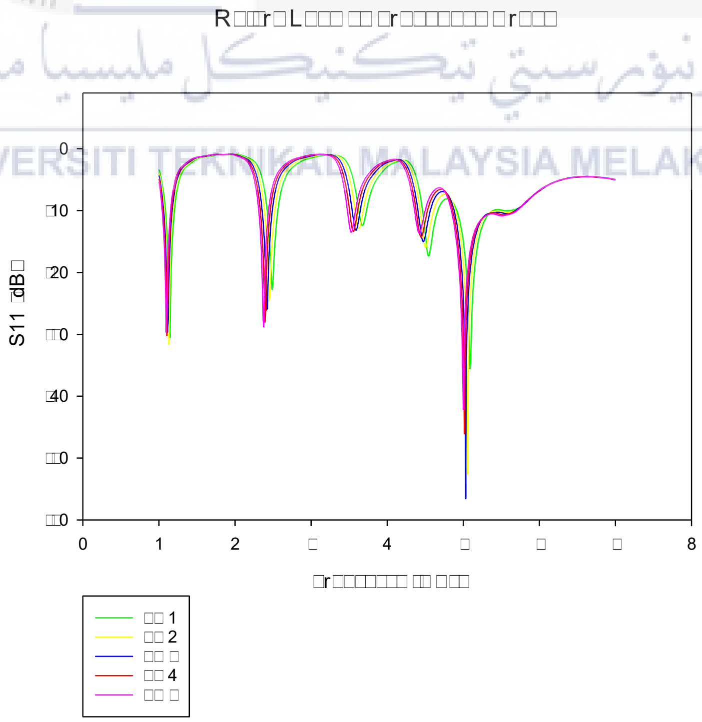


Figure 4.7: Parameter sweep 'f'

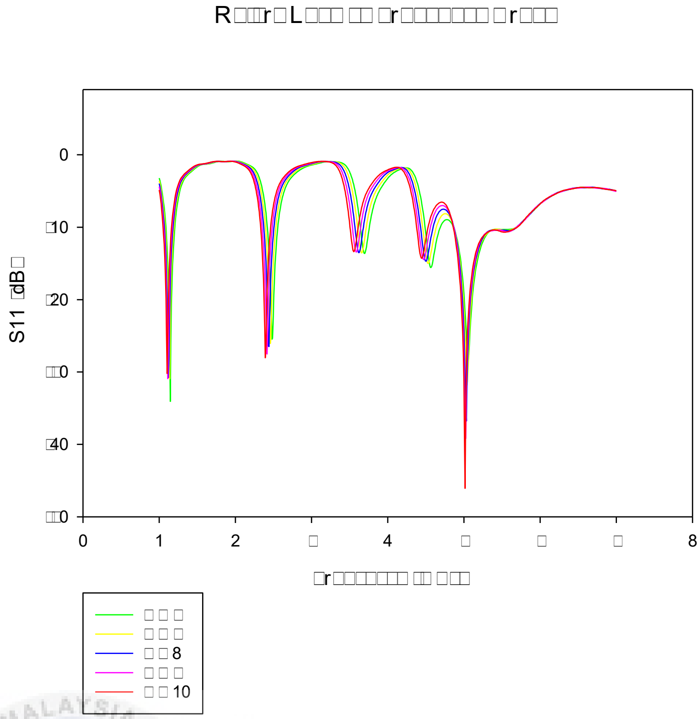


Figure 4.8: Parameter sweep 'g'

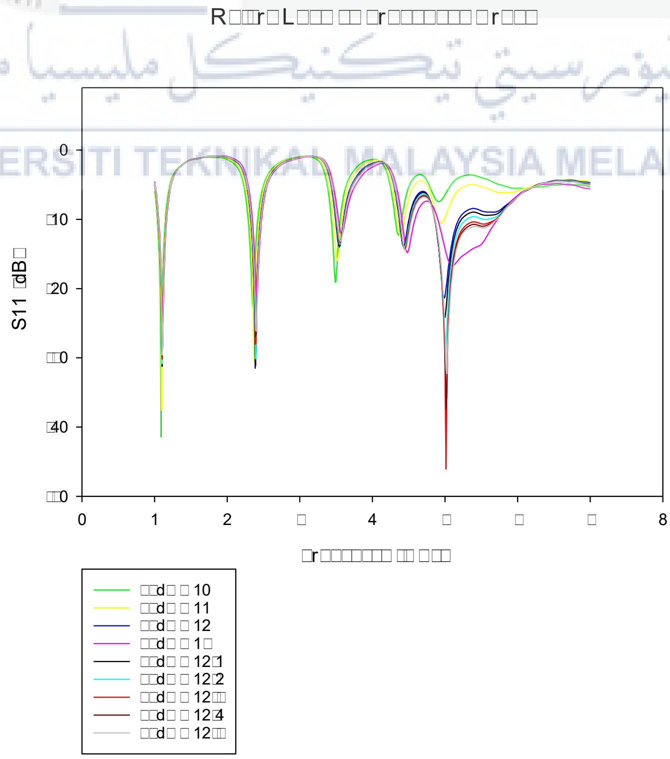


Figure 4.9: Parameter sweep 'gndy'

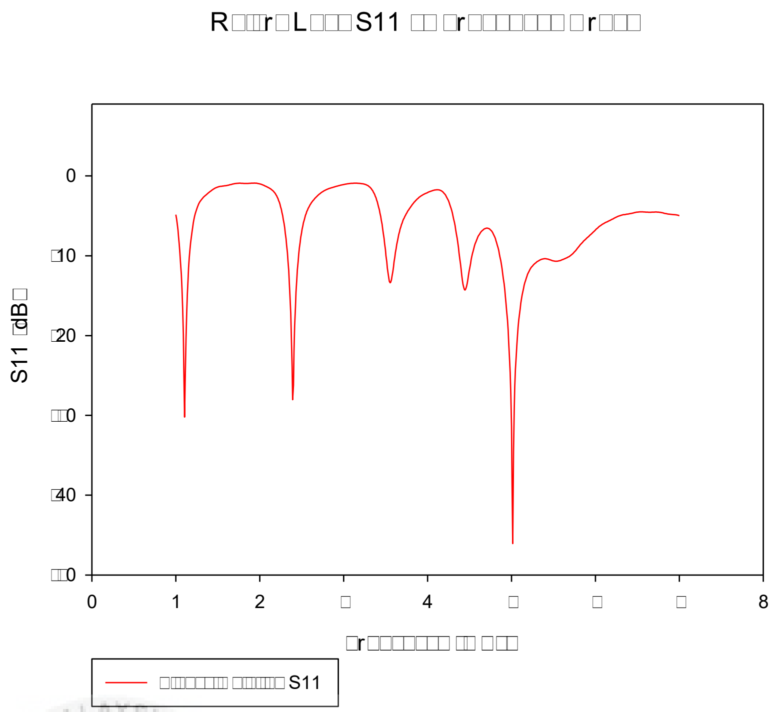


Figure 4.10: Final simulated S11 result for the proposed MLA

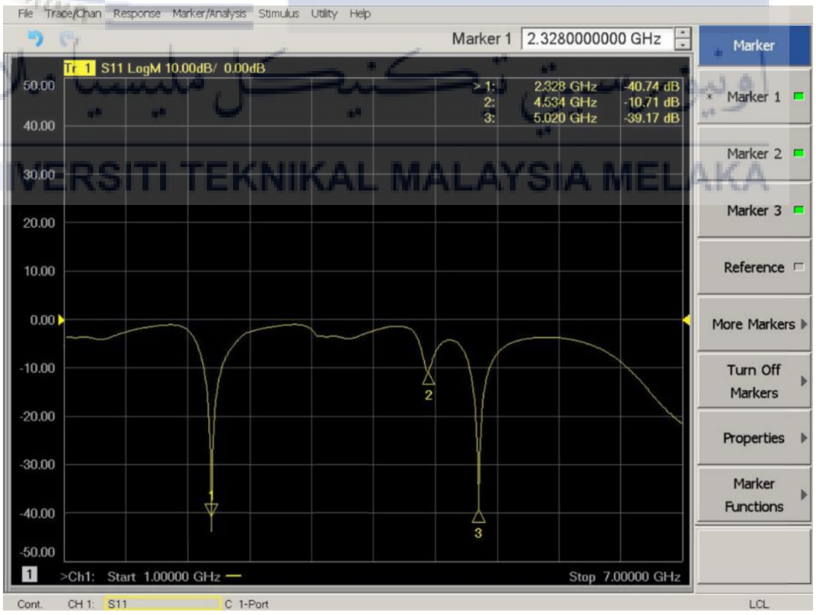


Figure 4.11: Return loss measurement of the fabricated MLA

As per the measured results depicted in Figure 4.11 the antenna has dual band response at 2.328 GHz and 5.020 GHz with S-parameter of -40.74dB and -39.17dB. When compared to the simulated result, the return loss of upper band 5 GHz of the fabricated MLA is similar to the simulated result. However, the return loss graph of the fabricated MLA is shifted to the left for the band of 2.4 GHz. This is due to the flaw in the fabricated copper trace on the MLA. The dimension of the copper on the MLA may not be exactly the same as in the CST software design. The result is still considered acceptable as the bandwidth cover over 2.4 GHz.

c. Reference impedance

The impedance value at 2.4 GHz and 5 GHz is 50.2 ohm as illustrated in Figure 4.12. Theoretically, antenna good impedance value is near 50 ohms. This is because coaxial cables, which are commonly used for transmitting RF signals, are optimized for 50 ohms impedance. Hence, the result shows the proposed fabricated antenna has a good impedance value.

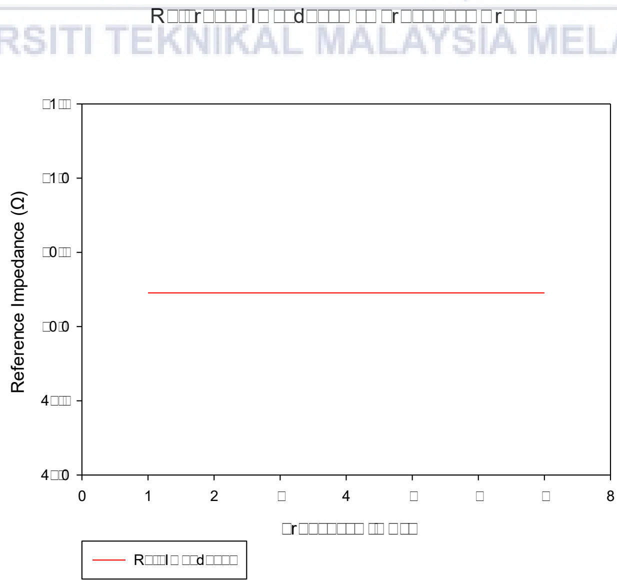


Figure 4.12: Reference impedance

d. Voltage Standing Wave Ratio voltage (VSWR)

The fabricated antenna has VSWR of 1.094 and 1.059 at 2.4 GHz and 5 GHz respectively. This shows that the antenna has a good VSWR as it is closer to 1. Figure 4.13 indicates the VSWR plot for the MLA.

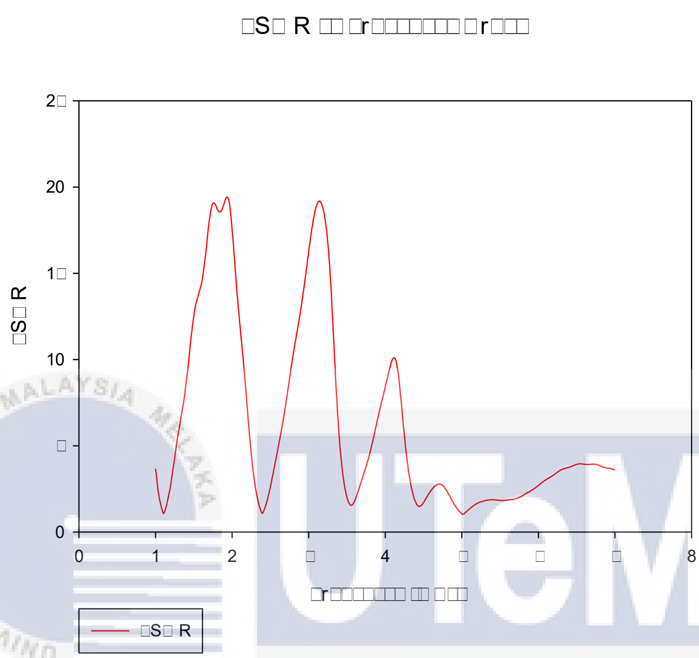


Figure 4.13: VSWR plot of the MLA

e. Radiation pattern

Figure 4.14 and Figure 4.15 below show the radiation pattern of the MLA. Based on the farfield plot, the radiation pattern is nearly omnidirectional for both bands. Omnidirectional antennas provide a consistent signal strength, reducing the likelihood of signal dropouts as users move through different locations. In addition, mobile devices are often used in different orientations (portrait, landscape, etc.). An omnidirectional antenna ensures that the device can maintain a reliable connection regardless of how it is held or positioned. "Decibels isotropic" (dBi) is a unit of measurement commonly used in antenna engineering to express the gain of an antenna relative to an isotropic radiator. The term "isotropic" refers to an idealized point source that radiates uniformly in all directions, creating a spherical radiation pattern. Both of these band achieved the expected gain. The 1D farfield results for 0° and 90° phi are depicted in Figure 4.16 and Figure 4.17.

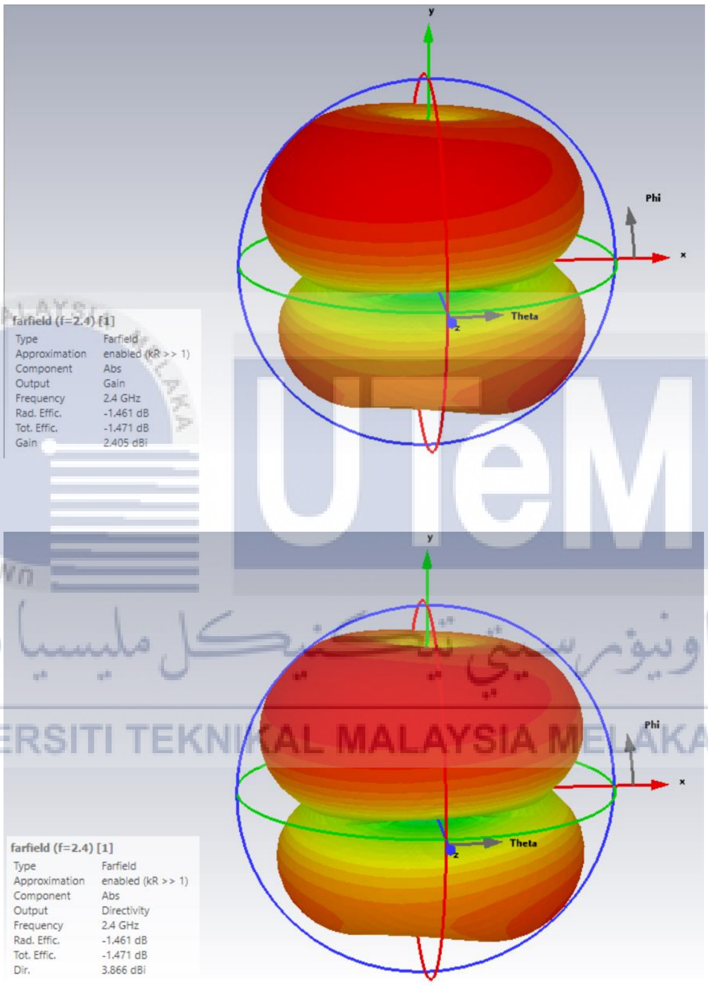
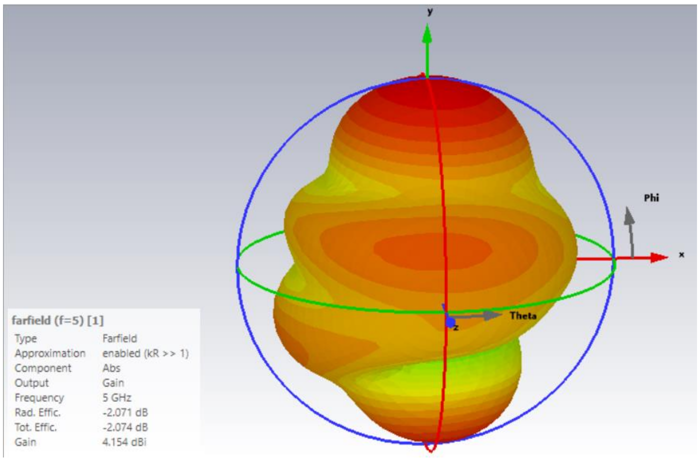


Figure 4.14: Radiation pattern of 2.4 GHz frequency band



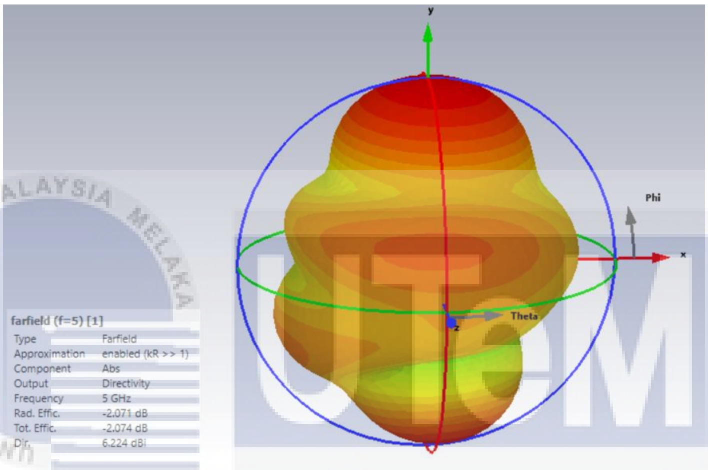


Figure 4.15: Radiation pattern of 5 GHz frequency band

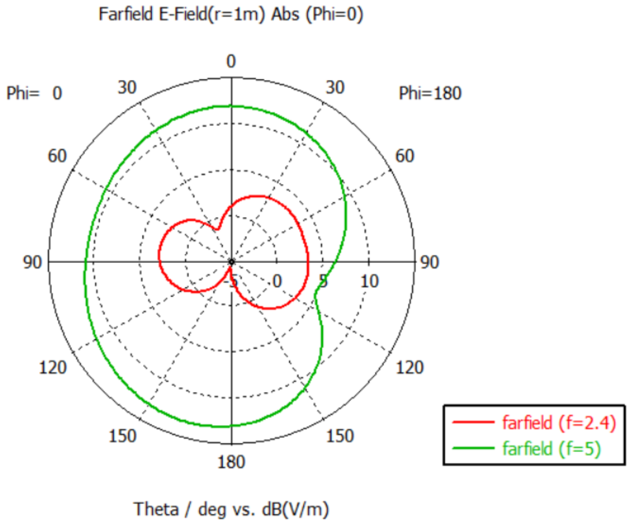


Figure 4.16: Phi = 0°

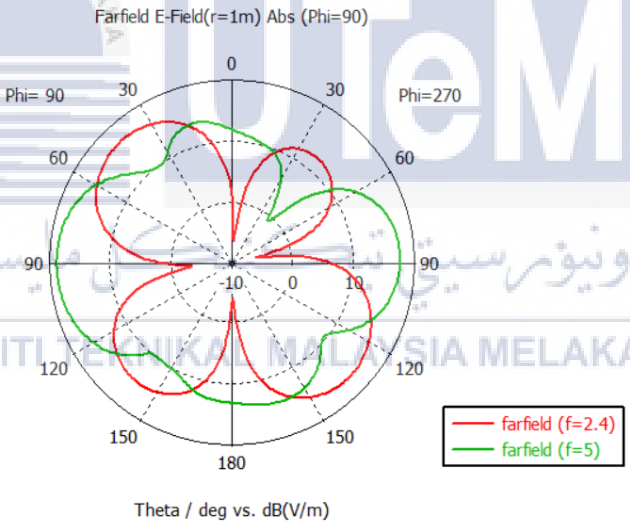


Figure 4.17: Phi = 90°

f. Gain

The simulation and measurement gain of the MLA is presented in Figure 4.18 and Figure 4.19. The antenna yields simulation gain of 2.405 dBi at 2.4 GHz and 4.154 dBi at 5 GHz. The measurement gain of the fabricated MLA is 2.94 dBi at 2.4 GHz and 4.117 dBi at 5 GHz.

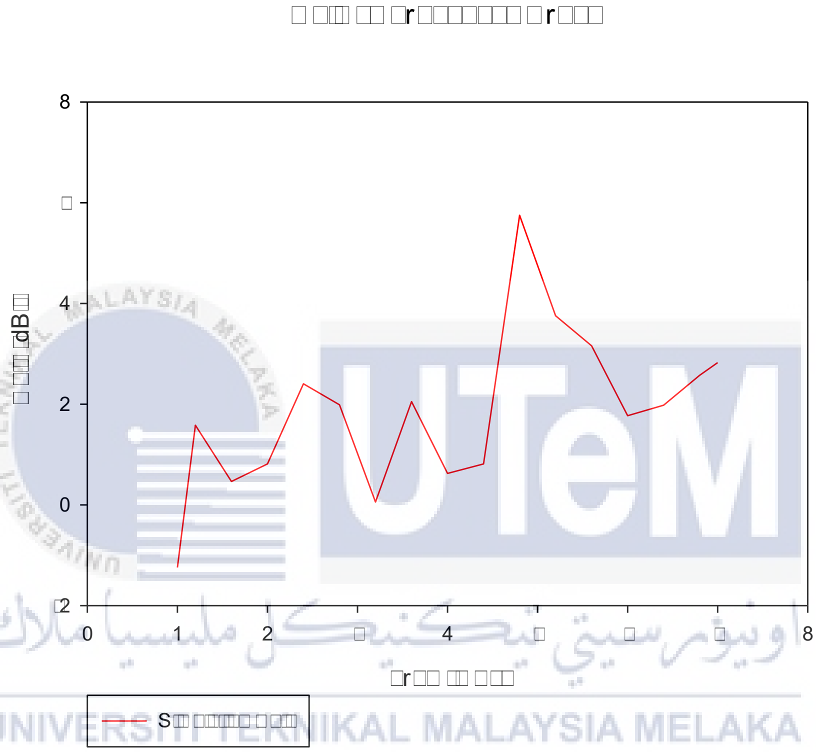


Figure 4.18: Simulation gain of the proposed antenna design

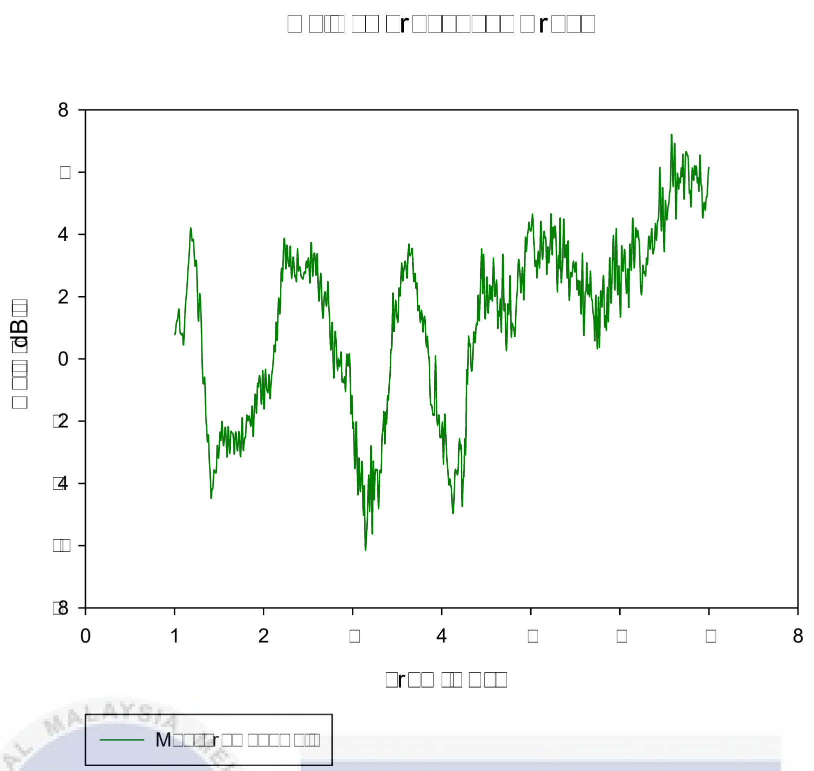


Figure 4.19: Measurement gain of the fabricated MLA

g. Directivity

The MLA design has directivity of 3.866 dBi for 2.4 GHz and 6.224 dBi for 5 GHz when simulated in CST software. The measurement result shows that the fabricated MLA has directivity of 4.033 dBi at 2.4 GHz and 6.752 dBi at 5 GHz. Figure 4.20 and Figure 4.21 depict the simulation and measurement result of the directivity of the MLA.

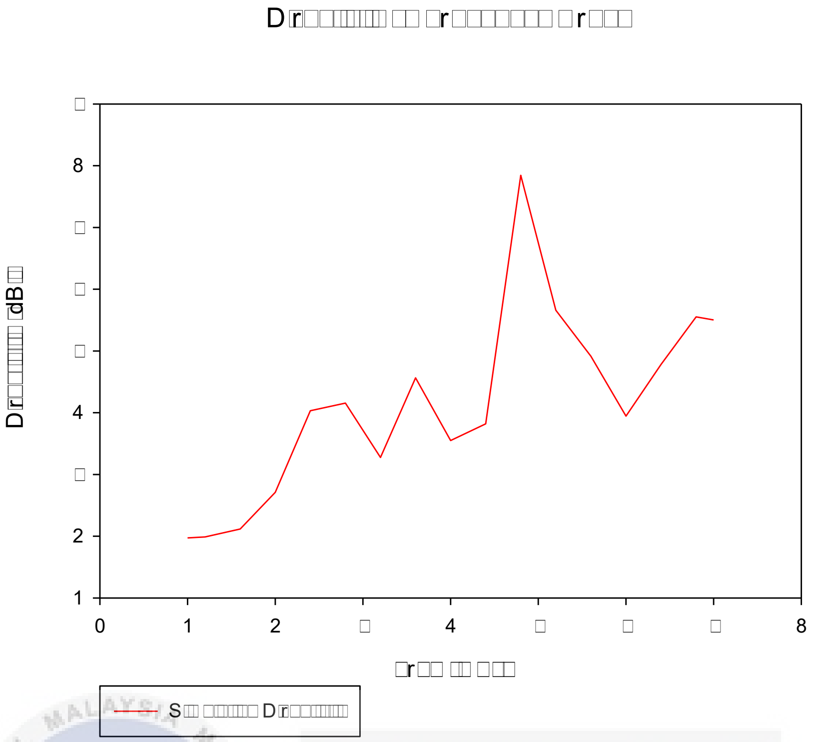


Figure 4.20: Simulation directivity of the proposed antenna design

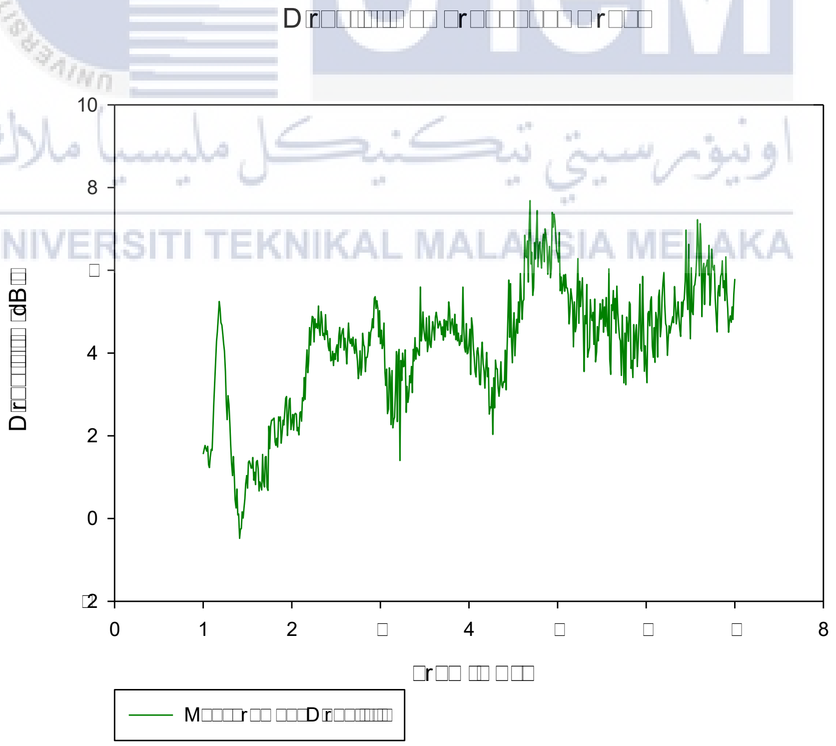


Figure 4.21: Measurement directivity of the fabricated MLA

h. Efficiency

Efficiency is a fundamental metric for evaluating the performance of an antenna. It provides insights into how effectively the antenna converts electrical power into radiated energy. A highly efficient antenna ensures that a significant portion of the input power is radiated as electromagnetic waves. The efficiency of the MLA can be calculated using directivity and gain of the antenna [27]:

$$Efficiency, \eta = \frac{gain}{directivity} \times 100\% \tag{4.1}$$

Efficiency for simulation result:

Efficiency for 2.4 GHz:

$$\eta = \frac{2.405}{3.866} \times 100\%$$

$$\eta = 62\%$$

Efficiency for 5 GHz:

$$\eta = \frac{4.154}{6.224} \times 100\%$$

$$\eta = 67\%$$

<u>Efficiency for measurement result:</u>

Efficiency for 2.4 GHz:

$$\eta = \frac{2.94}{4.033} \times 100\%$$

$$\eta = 73\%$$

Efficiency for 5 GHz:

$$\eta = \frac{4.117}{6.752} \times 100\%$$

$$\eta = 61\%$$

i. Comparison of simulation result and measurement result

Figure 4.22 shows the comparison graph of return loss between simulation and measurement result while Figure 4.23 and Figure 4.24 illustrate the comparison graph of gain and directivity between both simulation and measurement result. Based on the result plot, the results are similar between the simulation and measurement with slightly different due to fabrication errors such as cutting dielectric process and the SMA port soldered onto the transmission line of the MLA.

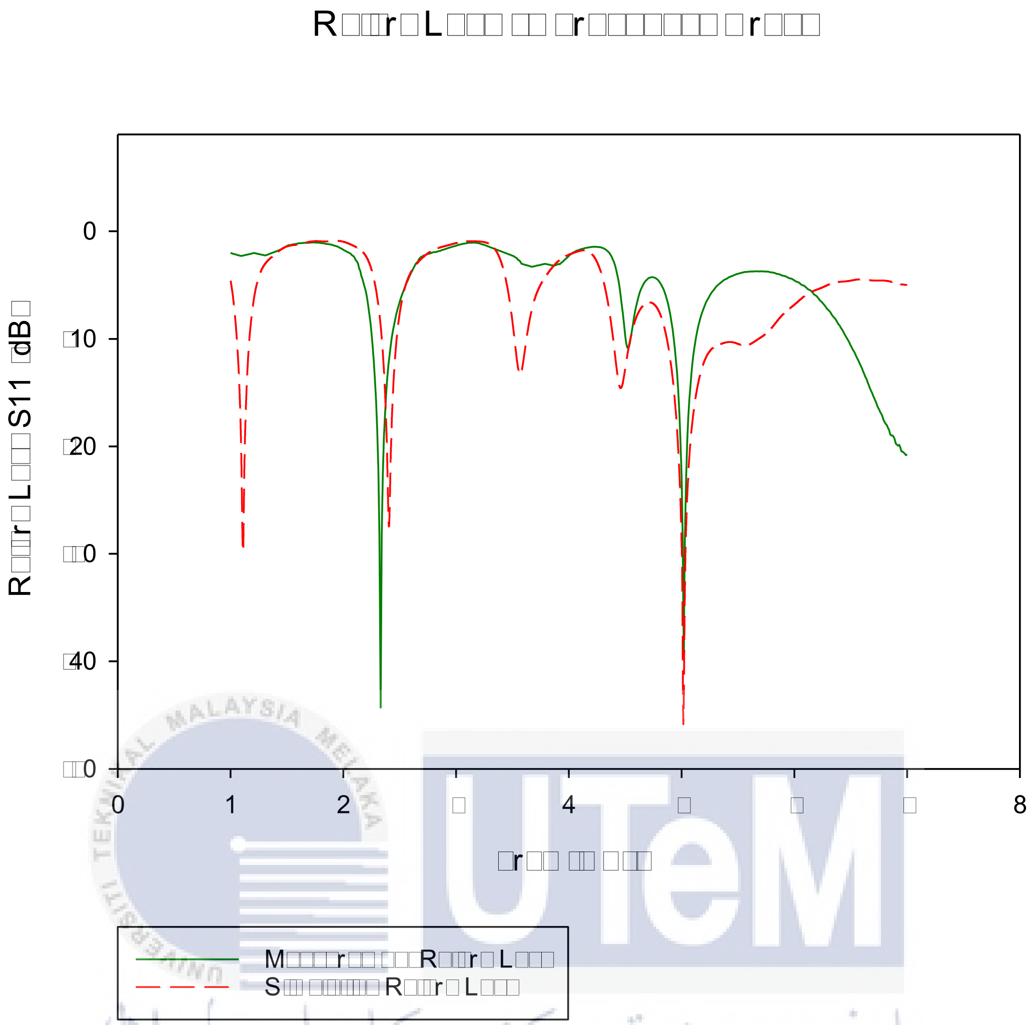


Figure 4.22: Comparison of S11 graph

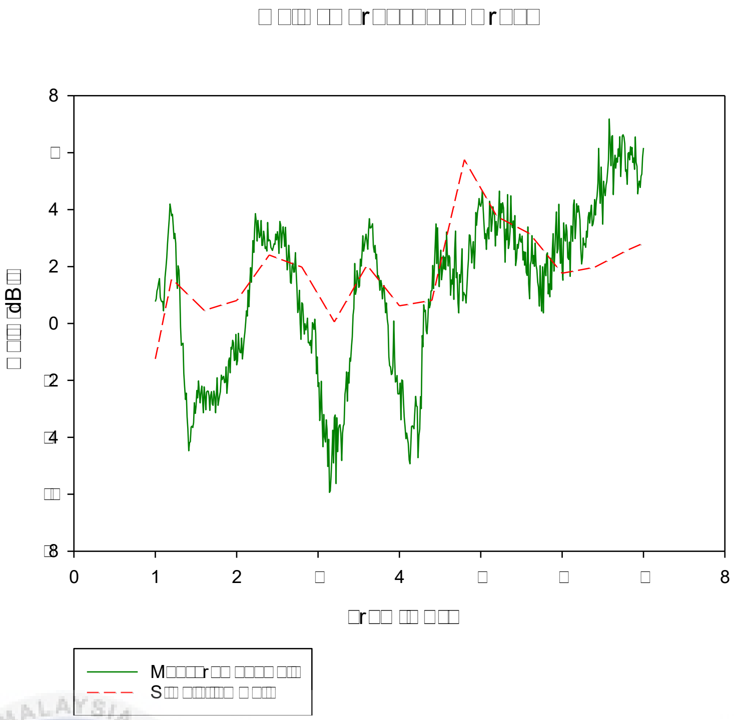


Figure 4.23: Comparison of gain graph

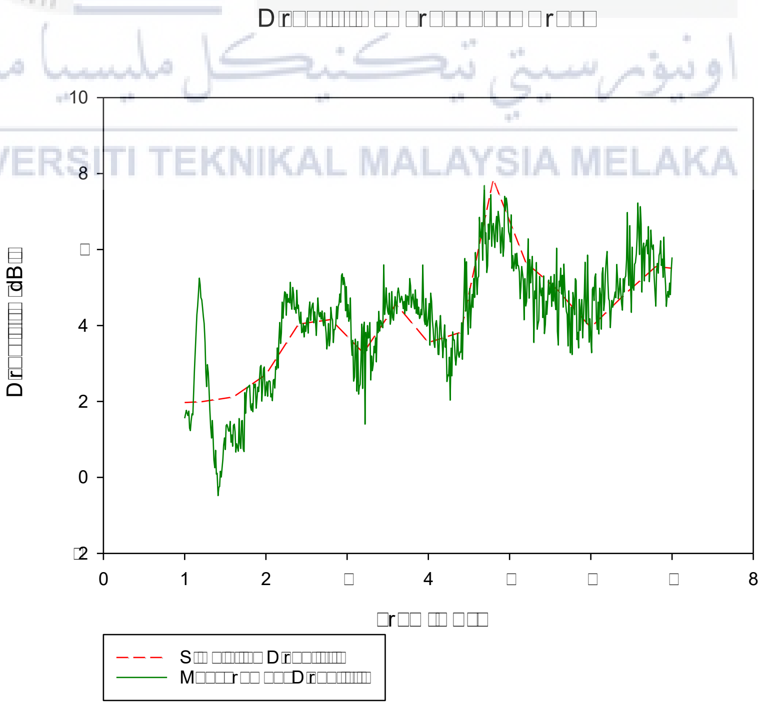


Figure 4.24: Comparison of directivity graph

The overall comparison result between simulation and measurement is expressed in Table 4.2. Based on the table, the simulation antenna performs better at 5 GHz than 2.4 GHz while the fabricated antenna performs better at lower frequency 2.4 GHz.

Table 4.2: Comparison between parameters of measurements and simulations

Resonance Frequency (GHz)	Type of results	S_{11} (dB)	Gain (dBi)	Directivity (dBi)	Efficiency (%)
2.4	Simulation	-26.92	2.405	3.866	62
	Measurement	-40.74	2.94	4.033	73
5	Simulation	-45.34	4.154	6.224	67
	Measurement	-39.17	4.117	6.752	61

j. Analysis of current and recent research

Table 4.3 shows the comparison of recent literature review. From the table, it can be observed that the antenna has a trade-off between the size and the gain. The proposed work design is to minimize the dimension of the size while maintaining a good return loss and high gain to increase its efficiency.

Table 4.3: A comparison of the recent literature concerning the proposed design

Reference	Dimension (mm^3)	Frequency (GHz)	S_{11} (dB)	Gain (dBi)
[15]	$46 \times 20 \times 1.6$	2.4	-15	0.5
		5	-27	2.5
[16]	$18 \times 12 \times 1.5$	2.4	-23	-
		5	-14	-
[17]	$25 \times 45 \times 1.6$	2.4	-25	1.15
		5	-35	4.75
[18]	$10 \times 50 \times 0.8$	2.4	-31.17	1.918
		5	-42.05	2.303
[19]	$30 \times 30 \times 1.6$	2.4	-34.88	2.99
		5	-12.56	1.25
[20]	$50 \times 150 \times 11.1$	2.4	-28	8.4
		5	-32	7
Proposed work	$19 \times 75 \times 1.6$	2.4	-40.74	2.94
		5	-39.17	4.117

CHAPTER 5

CONCLUSION AND FUTURE WORKS

In summary, this project has successfully achieved compact antenna size with good return loss and gain at desired resonant frequency. The antenna achieved resonant frequencies at 2.328 GHz and 5.020 GHz with S-parameter of -40.74 dB and -39.17 dB. It also possesses desirable gain at both resonant frequencies where 2.4 GHz has gain of 2.94 dBi and 5 GHz yield a gain of 4.117 dBi. Furthermore, the antenna also achieved efficiency over than 60%, for both frequency bands. This reduces the overall energy consumption of the communication system, contributing to energy efficiency and sustainability. Despite the project's successes, it is essential to acknowledge its limitations. Meander line antennas are often designed for specific frequency bands, and achieving broad bandwidth can be challenging. This limitation may restrict their applicability in systems that require wide frequency coverage. Thus, future work and research may be done to improve the bandwidth of meander line antenna while maintaining its compact size and performance.

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APPENDICES

Appendix A: Gantt Chart of Research Activities

A. PERANCANGAN PROJEK
PROJECT PLANNING (GANTT CHART)

Senaraikan aktiviti-aktiviti yang berkaitan bagi projek yang dicadangkan dan nyatakan jangka masa yang diperlukan bagi setiap aktiviti.
List all the relevant activities of the proposed project and mark the period of time that is needed for each of the activities.

	SEM I																			SEM BREAK					SEM II															
Aktiviti Projek *Project Activities*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PSM briefing and discussion with supervisor on introduction of the chosen topic	X																																							
Proposal writing				X																																				
Proposal approval and submission					X																																			
Proposal defense					X																																			
Software preparation -Install CST Software -CST Software learning tutorial							X				SEMINAR PSM I																											SEMINAR PSM II		
Project development -Design antenna -Simulation of antenna																												X												
Project fabrication																																		X						
Project testing and measurement																																		X						
Thesis writing																																					X			
Submission of final thesis																																							X	